

Geochemical characterization of gaseous
reservoirs in the enstatite-chondrite
forming-region of the proto-solar nebula:
Constraints from Li-isotope, O-isotope, and
trace-element compositions in chondrule
components

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September 12, 2025

Abstract

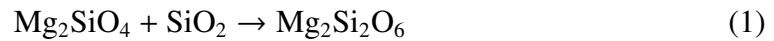
Due to isotopic similarities for an array of elements, enstatite chondrites have been proposed to be the potential building blocks of Earth. However, their respective Mg/Si ratios differ from each other. This makes it difficult to say for certain that enstatite chondrites are the building blocks of Earth. The precursor material for the solar system would have allowed for both enstatite chondrites and Earth to have formed. The evolutionary pathways and mechanisms that would result in the enstatite chondrites and Earth's distinct Mg/Si ratios and a few sets of isotope compositions are as of now uncertain. The motivation of this study is to investigate the potential evolutionary pathway of the enstatite chondrites and see if this can shed some light on why the respective Mg/Si ratios of enstatite chondrite and Earth differ.

An initial petrographic survey was conducted on an array of enstatite chondrites that differ in degree of heating on asteroids, ranging from E3 to E7. At the first order, the mineralogies of the different enstatite chondrites were similar to one another. This initial survey sought to understand whether enstatite chondrites undergo reduction in the nebula or on the asteroid. The presence of sulphides and metal with a lack of FeO-rich pyroxenes in all of the surveyed meteorites indicated that enstatite chondrites become reduced already at the E3 stage. An aim of this study was to gain an understanding of how the enstatite chondrite forms from the precursor material. To understand this, the geochemical properties of the nebula environment that produces enstatite chondrites needs to be determined. As chondrules formed in the nebula, an array of chondrules from the least heated enstatite chondrites were examined.

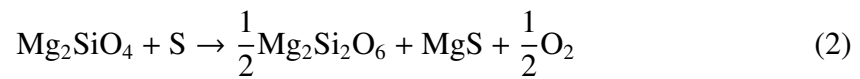
Previous studies proposed that enstatite chondrite chondrules may have originated from olivine-rich precursor chondrules. To confirm this and determine the isotopic composition of the gas reservoir that interacted with the olivine-rich precursor chondrules, in situ ion-microprobe analyses of Li- and O-isotope compositions for chondrule components were carried out. EH3 chondrules are the least metamorphosed of the enstatite chondrites, making them ideal analogues for understanding the protosolar nebula in the enstatite-chondrite forming-region. However, the supply of EH3 chondrites is limited. EH4 chondrites are the next best option for this study as their chondrules still retain a record of their nebula environment and have been subjected to a relatively minor degree of metamorphism compared to E5-E7 chondrites. This study makes use of both EH3 and

EH4 chondrules. On this study, enstatite, FeO-rich pyroxene, olivine, glass, and cristobalite in six chondrules from the Sahara 97103 EH3, one chondrule fragment from the Indarch EH4, and two chondrules from the Y74370 EH4 chondrite are analyzed.

The O-isotope composition of the enstatites in the EH3 chondrules scatters on the intersection between terrestrial fractionation and primitive chondrule minerals lines while that of olivine varies on the primitive chondrule minerals line. Raman spectroscopy allowed the high temperature silica phase cristobalite to be identified in five of the EH3 chondrules. Due to a lack of accompanying metal, the cristobalite was interpreted to have formed due to Si saturation rather than the reduction of FeO-rich silicates. This is consistent with the Si-enrichment of whole-rock enstatite-chondrites. Relict olivines were identified in three chondrules based on their petrography and O-isotope compositions. These chondrules were observed to lack or contain very minor niningerite [(Mg,Fe,Mn)S]. This indicates that the process of adding SiO₂ referred to here as sili-cification to the melted or partially melted olivine-rich precursor by the following reaction:



This is the dominant process for producing enstatite in the enstatite-chondrite-chondrule forming-region, rather than sulphidation by the following reaction:



In the EH4 chondrules the O-isotope compositions of the enstatites were consistent with those of the EH3 enstatites. The O-isotope composition of the enstatites in the EH3 chondrules is the result of those of the precursor olivine and additional SiO₂. The O-isotope composition of the SiO₂ was estimated from a mass balance equation using the O-isotope compositions of the olivines and the enstatites. The Si-rich gas in the enstatite-chondrite forming-region during chondrule formation was estimated to be ($\delta^{18}\text{O}, \delta^{17}\text{O}, \Delta^{17}\text{O}$)=(5.4,3.7,1.0‰). The $\Delta^{17}\text{O}$ of the Si-rich gas was determined to be consistent with the enstatite whole-rock-value.

Enstatite was determined to be the major Li carrier in EH3 chondrules as they are enriched in Li compared to the olivines. The Li-isotope composition of the enstatites is consistent with the whole EH3 chondrite value and is larger than that of the olivines. In the EH4 chondrules the Li concentration of the enstatites was consistent with those

of the EH3 enstatites, while those of the EH4 olivines are consistent with the enstatites in the same chondrule. The $\delta^7\text{Li}$ values of the EH4 enstatites and olivines were also consistent with each other. This may be the result of secondary processes on the enstatite asteroid causing the $\delta^7\text{Li}$ and Li concentration values to become more homogenised.

A similar mass balance calculation that was used for the O-isotope composition was applied for the Li-isotope composition of the Si-rich gas. When the enstatite is assumed to be in equilibrium with the added SiO_2 , the estimated Li-isotope composition of the Si-rich gas was also found to be consistent with the result of the mass balance calculation. Thus, the gas was estimated to have a $\delta^7\text{Li}$ value of 2‰. The estimated $\delta^7\text{Li}$ of the Si-rich gas in the enstatite-chondrite forming-region differs significantly from the $\delta^7\text{Li}$ value of the Si-rich gas on carbonaceous-chondrule forming-region was estimated to be -11‰ by Kunihiro et al. (2019a). This suggests that the $\delta^7\text{Li}$ of Si-rich gas is heterogeneous throughout Solar nebula, indicating that distinct gas reservoirs were maintained during chondrule-formation.

The O- and Li-isotope compositions of the enstatite chondrules was concluded to have become homogenised during the recycling of enstatite chondrules. In this study it is speculated that the Si-rich gas in carbonaceous-chondrule forming-region maintained Li-isotope heterogeneity by inheriting light lithium synthesized by galactic cosmic-ray in the interstellar medium.

The isotope composition of the Si-rich gas in the enstatite-chondrite forming-region suggests that the reservoir should be well mixed. As the Earth and enstatite chondrites are isotopically similar, they should have formed in the same well mixed reservoir. However, there is not necessarily a direct first-class genetic link between enstatite chondrites and the Earth. This would imply that the difference in their respective Mg/Si ratios is the result of whether they interacted with a Si-rich gas or not. The Si-rich gas in the carbonaceous-chondrite forming-region may maintain its isotope heterogeneity which was inherited from the solar system precursor material. This will have allowed for the preservation of foreign light elements such for lithium and boron, with extreme isotope compositions, which will have reacted with the Si-rich gas. The mechanism that forms the Si-rich and S-rich gases responsible for silicification and sulphidation are unknown. The Si-rich gas may have been generated by the evaporation of SiO_2 -rich dust, or may have existed as a steady gas that excluded refractory elements. The form that the S-rich gas in the inner solar system would have taken is unknown. Future investigations into

the surface material of Mercury will likely shed new light on inner solar system S-rich gas.

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Chapter 1

Introduction

1.1 Study motivation and goals

Enstatite chondrites have been proposed to be the potential building blocks of Earth due to their isotopic similarities (Javoy et al., 1984; Clayton, 1993; Meisel et al., 1996; Dauphas et al., 2004; Trinquier et al., 2007, 2009; Regelous et al., 2008; Fischer-Gödde and Kleine, 2017; Huang and Jacobsen, 2017). However, they deviate from each other in terms of their respective Mg/Si and Si-isotope compositions (Tanaka and Nakamura, 2017). Weisberg et al. (1994) proposed that enstatite chondrites originated from olivine-rich precursors that had compositions similar to that of other chondrite types. This implies that chondritic material migrated from the outer solar system to the inner solar system. Ice will have been produced from beyond the snow line (Jacquet, 2014) and will migrate towards the inner solar system along with silicates (Stepinski and Valageas, 1997; Cuzzi and Zahnle, 2004). Non-carbonaceous asteroids occur closer to the Sun than carbonaceous asteroids, this is attributed to the migration of solid material from the outer to the inner solar system (Jacquet, 2014). This creates the potential for several evolutionary pathways for enstatite chondrites and Earth. Everything in the solar system will have originated from solar-system precursor material, which would have formed the carbonaceous chondrites. However, it is uncertain if this precursor material directly formed enstatite chondrites, or if enstatite chondrites formed from a precursor chondrule with a composition similar to other chondrites, such as carbonaceous chondrites. It is also uncertain if Earth formed directly from the solar-system precursor material, or from enstatite chondrites. The processes that lead to the evolution of terrestrial

planetary bodies such as Earth are as of now uncertain, as is the process that differentiated enstatite- and carbonaceous-chondrites. Figure 1.1 shows the potential pathways for the production of enstatite chondrites. A key question that will be addressed in this study is “if enstatite chondrites formed from an initial olivine-rich precursors, what is the dominant process that produced them?”

Enstatite chondrites and the solar nebula have been extensively studied. However, the lithium-isotope composition of the enstatite chondrite chondrule forming region is as of yet unknown. Tanaka et al. (2021) found that in EH3 and EH4 chondrites, chondrules with larger $\Delta^{17}\text{O}$ have smaller $\delta^{30}\text{Si}$. They proposed that the oxygen- and silicon-isotope compositions of the EH3 and EH4 chondrules reflect the isotope compositions of differentiated planetary body precursors (Tanaka et al., 2021).

In this project the major aims are as follows. (1) What stage in the production of enstatite chondrites is the low Mg/Si ratio and reduced nature established. (2) Determine whether silicification or sulphidation is the dominate process in producing enstatite from olivine-rich precursors in the enstatite-chondrite forming-region. (3) Gain an understanding of the geochemical properties of a gas reservoir in the enstatite chondrite forming region. The lithium-isotope, oxygen-isotope, and trace-element compositions of chondrule components in the Sahara 97103 (EH3), Indarch (EH4), and Yamato 74370 (EH4) meteorites will be determined. Enstatite is the product of gas-melt interactions between the reservoir and the melted or partially melted olivine-rich precursor. Thus the O- and Li-isotope compositions of the gas reservoir will be estimated from those of the enstatites and the olivines in the EH3 and EH4 chondrules.

The reasoning for selecting these meteorites is because the EH3 preserves the most pristine record of the early proto-solar nebula in the enstatite chondrite chondrule forming region, and the EH4 will give an indication of how the region evolved at the beginning of the accretion of the EH asteroid. These meteorites were also analysed by Tanaka et al. (2021). In their study, Tanaka et al. (2021) determined the O- and Si-isotope compositions of EH chondrules and found that chondrules with a large $\Delta^{17}\text{O}$ typically has smaller $\delta^{30}\text{Si}$ values, which is consistent with non-carbonaceous differentiated planetary bodies. Tanaka et al. (2021) suggests this consistency is an indicator that EH chondrules record the isotope compositions of the major precursors of differentiated planetary bodies. This is relevant to my study because Tanaka et al. (2021) attributed the O- and Si-isotope variations in the EH chondrule to gas-melt interactions between an olivine-

rich precursor and a Si-rich gas. If a similar correlation that was observed between $\Delta^{17}\text{O}$ and $\delta^{30}\text{Si}$ is observed between $\Delta^{17}\text{O}$ and $\delta^7\text{Li}$, this will give an indicator as to the mechanisms that control isotope fractionation in the enstatite chondrule forming region. This is the first study to examine the Li-isotope compositions of individual chondrule constituents in EH3 and EH4 chondrites.

This study is important because it is the first study to determine the Li-isotope composition of enstatite chondrule components. This study is also the first to estimate the Li-isotope composition of a Si-rich gas in the enstatite-chondrite forming-region, and compare it to the estimated Li-isotope composition of a Si-rich gas in the carbonaceous-chondrite forming-region. This allows for the variations between the inner and outer solar system to be compared.

1.2 What are chondrites?

Meteorites are broadly classified as melted and unmelted meteorites (Russell et al., 2018). The melted meteorite group are made up of irons, stony irons, and achondrites, and unmelted meteorites are known as chondrites (Russell et al., 2018). Primitive achondrites are partially melted meteorites and some have been found to contain rare chondrules (Krot et al., 2014). Chondrites are undifferentiated stony meteorites that are considered to represent terrestrial planet precursors (Yoshizaki et al., 2021). They are considered to have formed from some of the oldest known rocks, produced during the formation of the solar system (Scott and Krot, 2014). Thus they retain records of the bulk composition of the early solar system and within a factor of 2, have similar bulk compositions as the Sun (Palme et al., 2014). Chondrites are comprised of several minerals that were formed and/ or altered due to solar nebula processes, heating events or aqueous alteration (Shu et al., 2001). The bulk of these minerals are ultramafic with their compositions dominated by iron, magnesium, silicon, and oxygen. Many chondrites are enriched in refractory elements. They are interpreted to be highly resilient fragments that were broken off of their asteroidal parent bodies during impact events (Scott and Krot, 2014). Chondrites are comprised of spherical igneous particles called chondrules, fine-grained interstitial matrix, refractory inclusions, and amoeboid olivine aggregates (AOAs) (Krot et al., 2009).

According to Connolly and Jones (2016) there are seven primary reasons why chon-

drites are important. The first is that many chondrites contain minerals that formed from processes that occurred prior to accretion (Brearley and Jones, 1998; Scott and Krot, 2005; Weisberg et al., 2006). The second is that with the exception of volatiles, chondrite bulk composition are considered to be similar to the photosphere of the Sun (Sears and Dodd, 1988; Brearley and Jones, 1998; Scott and Krot, 2005; Weisberg et al., 2006; Palme et al., 2014). The third is that they contain refractory inclusions which are considered to be some of the oldest known materials, providing a solar system age of 4567 Ma (Amelin et al., 2002; Bouvier and Wadhwa, 2010; Desch et al., 2010; Connelly et al., 2012; MacPherson et al., 2012; Scott and Krot, 2014). The fourth is that chondrules record the chronological evolution of minerals (Russell et al., 2006; Kita and Ushikubo, 2011; Bollard et al., 2015). The fifth is the presence of organic matter (Sephton, 2005; Pizzarello et al., 2006; Burton et al., 2013). They record some nucleosynthetic processes in the form of pre-solar grains (Huss and Lewis, 1995; Brearley and Jones, 1998; Zinner, 2007; Weisberg et al., 2006; Nguyen et al., 2007). The seventh is that some chondrites record thermal metamorphism and aqueous alteration post accretion (Sears and Dodd, 1988; Brearley and Jones, 1998; Scott and Krot, 2005; Weisberg et al., 2006).

Chondrites are separated into three primary classes. These are the ordinary and Rumuruti-like, carbonaceous and enstatite chondrites (Sears, 2004; Weisberg et al., 2006, 2015). Two minor chondrite groups have been identified. These are referred to as the K and G groups (Weisberg et al., 2006, 2015). The carbonaceous and non-carbonaceous chondrites are considered to have formed in distinct regions in the outer solar system and closer to the inner system, with Kleine et al. (2020) suggesting that there was a mixing between the different regions but the formation of Jupiter prevented the distinct regions from becoming homogenised. This study will focus on Enstatite chondrites. Details of the study's goals will be discussed in Sub Section 1.7 Aims and Objectives. Chondrites are separated into 13 groups which have been interpreted to originate from different asteroid types (Russell et al., 2018). These include 8 carbonaceous groups (CI, CM, CO, CV, CK, CR, CH, CB), 3 ordinary groups (H, L, LL), 2 enstatite groups (EH, EL) (Weisberg et al., 2006). The behavior of iron and oxygen is very important in chondrites, thus they often play a role in determining the classification of chondrites (Sears, 2004). Chondrites are further separated using the classification scheme devised by Van Schmus and Wood (1967). This scheme assigns a number from

1 to 7 based on their petrological characteristics (Van Schmus and Wood, 1967). According to Russell et al. (2018) types 1 and 2 were subjected to aqueous alteration, types 3 to 6 underwent increasing degrees of heating, and type 7 underwent complete melting. Going from type 3 to type 6 shows a change in both texture and mineralogy, indicating progressive thermal metamorphism (Huss et al., 2006). Chondrites are made up of five primary components. These are chondrules, matrix, metal, sulphides, and in some cases refractory inclusions (Sears, 2004).

Chondrules are igneous textured droplets that form the primary component in chondrites and may have been the most abundant particle during planetesimal accretion (Connolly and Jones, 2016; Russell et al., 2018). This indicates that chondrules are the most important components of chondrites. Chondrules are generally spherical in shape, however, some chondrules have flattened shapes which have been attributed to an encumbrant load or shock (Sears, 2004). Many chondrites experienced shock due to impact events and the extent of the shock varies (Russell et al., 2018). Some chondrites that have undergone shock may lack evidence of it, while others have been melted or brecciated (Russell et al., 2018). Chondrule precursors are considered to have been superheated in the proto-solar nebula, then as the nebula cooled the composition of the precursor material changed (Blander et al., 2009). The spherical shape of chondrules supports this. The distribution of chondrule shapes and sizes depends on the production mechanisms and fragmentation of the chondrules (Sears, 2004). Each chondrite class exhibits specific distributions of chondrule sizes which can be used as potential parameters for classifying the chondrites (Sears, 2004; Weisberg et al., 2006; Russell et al., 2018). This is also true of metal grain sizes (Sears, 2004). Several phases make up their composition. These include ferromagnesian olivine, pyroxene, and metallic Fe,Ni (Krot et al., 2009; Scott and Krot, 2014; Russell et al., 2018), sulphides, and and glassy or microcrystalline mesostasis (Krot et al., 2009).

Chondrules are separated into different types. Type-I chondrules are Mg-rich with porphyritic textures, whereas type-II chondrules are Fe-rich (Krot et al., 2009). The difference in the relative Mg/Fe ratios in the olivines and pyroxene, the relative abundances of Fe,Ni metal, and the relative abundances of chromite in the type-I and type-II indicates that type-I chondrules are more reduced than type-II chondrules (Marrocchi et al., 2024a). Chondrules that have an olivine content of 90 percent or more are referred to as A chondrules, chondrules with pyroxene contents of 90 percent or more are referred to

as B chondrules (Marrocchi et al., 2024a). Chondrules that have a ratio of olivine and pyroxene that is close to 1:1 are referred to as AB chondrules (Marrocchi et al., 2024a).

The most commonly observed texture in chondrules is porphyritic (Russell et al., 2018). This texture is comprised of subhedral to euhedral grains enclosed by fine-grained to glassy mesostasis (Russell et al., 2018). The grains are always observed to be olivine and/ or pyroxene (Russell et al., 2018). Chondrules with just olivine are known as porphyritic olivine (PO) chondrules, chondrules that contain both olivine and pyroxene are porphyritic olivine-pyroxene (POP) chondrules, and the chondrules that only contain pyroxene are known as porphyritic pyroxene (PP) chondrules (Russell et al., 2018; Marrocchi et al., 2024a). PO, POP, and PP chondrules are considered analogues for A, AB, and B chondrules respectively (Marrocchi et al., 2024a). A second commonly observed texture is barred olivine (BO), which is comprised of skeletal olivine grains enclosed by mesostasis (Russell et al., 2018). The olivine forms subparallel plates within the same crystal (Russell et al., 2018). Less common chondrule textures are radial pyroxene (RP), cryptocrystalline (CC), and glassy (GC) (Russell et al., 2018). Metal and sulphides are mostly focused around the outer domains of chondrules and mesostasis consists of glass in lower petrological types or a fine-grained combination of high-Ca pyroxene and feldspar (Russell et al., 2018). Porphyritic chondrules often contain relict grains which tend to be less common in other chondrule types (Russell et al., 2018).

1.3 What are enstatite chondrites?

Enstatite chondrites are a class of highly reduced stony meteorites (Kallemeyn and Wasson, 1986; Hutchison, 2006) with textures similar to those of other chondrites (Jones, 2012). They are considered to be the rarest of the chondritic meteorites, with the least understood mineral assemblages (Hutchison, 2006). Enstatite chondrites display several features that give indications of their reduced nature. (1) Enstatite is favoured over olivine (Jacquet et al., 2018). (2) A high abundance of metallic Fe,Ni (Grossman et al., 1988; Scott, 1988; Weisberg et al., 1988, 1990), with the abundance of Fe,Ni in enstatite chondrites being larger than in ordinary and carbonaceous chondrites (Weisberg et al., 1994). (3) Opaque phases such as silicides and phosphides are in high abundances (Jacquet et al., 2018). (4) Ca and Mg sulphides and metals contain Si (Ringwood, 1960; Wood, 2005; Lehner et al., 2010; Horstmann et al., 2014), these metals include kamacite

(Fe-Ni alloy), perryite $[(\text{Ni}, \text{Fe})_8(\text{Si}, \text{P})_3]$, and schreibersite $[(\text{Fe}, \text{Ni})_3\text{P}]$ with average Si wt% of 2.6, 12, and 0.1 respectively in EH chondrites with EL chondrites exhibiting lower values (Keil, 1968; Ringwood, 1960). (5) Almost all metals in enstatite chondrites are present as low-Ni kamacite (Kallemeyn and Wasson, 1986). (6) Lithophile elements are locked in unique sulphide or nitride phases (Wood, 2005; Jacquet et al., 2018). (7) Elements that are generally lithophile often display chalcophile behaviours (El Goresy et al., 1988; Weisberg et al., 1994). (8) Olivine and low-Ca pyroxene are iron-poor (Wood, 2005).

Enstatite chondrites have been considered as representative material for the Earth (Javoy, 1995; Javoy et al., 2010; Boyet et al., 2018). This is because of isotope similarities between enstatite chondrites and Earth for many elements, such as O, N, Ca, Ti, Cr, Ni, Mo, Ru, Os (Javoy et al., 1984; Clayton, 1993; Meisel et al., 1996; Dauphas et al., 2004; Trinquier et al., 2007, 2009; Regelous et al., 2008; Fischer-Gödde and Kleine, 2017; Huang and Jacobsen, 2017). Recently Dauphas (2017) proposed that enstatite-chondrite-type material represents at least 70% of building blocks of Earth. On the basis of FeO content of the present-day mantle, Clesi et al. (2016) proposed that the Earth could have been accreted from 85 to 90% of material similar to the EH chondrite. This suggests that enstatite chondrites are comprised of material from the inner solar system, rather than an exotic reservoir (comprised of material that likely originated from the inner solar system) (Jacquet et al., 2018).

Enstatite chondrites are characterized by abundant metal, troilite (FeS), niningerite $[(\text{Mg}, \text{Fe}, \text{Mn})\text{S}]$, and oldhamite (CaS). Enstatite chondrites likely formed under a reduced environment, such as the protoplanetary disk close to the Sun. Abundant hydrocarbon in the disk or high C/O ratio around a very-low-mass star was observed by mid-infrared spectroscopy (Arabhazi et al., 2024). O-isotope composition of FeO-bearing pyroxenes from unequilibrated enstatite chondrites is similar to that of coexisting pure enstatite (Kimura et al., 2003; Weisberg et al., 2011). This indicates they formed from the same isotope reservoir, and migration from different chondrule forming-regions did not occur (Kimura et al., 2003; Weisberg et al., 2011). Thus enstatite chondrites may have formed in a similar environment. Since an FeO-bearing pyroxenes is enclosed by enstatite, the FeO-bearing pyroxenes formed prior to enstatite under more oxidized environment. This implies that the enstatite-chondrule forming-region was originally more oxidizing, and/or precursors of enstatite chondrule had chemical compositions similar

to the precursors of other chondrite groups (Weisberg et al., 2021).

The composition of enstatite chondrite differ from ordinary and carbonaceous chondrites. The composition of enstatite chondrites is generally comprised of approximately 5 vol% sulphides, 27 vol% chondrules, 16 vol% metal, and 52 vol% matrix (Sears, 2004). Whereas ordinary chondrites are comprised of 5 vol% sulphides, 67 vol% chondrules, 10 vol% metal and 18 vol% matrix (Sears, 2004).

According to Wood (2005), enstatite chondrites have three primary stages of development (Figure 1.2). In the first stage the chondrule precursor under goes heating, allowing for the production of the enstatite chondrule, dominated by enstatite, with accompanying sulphides and interfiling glass (Wood, 2005). In the second stage the chondrules are accreted into the enstatite asteroid (Wood, 2005). In the third stage, the enstatite asteroid undergoes heating, allowing it to approach chemical equilibrium (details are discussed in Chapter 2), with the grain size increasing and the glass turning into plagioclase (Wood, 2005).

Enstatite chondrites are separated into two groups. The first is the Fe-rich (high siderophile) EH group, and the second is the Fe-poor (low siderophile) EL group (Sears et al., 1982; Hutchison, 2006). Wood (2005) suggested that EL chondrites formed when metals were lost due to EH chondrites gaining metals during chondrule formation. The metal component in enstatite chondrites is primarily comprised of kamacite (FeNi), with EL chondrites also containing perryite ($[\text{Ni}, \text{Fe}]_8[\text{Si}, \text{P}]_3$) (Krot et al., 2014). The metal in EH chondrites is enriched in Si relative to the EL chondrites (Krot et al., 2014). Sears (2004) suggested that EH chondrites cooled rapidly relative to EL chondrites. This would indicate that EH chondrites did not undergo the same intensive metamorphism that EL chondrites were subjected (Sears, 2004). Keil (1989) determined that there are differences in the bulk composition of the two sub groups, especially with non-volatile major elements. This was considered to be due to nebula processes, rather than planetary processes (Keil, 1989). Both sub groups are brecciated but EH chondrites do not have EL clasts and vice versa (Keil, 1989). This indicates that the two sub groups do not originate from the same parent bodies (Keil, 1989). Schneider et al. (2002) observed three differences in the chondrules of the EH and EL chondrites. These are that the EH chondrules tend to be smaller than the EL chondrules, the presence of fine-grained sulphides and metal gives EL chondrules varying shades of red cathodoluminescence, the mesostasis in EH chondrules is Na-rich compared to the EL counterpart (Schneider

et al., 2002).

Enstatite chondrites contain between 60 and 80 vol% of chondrules (Scott and Krot, 2014). Schneider et al. (2002) determined that EH3 chondrules ranged from 45 to 1313 μm averaging 278 μm in diameter and EL3 chondrules ranged from 85 to 2125 μm averaging 476 μm . The most common texture observed for enstatite chondrules is the PP texture type (Jacquet et al., 2018). The enstatite chondrules are dominated by enstatite, with occasional olivine (mostly minor and sometimes observed as poikilitic inclusions and relict grains), with glassy mesostasis, Ca-rich pyroxene, and minor silica (Jacquet et al., 2018). The silica is usually present as cristobalite or tridymite, but can also be present as quartz and glass (Kimura et al., 2005).

Enstatite has three polymorphs, protoenstatite (orthorhombic), ortho-enstatite (orthorhombic), and clino-enstatite (monoclinic) (Jones et al., 2018). Proto-enstatite is only stable at temperatures over 1000 degrees C and is not quenchable (Jones et al., 2018). Proto-enstatite is never observed at room temperature as it can become either ortho- or clino-enstatite when the temperature decreases below 1000 degrees C. Smyth (1974) found that clino-enstatite forms when the sample is rapidly quenched and ortho-enstatite forms when the cooling rate is slower. Töpel-Schadt and Müller (1985) showed that in EH3 and EL3 chondrites, enstatite is present as clino-enstatite, and as ortho-enstatite at higher petrological types. This indicates that the enstatites in the E3 chondrites were rapidly quenched, whereas the enstatites in the E4 and higher cooled more slowly. This suggests that chondrules cooled rapidly in the nebula and E4 chondrites were likely heated by internal heating before cooling slowly in the asteroid interior.

Shukolyukov and Lugmair (2004) examined the ^{53}Mn - ^{53}Cr isotope systematics of the EH4 chondrites Indarch and Abee and the EL6 chondrite Khairpur. There is no significant difference in the Mn/Cr ratio of these meteorites and the Mn/Cr ratio of ordinary chondrites, however the ^{53}Cr abundance of the enstatite chondrites is three times smaller, compared to those of the ordinary chondrites (Shukolyukov and Lugmair, 2004). As enstatite chondrites are undifferentiated, Mn/Cr fractionation would not have occurred on the enstatite asteroids indicating that the ^{53}Mn was initially heterogeneous in the early solar system (Shukolyukov and Lugmair, 2004). Based on the ^{53}Cr excess observed for the enstatite chondrites and the observed gradient, Shukolyukov and Lugmair (2004) proposed that enstatite chondrites formed at approximately 1.4 AU. The ^{53}Mn - ^{53}Cr gave ages of 4565 Ma for the EH4 chondrites and the EL6 was determined

to be 4.5 Ma younger (Shukolyukov and Lugmair, 2004). This difference in age may be the result of EH chondrites cooling significantly faster than EL chondrites (Zhang and Sears, 1996; Zhang et al., 1996). Alternatively, as type 6 meteorites are from deeper in the asteroid compared to type 4 meteorites, the type 6 would be expected to cool more slowly and been subjected to higher metamorphic temperatures.

1.4 Production of low-Ca pyroxene from an olivine-rich precursor

The Mg/Si and Si-isotope composition of enstatite chondrites differs from those of Earth (Tanaka et al., 2021). This is an issue as it suggests that enstatite chondrites are not necessarily the building blocks of Earth (Tanaka et al., 2021). One of the ways to account for this is the presence of a Si-rich gas in the enstatite chondrite forming region of the solar nebula (Tissandier et al., 2002; Libourel et al., 2006; Chaussidon et al., 2008; Tanaka and Nakamura, 2017; Tanaka et al., 2021). Tissandier et al. (2002) determined that silica provided to chondrule melt from a Si-rich gas contributes to mineralogical zonation of olivine-bearing chondrules, pyroxene-rich rims, and olivine reabsorption textures. Libourel et al. (2006) analysed the bulk composition and modal abundances of chondrule components in carbonaceous chondrules and determined gas-melt interactions were responsible for the variation in their type I chondrules. Chaussidon et al. (2008) and Tanaka and Nakamura (2017) examined the O-isotope compositions of chondrule components in carbonaceous and enstatite chondrules respectively. Their studies suggests that low-Ca pyroxene was produced by olivine interacting with a Si-rich gas (Chaussidon et al., 2008; Tanaka and Nakamura, 2017). The O- and Si-isotope compositions of EH chondrules determined by Tanaka et al. (2021) also supports low-Ca production by olivine interacting with a Si-rich gas. There is no evidence of this gas still existing in the modern solar system. However, McClure et al. (2025) did observe a Si-rich gas in the inner disk of a young protostar. Details of this will be given in Chapter 5. Interactions with such as gas may explain why The Mg/Si and Si-isotope composition of enstatite chondrites differs from Earth (Tanaka et al., 2021).

Enstatite chondrites are unusual in the sense that enstatite is favoured over olivine (Weisberg et al., 1994). Some enstatite chondrites have been found to contain Fe-rich silicates which would have been expected in more oxidised chondrules (Weisberg et al., 1994). This is supported by textural relationships between Fe-rich and Fe-poor en-

statites indicating that at least some of the enstatite chondrite precursors were more oxidised (Weisberg et al., 1994). Thus the precursors of the enstatite chondrites were likely olivine-rich with similar compositions to that of ordinary chondrites (Weisberg et al., 1994). For enstatite to be produced from an olivine-rich precursor, the Mg/Si ratio needs to be reduced. The Mg/Si ratio of enstatite chondrites is 0.73 and 0.88 for EH and EL, while that of ordinary chondrites is 0.96, 0.93, and 0.94 for H, L, and LL, and that of carbonaceous chondrites is 1.07, 1.05, 1.10, and 1.06 for CI and CV, CM and CO, CK, and CH respectively (Dauphas et al., 2015).

Changing the Mg/Si ratio can be achieved by either removing Mg or adding Si. Varela et al. (2015) suggests that removing olivine during chondrule formation is a possible scenario that would allow the Mg/Si ratio to decrease. However, they do not provide evidence that indicate this has taken place. Considering the presence of relict olivine in EH3 and EH4 chondrules (Tanaka and Nakamura, 2017, eg.), the removal of olivine is less likely to have occurred. Lehner et al. (2013) suggests that Mg is removed from enstatite chondrules during the formation of niningerite (MgS) during a sulphidation reaction. In this scenario Mg from the silicates reacts with a S-rich gas to produce MgS (Lehner et al., 2013). This increases the volatility of the Mg resulting in Mg being evaporated until the ambient gas becomes saturated (Lehner et al., 2013). The Mg evaporation is also driven by the Mg/Fe ratio difference between MgS and the equilibrium composition of MgS at high temperatures (Lehner et al., 2013). The MgS would then reach equilibrium. An issue with this is that the Mg/Si and Si-isotope composition of enstatite chondrites differs from those of Earth. One of the ways to account for this is the presence of a Si-rich gas in the enstatite chondrite forming region of the solar nebula.

Petrological and experimental studies conducted by Tissandier et al. (2002), Krot et al. (2004a) and Libourel et al. (2006) suggests that type I chondrule melt composition is the result of gas-melt interactions. This relies on an open system where the melt composition is dictated by partial dissolution of precursor olivines and added SiO₂ in the chondrule melt, with the additional Si-rich components supplied by the nebula gas (Chaussidon et al., 2008). This leads to the production of low-Ca pyroxene and the disappearance of olivine in carbonaceous chondrites (Libourel et al., 2006; Chaussidon et al., 2008). This scenario is supported by the estimated nebula gas compositions determined from type 1 CV and CR chondrule constituents, as the results suggest gas-melt interactions between olivine-rich precursor chondrules and a Si-rich gas (Chaussidon

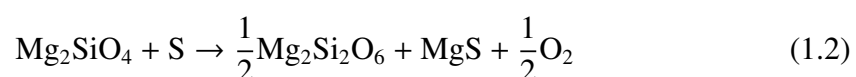
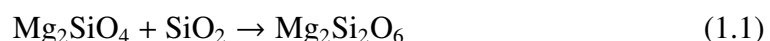
et al., 2008). This relies on the volume of silica in the melt, which is governed by the gas-melt interactions (Chaussidon et al., 2008). The dominate Si-bearing molecule in gases with solar compositions is considered to be SiO (Chaussidon et al., 2008; Javoy et al., 2010, 2012). Thus SiO₂ can be produced by a disproportionation reaction of SiO in the enstatite chondrite forming region (Javoy et al., 2012). Sikdar et al. (2023) determined that the $\delta^{30}\text{Si}$ composition of the SiO gas in the enstatite chondrite forming region was -4.8 ‰. This was determined from two EH3 chondrites (Sahara 97072 and Kota-Kota), one EH4 (Indarch), one EH4 impact melt breccia (Abee), and one EL3 (MAC 88184) chondrites (Sikdar et al., 2023). Based on the estimated $\delta^{30}\text{Si}$ composition of the SiO gas, Sikdar et al. (2023) proposed that the cristobalite or amorphous SiO₂ observed in the EH3 Sahara 97072 formed in the nebula at temperatures of 960K. Considering this temperature the SiO₂ may have resulted from condensed supersaturated gas that has been reduced, while metals are condensing (Sikdar et al., 2023).

Tanaka and Nakamura (2017) observed that contained in the some of the enstatites of EH3 and EH4 chondrules, there were relict olivines. This observation strongly supported the model that to form enstatite from an olivine-rich precursor, there requires a reaction between olivine-rich chondrule melt and added SiO from the nebula (Tissander et al., 2002; Libourel et al., 2006; Chaussidon et al., 2008, eg.). For this reaction to produce silica-rich-chondrules (SRC), it would need to take place at high temperatures in excess of 1960K (Tanaka and Nakamura, 2017). An important observation made by Tanaka and Nakamura (2017) was that EH3 and EH4 chondrules varied in their $\Delta^{17}\text{O}$ values from the bulk enstatite chondrites and with the exception of the SRC, their $\delta^{18}\text{O}$ and $\delta^{17}\text{O}$ values lay on a linear trend. To explain this, Tanaka and Nakamura (2017) followed a similar gas-melt interaction model as Marrocchi and Chaussidon (2015). The results indicated that the chondrule melt and surrounding gas were not in thermodynamic equilibrium (Tanaka and Nakamura, 2017).

In addition to the occurrence of low-Ca pyroxene in type-IAB chondrules, Rubin (2018) suggests that SiO-rich gas in the nebula at high partial pressures can account for several chondrule features. These include compositional zoning in glass-rich mesostasis within ordinary chondrules (Nagahara et al., 1999, 2008), and free silica in the igneous rims of type-IAB CR chondrules (Rubin, 2018). The silica-rich igneous-rims (SIR) surrounding the type-IAB CR chondrules may be the result of Na, K, and Mn enriched pyroxene-dust aggregates from volatilised chondrules surrounding the type-I chondrules

then melting (Rubin, 2018). The SiO_2 and Na_2O in the mesostasis of the chondrules of the LL3.0 Semarkona chondrite increases from the core to the rim (Rubin, 2018). This may be because the chondrules were affected by SiO_2 and Na_2O condensation during chondrule formation, or aqueous alteration on the LL asteroid resulted in compositional zoning (Rubin, 2018).

In this study, the process of adding Si to the melted or partially melted olivine-rich precursor chondrule by gas-melt interactions with a Si-rich gas is referred to as silicification. The processes of producing enstatite from olivine-rich precursors in the enstatite-chondrite forming-region by silicification and sulphidation is represented by the following equations:



It is uncertain if the gas reservoir in the enstatite-chondrite forming-region is Si- and S-rich, or if there are two distinct gas reservoirs in this region that both interacted with the chondrule melt and/ or the heated enstatite asteroid (Figure 1.3).

1.5 Previous work on oxygen-isotope compositions of enstatite chondrites

The O-isotope composition of enstatite chondrites has been extensively documented. The non carbonaceous chondrites are depleted in ^{16}O compared to the carbonaceous. This is attributed to late stage migration of ^{16}O depleted water from the outer solar system to the inner solar system (Jacquet, 2014). Clayton et al. (1984) examined ten EH chondrites, eight EL, and nine aubrites. The average $\delta^{18}\text{O}$ and $\delta^{17}\text{O}$ of the EH, EL, and aubrites were determined to be 5.31 and 2.74, 5.57 and 2.96, 5.24 and 2.70 respectively (Clayton et al., 1984). Among the EH chondrites, those with a higher petrological type tended to have larger $\delta^{18}\text{O}$ and $\delta^{17}\text{O}$ values. However, the EL chondrites plot in a tighter group compared to the EH chondrites (Clayton et al., 1984). The O-isotope composition of the aubrites is tightly packed and similar to the EH chondrite averages (Clayton et al., 1984). All three types of enstatite meteorite lie along the Terrestrial Fractionation

(TF) line, indicating that they share a common oxygen-gas reservoir (Clayton et al., 1984). Considering this, and the similarities of the $\delta^{18}\text{O}$ values of the enstatite meteorites and the terrestrial and lunar pyroxenes suggests a genetic link between enstatite meteorites, the Earth, and the Moon (Clayton et al., 1984).

Newton et al. (2000) determined the O-isotope composition on an array of enstatite meteorites including EH, EL, and aubrites. Their results are similar to those of Clayton et al. (1984) with the majority of the chondrites plotting close to the TF line (Newton et al., 2000). Between the three meteorite types, they report no significant differences, with both EH and EL chondrites showing an increase in $\delta^{18}\text{O}$ with increasing petrological type (Newton et al., 2000).

Weisberg et al. (2011) determined the O-isotope composition of olivines and pyroxenes in three E3 chondrites, these are the EH3 chondrites Sahara 97096 and Y691 and the E3 chondrites with anomalous properties LEW 87223. They report that most of the enstatites plot close to the TF line close to the whole rock values, with others plotting close to where ordinary chondrites often plot on a 3-isotope diagram (Weisberg et al., 2011). The pyroxenes with a larger FeO content typically plot on the TF line with similar values to the enstatites, indicating that they formed in the enstatite chondrite forming region and that some of the enstatite chondrite forming region was more oxidised and some of the region was more reduced (Weisberg et al., 2011). The range of the E3 chondrite O-isotope compositions and their mixing behaviour was determined to be similar to those of the ordinary and carbonaceous chondrites (Weisberg et al., 2011). This indicates that although E3 chondrites formed in an oxygen reservoir that is distinct from those of ordinary and carbonaceous chondrites, the chondrules of all three chondrites classes may have been generated by similar processes (Weisberg et al., 2011). In addition, all three chondrite classes may have experienced similar solid-gas interactions and similar ^{16}O -rich precursors (Weisberg et al., 2011). Heterogeneity observed among phases in the same chondrule suggests that the chondrules were not completely melted, some grains such as olivine may be relict, and the chondrule material had been recycled (Weisberg et al., 2011). One of the chondrules has an O-isotope composition similar to that of R chondrites, indicating that there was in part some mixing of materials from different reservoirs (Weisberg et al., 2011). Refractory inclusions observed in the E3 chondrites do not show any significant differences from their counter parts on the other classes of chondrites, but the E3 chondrules differ from their counter parts in the ordi-

nary and carbonaceous chondrites (Weisberg et al., 2011). This indicates that chondrule forming events occurred locally however, refractory inclusion formation was limited to a single location and a specific event, implying that transport mechanisms were not as active during refractory inclusion formation and post chondrule formation (Weisberg et al., 2011).

Weisberg et al. (2021) determined the O-isotope composition of the silicate phases in the chondrules, fragments, metal-rich nodules, and refractory inclusions in an EH3 (ALH 81189) and a EL3 (MAC 88136) chondrite. They determined that the O-isotope compositions of the silicates formed a trend that followed the PCM line with most of the silicates laying at the intersect between the PCM and TF lines (Weisberg et al., 2021). No significant differences were observed between the EH3 and EL3, indicating they share similar precursors or formed in similar gas-rich environments (Weisberg et al., 2021). However, the differences in the mineral composition implies that their respective nebula environments and/ or parent bodies differed (Weisberg et al., 2021). The silicates associated with the metal-rich nodules exhibited similar O-isotope and mineral compositions as their counter parts in the chondrules, suggesting that the metal-rich nodules formed in similar environments to the chondrules with similar processes, occurring prior to accretion (Weisberg et al., 2021). Olivines observed in an AOA (amoeboid olivine aggregates [Jacquet and Marrocchi (2017)]) in the EH3 were enriched in ^{16}O (Weisberg et al., 2021). The O-isotope compositions of these olivines are -46.5‰ for $\delta^{18}\text{O}$ and -48.0‰ for $\delta^{17}\text{O}$ (Weisberg et al., 2021). This is consistent with AOAs and refractory inclusions in other E3 chondrites as well as their counter parts in the other chondrite types (Weisberg et al., 2021). The O-isotope compositions of the chondrules in E3 chondrites are distinct from those of in LL, R, CV, and CM chondrites (Weisberg et al., 2021). However, the enstatite chondrules and those in CR chondrites plot close to the PCM line relative to the other chondrite groups, with E3 chondrules generally being ^{16}O -poor compared to CR chondrules (Weisberg et al., 2021). Based on the distribution of enstatite chondrules along the PCM, Weisberg et al. (2021) proposed that the different chondrite types formed from similar precursors with varying volumes of ^{16}O -rich refractory materials. This would have occurred before the inner and outer solar systems were separated by the theorized Jupiter divide, or Jupiter did not manage to completely separate these materials (Weisberg et al., 2021).

Tanaka et al. (2021) determined the O- and Si- isotope compositions in unequilibrium enstatite chondrite (UEC) chondrules. These included 2 EH3, 3 EH4, 1 EH5, 1 EH6, and 15 ureilites (Tanaka et al., 2021). Ureilites are a type of carbon-bearing achondrite generally composed of olivine and pigeonite (Berkley et al., 1980). Achondrite meteorites are a form of melted and in some cases homogenised and differentiated meteorite that do not retain their isotope composition from before accretion into their respective asteroids (Clayton and Mayeda, 1996). Tanaka et al. (2021) determined that chondrules with larger $\Delta^{17}\text{O}$ have smaller $\delta^{30}\text{Si}$, this is consistent with most non-carbonaceous differentiated planetary bodies (Tanaka et al., 2021). This suggests that Si- and O-isotope compositions of enstatite chondrules are inherited from their precursors (Tanaka et al., 2021). The ureilites did not exhibit a similar correlation to the EH chondrules (Tanaka et al., 2021). The Si-isotope composition of the ureilites was consistent with the chondritic value (-47‰), suggesting that the isotope composition of the ureilites may reflect that of the olivine-rich precursor (Tanaka et al., 2021). The variations in Si- and O-isotope compositions of enstatite chondrules are proposed to be due to interactions between SiO-rich gas and melted or partially melted olivine-rich precursor chondrules (Tanaka et al., 2021). The Mg/Si ratio and $\delta^{30}\text{Si}$ of the inner planetary bodies may have increased as a result of increasing silicate/metal ratio in the evaporated dust (Tanaka et al., 2021).

The O-isotope compositions of enstatite chondrites represent a distinct population within a local region of the solar nebula, and is mostly related to the ordinary and R chondrites (Jacquet et al., 2018). The range of $\Delta^{17}\text{O}$ values of enstatite chondrules overlaps with those of LL3 and R3 chondrules, however, most E3 chondrules exhibit values close to the Earth-Moon value of 0 (Jacquet et al., 2018). LL3 and R3 chondrules generally have larger $\Delta^{17}\text{O}$ by comparison and carbonaceous chondrites exhibit negative values (Jacquet et al., 2018).

1.6 Previous work on lithium-isotope compositions of enstatite chondrites

Pogge von Strandmann et al. (2011) determined the bulk Li- and Mg-isotope composition of several chondrites including nine carbonaceous, ten ordinary, and seven enstatite chondrites. The enstatite chondrites in their study are two EH4 (Indarch and

Abee), one EH5 (St. Mark's), and 4 EL6 (Daniel's Kuil, Khairpur, Yilmia, and Hvit-tis) chondrites. The Li concentrations of the enstatite chondrites ranged from 1.2 to 2.2 $\mu\text{g} \cdot \text{g}^{-1}$ (Pogge von Strandmann et al., 2011). These values are similar to those of the ordinary chondrites (1.1 to 2.1 $\mu\text{g} \cdot \text{g}^{-1}$) and generally larger than the Li concentrations of the carbonaceous chondrites (0.7 to 1.5 $\mu\text{g} \cdot \text{g}^{-1}$). The average $\delta^7\text{Li}$ composition of the enstatite, carbonaceous, and ordinary chondrites was determined to be $1.7 \pm 1.6\text{‰}$, $3.3 \pm 1.4\text{‰}$, and $2.8 \pm 1.5\text{‰}$ respectively (Pogge von Strandmann et al., 2011). The lighter $\delta^7\text{Li}$ of the enstatite chondrites may be due to spallation resulting from irradiation (Pogge von Strandmann et al., 2011). Given the well documented Li-isotope heterogeneity in chondrites, this interpretation required additional evidence to confirm using a larger range of samples (Pogge von Strandmann et al., 2011).

Seitz et al. (2007) also determined the bulk Li-isotope composition of an array of chondrites, including an EH3 (Quingzhen), an EH4 (Indarch), and an EL6 (Neuschwanstein). Unlike Pogge von Strandmann et al. (2011), Seitz et al. (2007) reports no significant differences between the enstatite chondrite Li-isotope compositions and those of the carbonaceous and ordinary chondrites. Tomascak et al. (2016) states that all three chondrite types display similar variations in $\delta^7\text{Li}$ with only some differences in their mean values. Based solely on the available Li-isotope compositions of enstatite chondrites, it is unlikely that enstatite chondrites are the major building block of Earth and other large planetary bodies (Tomascak et al., 2016). This is because the major-element composition of enstatite chondrites differs from that of Earth (Tomascak et al., 2016), with CV chondrites exhibiting a major-element composition similar to that of Earth (Palme and O'Neill, 2014). Earth may have formed from material that underwent the same chemical fractionation processes as chondrites, this will have occurred during early solar system formation (Palme and O'Neill, 2014). However, stable isotope compositions suggests that chondrites are not necessarily the building blocks of Earth (Palme and O'Neill, 2014).

1.7 Aims and objectives

This study has 4 primary aims. (1) Characterise the processes in the protosolar nebula that are responsible for producing enstatite from an olivine-rich precursor in the enstatite-chondrite chondrules. (2) Determine the geochemical properties of the

reservoir that is involved in this process. (3) Discuss the O- and Li-isotope distribution in the enstatite- and carbonaceous-chondrite forming-regions. (4) Estimate the isotope composition of the reservoir involved in the production of enstatite. The primary goals of this study will be addressed in Chapters 2, 3, and 4.

In Chapter 2 a survey will be conducted on an array of enstatite meteorites classed as EH, EL, and achondrites with petrological types ranging from 3 to 7. From this, it will be determined whether the production of enstatite from an olivine-rich precursor by silicification and sulphidation occurs during chondrule formation or on the asteroid. This will also aid in determining if the reduction of enstatite chondrites occurs during chondrule formation or on the asteroid.

In Chapter 3 selection and description of olivine-bearing chondrules from the least heated enstatite chondrite (EH3) will be discussed and the major-element, trace-element, O-isotope, and Li-isotope compositions of the chondrule components will be determined. The O- and Li-isotope composition of a gas reservoir will be estimated from the isotope compositions of the enstatites and olivines. This is because the enstatite is the product of the olivine-rich precursors interacting with the gas reservoir while melted or partially melted.

In Chapter 4 three EH4 chondrules will be examined and their major-element, O-isotope, and Li-isotope compositions of the chondrule components will be determined. These will then be compared to the results of the EH3 chondrules to determine if there are any variations of the isotopic composition of the gas reservoir. As EH4 chondrules are more heated than those of the EH3 chondrules, the recycling of enstatite chondrules from inside of the asteroid will be addressed in this chapter.

Table 1.1: Summary of meteorites and chondrules of interest.

meteorite	class	chondrule	remark
Sahara 97103	EH3	I6p	PP
		D6a	PP aggregate
		D3g	POP
		J5l	POP
		C5b	POP
		K4	POP aggregate
Indarch	EH4	Ch1	PP fragment
Y74370	EH4	Ch1	POP fragment
		Ch5	PP fragment

Table 1.2: Summary of O-isotope compositions of enstatite chondrites, chondrules, and chondrule components determined by previous studies: Mf refers mineral fragments. Ch comp refers to chondrule composites.

	ref	meteorite	class	component	phase	n	$\delta^{18}\text{O}$	σ_{18}	$\delta^{17}\text{O}$	σ_{17}	$\Delta^{17}\text{O}$	σ_{Δ}
Clayton et al. (1984)	Qingzhen	EH3	-	-	2	4.70	-	2.42	-	-0.03	-	-
	Parsa	EH3	-	-	2	4.55	-	2.38	-	0.01	-	-
			-	-	2	5.33	-	2.82	-	0.05	-	-
	Y691	EH3	-	-	1	4.83	-	2.46	-	-0.05	-	-
	Kota-Kota	EH3	-	-	2	5.12	-	2.52	-	-0.15	-	-
	Abee	EH4	clast	-	1	6.08	-	3.27	-	0.11	-	-
			-	-	2	5.52	-	3.02	-	0.15	-	-
	Adhi Kot	EH4	-	-	1	5.42	-	2.77	-	-0.05	-	-
	Indarch	EH4	-	-	2	5.46	-	2.96	-	0.12	-	-
				chondrule S1	-	5.83	-	3.17	-	0.13	-	-
				chondrule S2	-	5.60	-	3.00	-	0.09	-	-
				chondrule S3	-	5.37	-	2.85	-	0.06	-	-
	South Oman	EH4	-	-	3	5.41	-	2.44	-	-0.37	-	-
	St. Mark's	EH5	-	-	2	5.24	-	2.83	-	0.11	-	-
	St. Sauveur	EH5	-	-	2	5.93	-	3.13	-	0.04	-	-
	Atlanta	EL6	-	-	2	5.63	-	2.96	-	0.03	-	-
	Blithfield	EL6	-	-	1	5.29	-	2.82	-	0.07	-	-
	Daniel's Kuil	EL6	-	-	1	5.74	-	2.98	-	0.00	-	-
	Hvittis	EL6	-	-	1	5.68	-	3.02	-	0.07	-	-
	Jajh deh Kot Lalu	EL6	-	-	1	5.58	-	2.97	-	0.07	-	-
	Khairpur	EL6	-	-	1	5.54	-	2.98	-	0.10	-	-
	Pillistfer	EL6	-	-	1	5.58	-	2.92	-	0.02	-	-
	Ufana	EL6	-	-	4	5.54	-	3.00	-	0.12	-	-
	Bishopville	aubrite	-	-	3	5.37	-	2.80	-	0.01	-	-
	Bustee	aubrite	-	-	4	4.90	-	2.51	-	-0.04	-	-
	Cumberland Falls	aubrite	-	-	2	5.04	-	2.55	-	-0.08	-	-
	Khor Temiki	aubrite	-	-	1	5.31	-	2.66	-	-0.10	-	-
	Mayo Belwa	aubrite	-	-	4	5.48	-	2.82	-	-0.03	-	-
	Norton County	aubrite	-	-	2	5.02	-	2.58	-	0.01	-	-
	Pena Blanca Spring	aubrite	-	-	2	5.32	-	2.76	-	0.01	-	-

Table 1.2: Continued

	ref	meteorite	class	component	phase	n	$\delta^{18}\text{O}$	σ_{18}	$\delta^{17}\text{O}$	σ_{17}	$\Delta^{17}\text{O}$	σ_{Δ}
Newton et al. (2000)	Pesyanoe	aubrite	-	-	1	5.37	-	2.82	-	0.03	-	
	Shallowater	aubrite	-	-	2	5.34	-	2.76	-	-0.02	-	
	Sahara 97096	EH3	bulk	-	2	2.77	0.04	5.45	0.03	-0.07	0.02	
	ALH 84206	EH3	bulk	-	3	2.45	0.09	4.78	0.12	-0.03	0.04	
			HCl-residue	-	2	2.26	0.20	4.42	0.52	-0.04	0.07	
	ALH 88046	EH3	bulk	-	2	2.18	0.04	4.26	0.04	-0.04	0.02	
			HCl-residue	-	2	2.42	0.04	4.91	0.10	-0.13	0.01	
	EET 83322	EH3	bulk	-	2	0.86	0.09	1.79	0.22	-0.07	0.02	
			HCl-residue	-	2	2.69	0.04	5.18	0.16	-0.01	0.05	
	Kota-Kota	EH3	bulk	-	4	3.19	0.18	6.22	0.37	-0.04	0.04	
	PCA 91461	EH3	bulk	-	2	1.04	0.00	2.47	0.02	-0.24	0.01	
			HCl-residue	-	2	2.06	0.19	4.53	0.45	-0.30	0.04	
	Qingzhen	EH3	bulk	-	5	2.83	0.23	5.52	0.39	-0.04	0.03	
	Galim (b)	anomalous EH3	bulk	-	2	3.09	0.01	5.53	0.03	0.21	0.00	
	LEW 87223	anomalous E3	bulk	-	2	3.25	0.04	5.41	0.03	0.43	0.02	
			HCl-residue	-	1	2.80	-	4.70	-	0.35	-	
	Acfer 287	E4	bulk	-	2	2.22	0.03	4.60	0.03	-0.17	0.04	
			HCl-residue	-	2	1.98	0.04	4.16	0.07	-0.19	0.07	
	Indarch	EH4	bulk	-	2	3.28	0.05	6.06	0.12	0.13	0.01	
	South Oman	EH4	bulk	-	3	2.63	0.19	5.63	0.28	-0.30	0.05	
	Abee	EH4	bulk	-	2	3.47	0.00	6.32	0.26	0.19	0.19	
	Adhi-Kot	EH4	bulk	-	2	2.74	0.05	5.41	0.11	-0.07	0.01	
	LEW 88180	EH5	bulk	-	2	2.31	0.04	4.49	0.01	0.02	0.04	
			HCl-residue	-	2	2.75	0.05	5.30	0.12	-0.01	0.02	
	St. Marks	EH5	bulk	-	2	3.13	0.07	5.80	0.19	0.11	0.03	
	St. Sauveur	EH5	bulk	-	2	3.15	0.09	5.73	0.24	0.18	0.04	
	QUE 94204	EH7	bulk	-	2	1.09	0.14	2.06	0.23	0.02	0.02	
			HCl-residue	-	2	2.45	0.19	4.71	0.31	0.00	0.03	
	MAC 88136	EL3	bulk	-	2	2.01	0.07	4.07	0.07	-0.11	0.04	
			HCl-residue	-	2	2.51	0.04	5.00	0.06	-0.09	0.01	
	PCA 9 1 020	EL3	bulk	-	2	2.91	0.06	5.54	0.05	0.03	0.03	
			HCl-residue	-	2	2.74	0.07	5.27	0.01	0.00	0.07	

Table 1.2: Continued

ref	meteorite	class	component	phase	n	$\delta^{18}\text{O}$	σ_{18}	$\delta^{17}\text{O}$	σ_{17}	$\Delta^{17}\text{O}$	σ_{Δ}
QUE 94594	EL3	bulk	-	2	2.46	0.15	4.56	0.20	0.08	0.05	
Grein 002	EL4-5	bulk	-	2	3.03	0.12	5.86	0.26	-0.02	0.02	
		HCl-residue	-	2	2.91	0.07	5.57	0.08	0.01	0.03	
Tanezroufi 031	EL5	bulk	-	3	3.59	0.27	6.88	0.43	0.01	0.07	
		HCl-residue	-	3	2.77	0.59	5.26	1.11	0.04	0.05	
TIL91714	EL5	bulk	-	2	2.33	0.27	4.37	0.39	0.05	0.07	
		HCl-residue	-	2	2.83	0.08	5.28	0.24	0.09	0.05	
ALHA8 1021	EL6	bulk	-	2	2.87	0.10	5.58	0.13	-0.03	0.03	
		HCl-residue	-	2	2.85	0.10	5.50	0.07	-0.01	0.14	
Atlanta	EL6	bulk	-	2	3.06	0.03	5.56	0.14	0.17	0.04	
Blithfield	EL6	bulk	-	2	2.94	0.01	5.68	0.07	-0.01	0.02	
Daniel's Kuil	EL6	bulk	-	3	3.04	0.18	5.76	0.40	0.05	0.04	
EET 92063	EL6	bulk	-	2	3.06	0.01	5.84	0.07	0.03	0.02	
		HCl-residue	-	2	2.80	0.01	5.43	0.05	-0.03	0.04	
Hvittis	EL6	bulk	-	2	3.08	0.06	6.03	0.08	-0.05	0.02	
Jajh deh Kot Lalu	EL6	bulk	-	2	3.05	0.03	5.89	0.08	-0.01	0.01	
Khairpur	EL6	bulk	-	4	3.17	0.16	6.09	0.28	0.01	0.05	
LEW 87119	EL6	bulk	-	2	1.91	0.01	3.61	0.06	0.04	0.02	
		HCl-residue	-	1	2.93	-	5.53	-	0.06	-	
LEW 88714	EL6	HCl-residue	-	2	2.62	0.07	5.02	0.29	0.01	0.08	
NW Forrest 1971	EL6	bulk	-	2	3.52	0.03	6.85	0.02	-0.04	0.03	
		HCl-residue	-	1	3.15	-	5.88	-	0.09	-	
Pillistfer	EL6	bulk	-	2	3.10	0.08	6.04	0.21	-0.04	0.03	
Yilmia	EL6	bulk	-	2	2.85	0.01	5.47	0.03	0.00	0.03	
llafegh 009	EL7	bulk	-	2	3.38	0.17	6.39	0.40	0.06	0.03	
		HCl-residue	-	2	2.91	0.01	5.38	0.14	0.11	0.08	
Happy Canyon	EL6/7	bulk	-	2	2.53	0.02	4.99	0.07	-0.07	0.01	
Bustee	aubrite	bulk	-	5	2.91	0.10	5.61	0.24	-0.01	0.05	
Khor Timiki	aubrite	bulk	-	2	2.75	0.01	5.29	0.11	0.00	0.07	
Pesyanoe	aubrite	bulk	-	3	2.46	0.19	4.79	0.44	-0.03	0.05	
ALHA78113	aubrite	bulk	-	2	2.75	0.13	5.12	0.30	0.09	0.02	
ALH 84007	aubrite	bulk	-	3	2.78	0.25	5.25	0.44	0.05	0.03	

Table 1.2: Continued

	ref	meteorite	class	component	phase	n	$\delta^{18}\text{O}$	σ_{18}	$\delta^{17}\text{O}$	σ_{17}	$\Delta^{17}\text{O}$	σ_{Δ}
Weisberg et al. (2011)	Aubres	aubrite	bulk	-	2	2.82	0.06	5.29	0.06	0.07	0.10	
	Bishopville	aubrite	bulk	-	2	2.59	0.02	5.09	0.09	-0.06	0.06	
	Cumberland Falls	aubrite	bulk	-	4	3.36	0.11	5.44	0.25	0.53	0.05	
	Mayo Belwa	aubrite	bulk	-	2	2.55	0.14	4.95	0.31	-0.03	0.02	
	Norton County	aubrite	bulk	-	2	2.57	0.01	4.98	0.06	-0.02	0.02	
	Pena Blanca Spring	aubrite	bulk	-	2	2.64	0.04	5.27	0.09	-0.10	0.01	
	EET 90033	aubrite	bulk	-	2	2.62	0.17	5.03	0.26	0.01	0.03	
	EET 90757	aubrite	bulk	-	2	2.31	0.18	4.59	0.46	-0.08	0.05	
	Shallowater	aubrite	bulk	-	2	2.99	0.05	5.79	0.05	-0.02	0.02	
	Sahara 97096	EH3	C1	ol	4	4.23	0.69	2.17	0.27	-0.03	0.16	
			C2	Fe-pyx	4	3.38	0.36	1.36	0.58	-0.40	0.51	
				en	1	4.29	0.15	2.06	0.30	-0.17	0.33	
			C3	ol	2	5.11	0.17	2.81	0.38	0.15	0.30	
				en	1	4.53	0.15	2.98	0.30	0.62	0.33	
			C5	ol	2	5.57	0.35	2.68	0.16	-0.23	0.35	
				en	1	4.75	0.15	1.99	0.30	-0.48	0.33	
			C6	ol	1	5.10	0.30	2.50	0.46	-0.15	0.49	
				en	1	4.69	0.30	2.86	0.46	0.42	0.49	
			C10	ol	2	5.93	0.24	2.55	0.24	-0.53	0.24	
				en	1	5.54	0.30	2.44	0.46	-0.44	0.49	
			C11	ol	2	4.83	0.01	4.75	0.09	2.24	0.11	
				en	1	4.81	0.30	2.73	0.46	0.23	0.49	
			C12	ol	1	5.37	0.30	2.26	0.46	-0.53	0.49	
				en	1	5.41	0.30	2.49	0.46	-0.32	0.49	
			C15	en	1	5.60	0.30	2.58	0.46	-0.33	0.49	
	LEW 87223	anomalous E3	C23	Fe-pyx	3	3.50	0.30	1.91	0.37	0.09	0.39	
				en	3	4.68	0.30	3.46	0.37	1.03	0.39	
				en-mf	1	5.19	0.31	3.92	0.64	1.21	0.67	
			MF-2	en	1	4.67	0.31	2.09	0.64	-0.34	0.67	
			C21	Fe-pyx	1	3.86	0.31	1.99	0.64	-0.01	0.67	
				en	1	3.96	0.31	2.20	0.64	0.14	0.67	
			C1	ol	5	4.83	0.51	2.08	0.32	-0.43	0.33	

Table 1.2: Continued

ref	meteorite	class	component	phase	n	$\delta^{18}\text{O}$	σ_{18}	$\delta^{17}\text{O}$	σ_{17}	$\Delta^{17}\text{O}$	σ_{Δ}
ALH 85159	EH3	F5	en	6	4.42	0.34	1.99	0.19	-0.31	0.12	
		F9	en	3	4.06	0.85	1.47	0.61	-0.64	0.19	
		F17	ol	2	-46.49	0.34	-47.98	0.24	-23.81	0.20	
		M5	en	4	4.44	0.43	2.09	0.30	-0.22	0.18	
		C7	en	6	5.77	0.65	3.25	0.35	0.25	0.12	
		C13	en	6	5.54	0.35	2.70	0.25	-0.18	0.18	
		C25	en	5	6.26	0.36	3.55	0.21	0.30	0.15	
		C43	en	6	5.97	0.35	3.18	0.20	0.08	0.16	
		C46	en	6	6.39	0.39	3.54	0.32	0.22	0.19	
		C47	en	6	6.57	0.40	3.76	0.19	0.34	0.13	
		C50	en	6	6.28	0.39	3.44	0.26	0.17	0.12	
		C51	en	6	6.85	0.78	4.84	0.61	1.27	0.24	
		C52	en	6	5.82	0.37	2.79	0.23	-0.24	0.18	
		C1	diops/en	4	5.15	0.32	2.64	0.21	-0.04	0.16	
		C1	silica	1	8.33	0.15	4.22	0.23	-0.12	0.25	
MAC 88136	EL3	C1	silica	1	8.42	0.15	4.26	0.23	-0.12	0.25	
		C3	en	6	5.40	0.40	2.69	0.33	-0.12	0.19	
		C6	en	6	5.51	0.40	2.51	0.31	-0.35	0.20	
		C7	en	5	5.31	0.32	2.39	0.25	-0.38	0.21	
		C9	en	6	6.42	0.34	4.34	0.35	1.00	0.28	
		C10	en	6	5.45	0.35	2.94	0.38	0.11	0.30	
		C11	en	7	5.95	0.34	3.17	0.32	0.07	0.29	
		C16	en	6	5.93	0.34	3.10	0.25	0.01	0.20	
		C17	en	6	5.65	0.32	2.94	0.28	0.00	0.27	
		C30	silica	1	8.73	0.15	4.55	0.23	0.01	0.25	
		M1	en	4	5.55	0.35	2.81	0.24	-0.08	0.17	
		M8	en	2	5.81	0.38	3.07	0.27	0.05	0.19	
		M10	en	3	5.74	0.45	3.02	0.40	0.04	0.27	
		Ch1	-	4	5.85	0.01	3.07	0.01	0.03	0.03	
		En1	en	5	5.99	0.00	3.15	0.01	0.03	0.02	
Tanaka and Nakamura (2017) Tanaka et al. (2021)	Sahara 97103	EH3	Ch comp2	4	5.68	0.00	2.68	0.01	-0.28	0.02	
	Y691		Ch comp5	8	5.59	0.01	2.63	0.01	-0.28	0.03	

Table 1.2: Continued

ref	meteorite	class	component	phase	n	$\delta^{18}\text{O}$	σ_{18}	$\delta^{17}\text{O}$	σ_{17}	$\Delta^{17}\text{O}$	σ_{Δ}
Indarch	EH4	Ch1		8	5.64	0.01	3.04	0.01	0.10	0.01	
		Ch comp1		4	5.76	0.00	2.93	0.01	-0.07	0.02	
		Ch21		4	5.75	0.01	3.25	0.01	0.26	0.02	
		Ch23		4	5.31	0.00	2.87	0.01	0.11	0.02	
		Ch25		4	5.46	0.00	2.96	0.01	0.12	0.02	
Y74370	EH4	Ch5		8	5.23	0.01	2.37	0.01	-0.36	0.02	
		Ch comp1		5	5.26	0.01	2.45	0.00	-0.28	0.01	
Y791810	EH4	Ch5		4	5.77	0.01	3.12	0.01	0.12	0.03	
		Ch comp1		5	5.77	0.00	3.18	0.01	0.17	0.02	
St. Mark's	EH5	Ch comp 1		4	5.87	0.00	3.20	0.01	0.15	0.02	
Y980223	EH6	EN1	en	4	5.87	0.00	3.20	0.01	0.15	0.02	

Table 1.3: Summary of Li-isotopes from enstatite chondrites determined by previous studies.

meteorite	class	n	[Li]	2σ	$\delta^7\text{Li}$	2σ	ref
Qingzhen	EH3	5	1.50	0.30	2.90	1.40	Seitz et al. (2007)
		-	-	-	2.75	-	Tomascak et al. (2016)
Indarch	EH4	3	2.10	0.70	2.20	0.80	Seitz et al. (2007)
		-	2.20	-	2.00	-	Pogge von Strandmann et al. (2011)
		-	-	-	2.00	-	Tomascak et al. (2016)
		-	-	-	2.25	-	Tomascak et al. (2016)
Abee	EH4	-	1.60	-	2.80	-	Pogge von Strandmann et al. (2011)
		-	-	-	2.70	-	Tomascak et al. (2016)
St. Mark's	EH5	-	1.30	-	0.50	-	Pogge von Strandmann et al. (2011)
		-	-	-	0.50	-	Tomascak et al. (2016)
Neuschwanstein	EL6	3	1.60	0.30	2.10	0.60	Seitz et al. (2007)
		-	-	-	2.30	-	Tomascak et al. (2016)
Daniel's Kuil	EL6	-	-	-	1.70	-	Pogge von Strandmann et al. (2011)
		-	-	-	1.75	-	Tomascak et al. (2016)
Khairpur	EL6	-	1.60	-	1.20	-	Pogge von Strandmann et al. (2011)
		-	-	-	1.25	-	Tomascak et al. (2016)
Yilmia	EL6	-	1.20	-	2.10	-	Pogge von Strandmann et al. (2011)
		-	-	-	2.10	-	Tomascak et al. (2016)
Hvittis	EL6	-	1.70	-	1.50	-	Pogge von Strandmann et al. (2011)
		-	-	-	1.60	-	Tomascak et al. (2016)
Khor Temiki	aubrite	-	0.60	-	-0.30	-	Pogge von Strandmann et al. (2011)

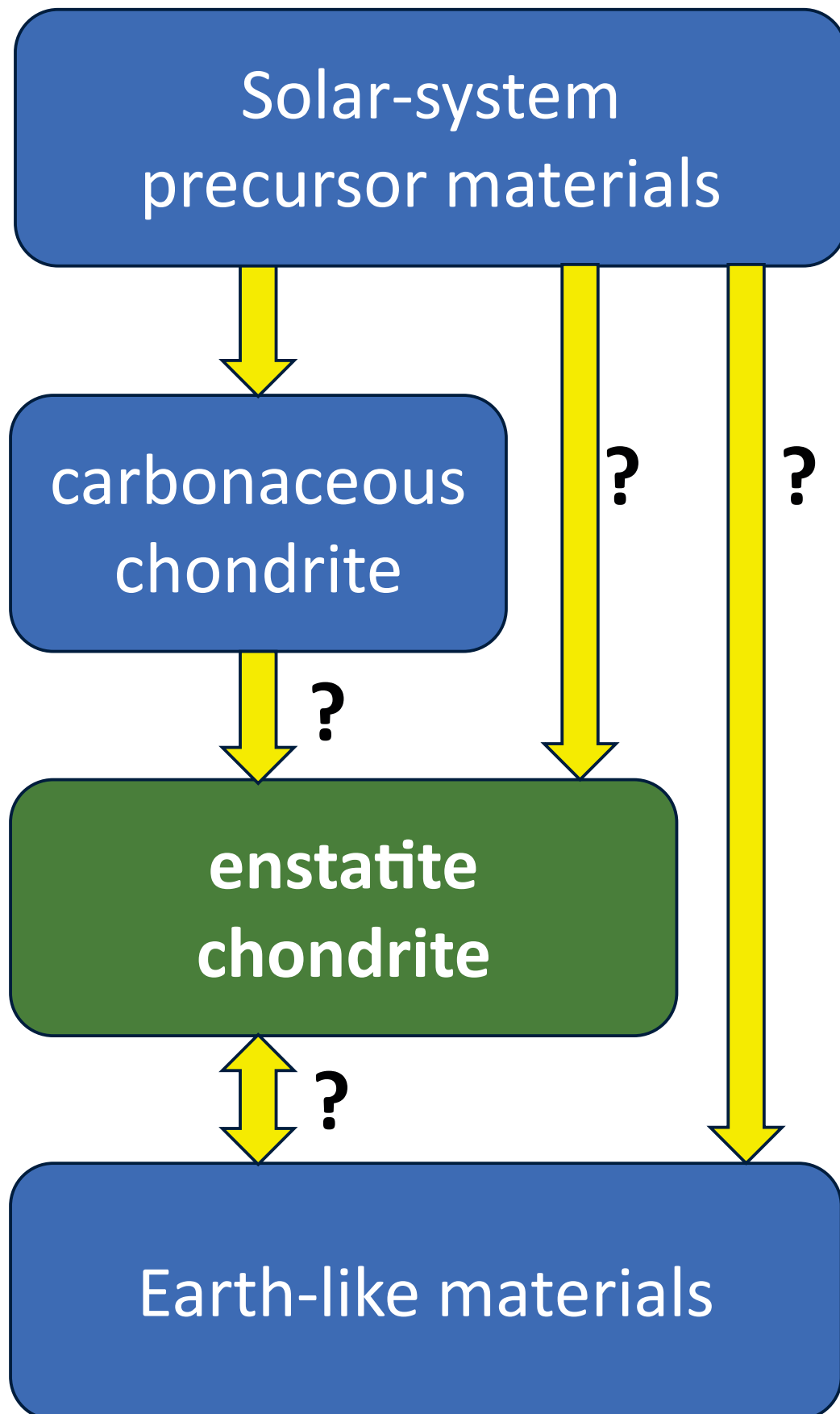


Figure 1.1: Potential pathways for the evolution of enstatite chondrites and the Earth: The arrows indicate the potential evolution pathways. It is known that carbonaceous chondrites are derived from the solar system precursor material. However, it is uncertain if enstatite chondrites are formed from the same precursor material, or if they are

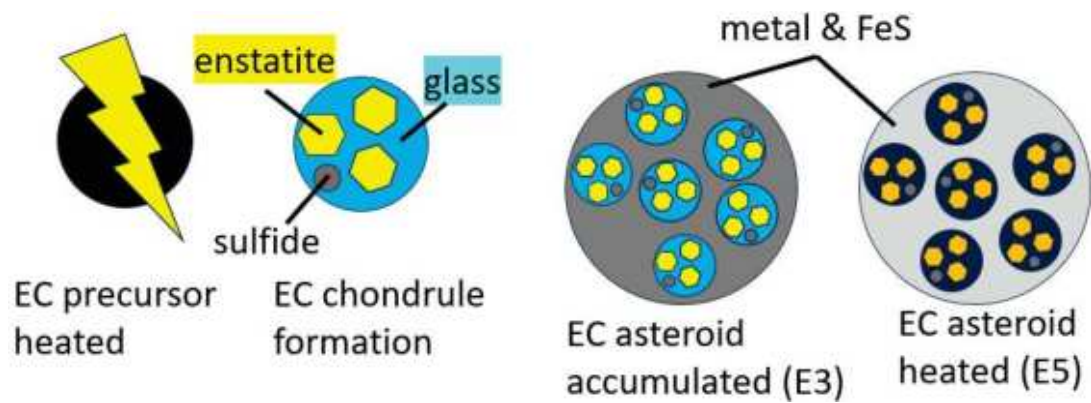


Figure 1.2: The primary stages of enstatite chondrite formation.

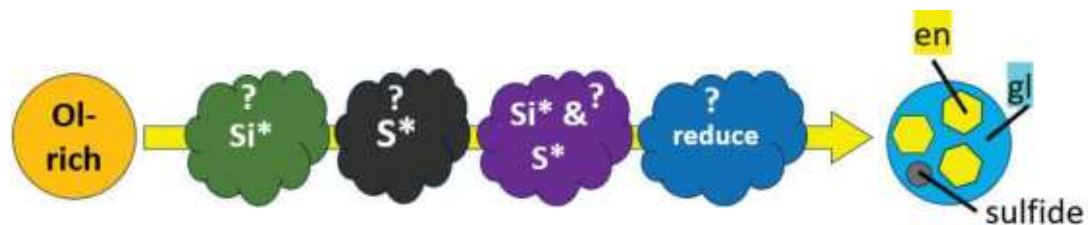


Figure 1.3: Potential pathway for the formation of the enstatite chondrule from an olivine-rich precursor: It is uncertain if the gas reservoir that interacted with the precursor chondrule is enriched in both Si and S, or if there were separate gas reservoirs for Si and S. The * symbol indicates that it is unknown what the chemical formula of the Si-rich component and the S-rich components are.

Chapter 2

Progressive metamorphism in the enstatite asteroids

2.1 Introduction

The mechanism/ process that causes the Mg/Si ratio of enstatite chondrites to differ from that of Earth is unknown. However, the difference in the Mg/Si ratio between carbonaceous chondrite and enstatite chondrite is the result of olivine dominating the carbonaceous chondrules and enstatite dominating the enstatite chondrules. The mechanisms that result in the respective mineralogies of enstatite and carbonaceous chondrites and why they vary from each other are also uncertain.

Earlier the terms silicification and sulphidation were introduced. Both of these processes were shown to be capable of producing enstatite from an olivine-rich precursor and may be possible explanations as for why enstatite and carbonaceous chondrules differ from each other. However, it is uncertain which of the two processes is dominant in producing enstatite from an olivine-rich precursor. Studies such as Tissandeer et al. (2002), Krot et al. (2004a), Libourel et al. (2006), Tanaka and Nakamura (2017), and Tanaka et al. (2021) favour silicification as the dominate process over sulphidation. Whereas Lehner et al. (2013) favours sulphidation as the reason for the low Mg/Si ratio of enstatite chondrites. Although Tissandeer et al. (2002), Krot et al. (2004a), Libourel et al. (2006) did not focus on enstatite chondrites, their studies support that silicification occurs in carbonaceous chondrites. This gives merit to the occurrence of silicification in enstatite chondrites. In this chapter, the timing of silicification and sulphidation in the

evolution of the enstatite chondrite will be addressed as will when enstatite chondrite become reduced and their Mg/Si ratio lowers from the chondritic value to the enstatite chondrite value. This will be done by surveying the petrography of an array of enstatite chondrites including EH, EL, and ungrouped enstatite a chondrites. The petrological types of these meteorites range from 3 to 7 and includes one EH impact melted chondrite.

The production of enstatite chondrites begins with precursor material and/or precursor chondrules which undergo heating that result in melting or partial melting with precipitation of refractory elements leading to their removal from the chondrule melt. These refractory elements include Mg and Ca, with Al being more depleted in enstatite chondrules compared to ordinary chondrules (Wood, 2005). This is followed by chondrule formation, after which the chondrules accreted into their respective EH and EL asteroid bodies (Wood, 2005). The enstatite asteroids are then heated and achieve chemical equilibrium. Silicification will likely have occurred during the enstatite chondrule formation event. However, sulphidation could have occurred during chondrule formation, or on the asteroid. This makes it uncertain if the low Mg/Si ratio and the reduced nature of the enstatite chondrites occurs during chondrule formation or on the asteroid. In this chapter the petrography of a series of EH chondrites, EL chondrites, and enstatite-rich achondrites is determined in order to assess when sulphidation resulting in the production of enstatite in the enstatite chondrites occurs. An enstatite chondrite of the EH group has been impact melted and it is referred to as “EH-imp melt”. Since the three enstatite-rich achondrites are ungrouped, they are referred to as “En-rich-achon ung”. Note that they are not grouped as enstatite achondrite (aubrites) (Keil, 2010).

A summary of the samples surveyed on this chapter are shown in Table 2.1. A summary of the phases observed by previous studies are shown in Table 2.2. A summary of the major and minor phases observed in this study are shown in Table 2.3.

2.2 Experimental

The images in this survey were collected using a JEOL JSM-7001F SEM with Aztec software. This particular device was equipped with a Schottky field emission electron gun that heats the tungsten cathode surface from approximately room temperature to 1800 K. The accelerating voltage for this model ranges from 0.5 to 30 kV and was

generally kept at 15 kV with the emission current set to 76 μA . The resolution of this model is defined as 1.2 nm at 30 kV and 3 nm at 1 kV. The stage is mechanically eucentric at all working distances; with the working distance for this study generally set to 10 mm. The vacuum within the chamber was generally maintained at 9.6×10^{-5} Pa. The RGB images were then generated from the collected individual element maps by stitching them together and applying an R:G:B colour scheme using an R program.

2.3 EH chondrites

2.3.1 EET 87746 (EH3)

Site 1 (Figure 2.1) contains 31 identified chondrules and fragments. The diameters of these objects range from 33 to 167 μm . All diameters in this chapter are apparent diameters based on the scale of the images. The low-Ca pyroxene in the chondrules and fragments range from 5 to 61 μm in diameter. 12 chondrules and fragments contain olivine. The olivine grains range from 5 to 44 μm in diameter. 2 fragments are dominated by olivine. The olivines often occur close to the chondrule and fragment edges. They are mostly anhedral in shape. This may be the result of the fragments being broken off of the whole chondrules. Some of the smaller olivines are surrounded by low-Ca pyroxene. This and the shape of the olivines indicate that they are relict. 20 chondrules and fragments contain Na-rich glass. The glass is interstitial to the low-Ca pyroxene and olivine. 12 chondrules and fragments contain silica, which mostly occurs close to the edge of the chondrules and fragments. The silica is usually accompanied by the glass. One fragment is dominated by silica. Most of the chondrules and fragments contain minor FeS (5 to 17 μm). 4 chondrules and fragments contain minor metal (5 to 39 μm). A Cr rich sulphide (likely to be daubreelite) is observed in two of the aggregates. As this was not confirmed to be daubreelite, observed Cr-rich sulphides will be referred to as CrS. The CrS ranges from 21 to 44 μm . The smaller CrS is completely surrounded by metal. The larger CrS accompanies both FeS and metal.

Site 2 (Figure 2.2) contains 32 identified chondrules and fragments. The diameters of these objects range from 22 to 289 μm . The low-Ca pyroxene in the chondrules and fragments range from 5 to 56 μm in diameter. 11 chondrules and fragments contain anhedral olivine. The olivines range from 5 to 56 μm . 4 fragments are dominated by

olivine. The olivines often occur close to the chondrule and fragment edges. Some of the smaller olivines are surrounded by low-Ca pyroxene. One olivine grain is surrounded on 2 sides by Na-rich glass. Being surrounded by low-Ca pyroxene and the anhedral shapes indicate that the olivine is relict. However, some of the anhedral shapes may be the result of pieces breaking off of the whole chondrule. 24 chondrules and fragments contain Na-rich glass. The glass mostly occurs interfilling between the low-Ca pyroxene and olivine. 2 fragments are dominated by glass and silica. The silica is present in 12 chondrules and fragments. The silica often occurs at the edges of the chondrules and fragments, accompanied by the glass. 10 chondrules and fragments contain minor FeS (5 to 22 μm). Metal (5 to 43 μm) is observed in 4 chondrules and fragments. Three grains of CaS are observed (4 to 8 μm). Two of these grains occur in an aggregate with FeS, the third is observed at the edge of a chondrule fragment.

Site 3 (Figure 2.3) contains 31 identified chondrules and fragments. The diameters of these objects range from 20 to 282 μm . The low-Ca pyroxene in the chondrules and fragments range from 4 to 65 μm in diameter. 14 of the chondrules and fragments contain olivine (4 to 48 μm in diameter). Most of the olivines are anhedral, most of which are surrounded by low-Ca pyroxene. This may indicate that they are relict olivines. A small number of the anhedral olivines are observed at the edges of the fragments. The anhedral shape of these grains may be the result of the fragments being broken off of a previous generation of chondrules. However, it is not possible to confirm this at this time. A small number of olivines are euhedral in shape. This may indicate that they are young olivines. Apart from one exception, all of the chondrules and fragments contain Na-rich glass. The glass is observed throughout the chondrules and fragments, between the low-Ca pyroxenes and olivines. 15 of the chondrules and fragments contain silica. The silica is mostly observed at the edges of the chondrules and fragments, often accompanied by the glass. 11 of the chondrules and fragments contain minor FeS (4 to 24 μm). 5 of the chondrules and fragments contain minor metal (4 to 20 μm). A single grain of CaS (4 μm) is observed in an aggregate with FeS at the edge of the largest chondrule fragment.

Site 4 (Figure 2.4) contains 35 identified chondrules and fragments. The diameters of these objects range from 16 to 218 μm . Most of the chondrules and fragments are dominated by low-Ca pyroxene. However, 3 fragments are dominated by olivine. One fragment is dominated by both low-Ca pyroxene and olivine. One fragment is

dominated by mesostasis comprised of Na-rich glass, low-Ca pyroxene, and high-Ca pyroxene. The low-Ca pyroxene ranges from 4 to 52 μm in diameter. 12 of the chondrules and fragments contain olivine. The olivine ranges from 4 to 57 μm in diameter. Both euhedral and anhedral olivines are observed. This indicates that both relict and young olivine are present. Some of the anhedral olivines may be the result of pieces being broken off of the whole chondrule. Na-rich glass is present in all chondrules and fragments. 15 of the chondrules and fragments contain silica. The silica is observed accompanying the glass. The silica is not limited to the chondrule and fragment edges. Several chondrules and fragments contain minor FeS (4 to 32 μm). 4 fragments contain cracks that are infilled by FeS. Metal is present in 4 fragments contain minor metal (4 to 12 μm). MgS (4 to 15 μm) is observed three of the aggregates. CaS (4 μm) is observed in three aggregates of FeS and metal. The CaS is also observed in two of the chondrule fragments.

Site 5 (Figure 2.5) contains 35 identified chondrules and fragments. The diameters of these objects range from 22 to 194 μm . The low-Ca pyroxene ranges from 5 to 72 μm in diameter. 17 chondrules and fragments contain olivine. 4 fragments are dominated by olivine. The olivines range from 5 to 100 μm in diameter. The olivines are anhedral in shape. The olivines are either occur surrounded by low-Ca pyroxene, or at the chondrule and fragment edges. 1 olivine is mostly surrounded by glass. The shape of the olivines and being surrounded by low-Ca pyroxene are indicators that the olivine is relict. 27 chondrules and fragments contain Na-rich glass interfilling between the low-Ca pyroxene and olivine. 1 olivine grain contains glass inclusions. This olivine may be a young olivine. 9 chondrules and fragments contain silica. The silica is always close to the edge of the chondrules and fragments and mostly accompanied by glass. 10 chondrules and fragments contain minor FeS (5 to 11 μm). 3 fragments contain minor metal (5 to 17 μm). CaS (4 to 8 μm) is observed in three aggregates, one of which is contained in a chondrule fragment. A single CrS (17 μm) is observed completely surrounded by FeS.

Site 6 (Figure 2.6) contains 42 identified chondrules and fragments. The diameters of these objects range from 28 to 165 μm . The chondrules and fragments are dominated by low-Ca pyroxene (4 to 73 μm). One fragment is dominated by both low-Ca pyroxene and olivine. One fragment is dominated by Na-rich glass. 19 chondrules and fragments contain olivine (4 to 40 μm). Both euhedral and anhedral olivines are observed. Most of the smaller olivines are enclosed by low-Ca pyroxene. This indicates that both relict

and young olivine are present. Some of the anhedral olivines may be the result of pieces being broken off of the whole chondrule. 4 fragments do not contain glass, the rest do. 14 chondrules and fragments contain silica. The silica is mostly observed accompanied by glass. The silica is mostly observed at the edges of the chondrules and fragments, but not exclusively. A small number of low-Ca pyroxenes and olivines contain high-Ca pyroxene (4 to 12 μm). Minor FeS (4 to 12 μm) is observed in 8 chondrules and fragments. Minor metal (4 to 16 μm) in 5 chondrules and fragments. CaS (4 μm) is observed in two of the chondrule fragments.

Site 7 (Figure 2.7) contains 29 identified chondrules and fragments. The diameters of these objects range from 20 to 182 μm . The chondrules and fragments are dominated by low-Ca pyroxene (diameters of 8 to 73 μm). 11 of the chondrules and fragments contain olivine (diameters of 4 to 69 μm). Several of the olivine grains are anhedral in shape and completely surrounded by low-Ca pyroxene. This indicates that these olivines were shrinking as they are replaced by low-Ca pyroxene. This suggests that they are relict. Larger olivine grains not enclosed by low-Ca pyroxene are observed close to the edges of chondrule fragments. These olivines are anhedral in shape. It is uncertain if these olivines are relict as the anhedral shapes may be the result of the fragments breaking off of the whole chondrule. Majority of the chondrules and fragments contain Na-rich glass infilling between the low-Ca pyroxenes and olivines. 11 chondrules and fragments contain silica. This occurs primarily around the edges of the chondrules and fragments accompanied by the glass. Minor FeS (4 to 24 μm) is present in a large number of the chondrules and fragments. A small number of chondrules and fragments contain minor metal (4 to 32 μm). CaS (4 μm) is observed in cracks that are filled in by FeS and in aggregates at the edges of the chondrule fragments. A single CrS (17 μm) is observed completely surrounded by FeS.

Site 8 (Figure 2.8) contains 30 identified chondrules and fragments. The diameters of these objects range from 31 to 362 μm . The chondrules and fragments are dominated by low-Ca pyroxene (diameters of 4 to 77 μm). 12 of the chondrules and fragments contain olivine (diameters of 4 to 62 μm). Three chondrule fragments are dominated by olivine. The olivines are euhedral in shape and are not surrounded by the low-Ca pyroxenes. This indicates that they are unlikely to be relict. Most of the chondrules and fragments contain Na-rich glass (4 to 38 μm). The glass is often accompanied by silica (4 to 38 μm). The silica is mostly observed close to the edges of the chondrules

and fragments. One chondrule and one fragment are observed to have silica close to the centers of the chondrule and fragment. The silica is observed without accompanying glass in three fragments. Between the chondrules and fragments are aggregates of FeS (4 to 22 μm) and metal (4 to 65 μm) that range from 13 to 117 μm in diameter. Several of these aggregates contain low-Ca pyroxene and silica inclusions. This indicates that the aggregates formed after the production of the chondrules.

Site 9 (Figure 2.9) contains 21 identified chondrules and fragments. The diameters of these objects range from 46 to 269 μm . The chondrules and fragments are dominated by low-Ca pyroxene (diameters of 4 to 77 μm). 16 chondrules and fragments contain olivine (4 to 62 μm). 3 chondrules and fragments are dominated by olivine rather than low-Ca pyroxene. In the chondrules, the olivines are mostly confined to the centers of the chondrules. In the chondrules, the olivines are anhedral and often surrounded by low-Ca pyroxene. This may be an indicator that the olivines are potentially relict. Na-rich glass (4 to 31 μm) is observed in all of the chondrules and fragments with one exception. 9 of the chondrules and fragments contain silica (4 to 31 μm) accompanying the glass. The silica is primarily confined to the edges of the chondrules and fragments. Between the chondrules and fragments are aggregates (8 to 161 μm). These aggregates are mostly composed of FeS (4 to 87 μm) and metal (4 to 43 μm). 4 of the aggregates contain silica inclusions, with 2 of these aggregates also containing low-Ca pyroxene inclusions. The largest aggregate contains CrS (48 μm) occurring between the FeS and metal. CaS (4 μm) is observed in a single aggregate.

Site 10 (Figure 2.10) contains 16 identified chondrules and fragments. The diameters of these objects range from 38 to 823 μm . The chondrules and fragments are dominated by low-Ca pyroxene (diameters of 4 to 115 μm). 9 chondrules and fragments contain olivine (4 to 92 μm). The olivines are mostly confined to areas close to the centers of the chondrules and fragments. An olivine in the largest chondrule contains a glass inclusion. 1 of the fragments is dominated by olivine. Some of the olivines are euhedral and some are anhedral. Most of the olivines are surrounded by low-Ca pyroxene. It is possible that some of the olivines are relict. 9 of the chondrules and fragments contain Na-rich glass (4 to 31 μm). Silica (4 to 38 μm) is observed accompanying the glass in 7 of the chondrules and fragments. The silica is mostly confined to the edges of the chondrules and fragments. Contained in the largest chondrule is FeS, concentrated in the center of the object. However, FeS is also observed close to the edges of

this chondrule. 3 of the other chondrules and fragments contain FeS, occurring at the edges of the chondrules and fragments and at the centers. Between the chondrules and fragments are aggregates (13 to 74 μm) of FeS and metal. The FeS in the chondrules, fragments, and aggregates range from 4 to 74 μm . The metal ranges from 4 to 39 μm . CaS (4 to 8 μm) is observed with the FeS in the largest chondrule.

Site 11 (Figure 2.11) contains 40 identified chondrules and fragments. The diameters of these objects range from 38 to 423 μm . The chondrules and fragments are dominated by low-Ca pyroxene (diameters of 4 to 69 μm). 19 of the chondrules and fragments contain olivine (4 to 108 μm). 4 of chondrules and fragments are dominated by olivine. Some of the olivines are euhedral, whereas others are anhedral. The anhedral olivines are mostly observed close to the centers of the chondrules and fragments, surrounded by low-Ca pyroxene. This indicates that the anhedral olivines are potentially relict. 32 of the chondrules and fragments contain Na-rich glass (4 to 31 μm). 24 of the chondrule and fragments contain silica (4 to 46 μm). The silica is mostly observed accompanying the glass and generally occurs close to the edges of the chondrules and fragments. Several of the chondrules and fragments contain rounded FeS. Between the chondrules and fragments are aggregates (13 to 100 μm) of FeS and metal. The FeS in the chondrules, fragments, and aggregates range from 4 to 46 μm . The metal ranges from 4 to 43 μm . CrS (4 to 35 μm) is observed in two of the aggregates, in contact with both the FeS and the metal. CaS (4 μm) is observed in 2 of the aggregates, in contact with FeS.

Site 12 (Figure 2.12) contains 28 identified chondrules and fragments. The diameters of these objects range from 38 to 315 μm . The chondrules and fragments are dominated by low-Ca pyroxene (diameters of 4 to 138 μm). 18 of the chondrules and fragments contain olivine (4 to 77 μm). 3 of the chondrule fragments are dominated by olivine. The majority of the olivines occur close to the centers of the chondrules and fragments. They are surrounded by low-Ca pyroxene and have anhedral shapes. This indicates that they are potentially relict. 21 of the chondrules and fragments contain Na-rich glass (4 to 77 μm). Silica (4 to 31 μm) is observed in 19 of the chondrules and fragments. The silica is mostly observed accompanying glass close to the edges of the chondrules and fragments. However, some silica is observed in the centers of the chondrules and fragments. 9 of the chondrules and fragments contain FeS. Some of the FeS in the chondrules and fragments are rounded. The FeS can occur in the center or at

the edges of the chondrules and fragments. Between the chondrules and fragments are aggregates (13 to 139 μm) of FeS and metal. The FeS in the chondrules, fragments, and aggregates range from 4 to 57 μm . The metal ranges from 4 to 78 μm .

Site 13 (Figure 2.13) contains 32 identified chondrules and fragments. The diameters of these objects range from 46 to 338 μm . The chondrules and fragments are dominated by low-Ca pyroxene (diameters of 4 to 62 μm). 18 of the chondrules and fragments contain olivine (4 to 54 μm). The olivines are anhedral in shape and many of them are surrounded by low-Ca pyroxene. This indicates that the olivines are potentially relict. 21 of the chondrules and fragments contain Na-rich glass (4 to 46 μm). 18 chondrules and fragments contain silica (4 to 38 μm). The silica mostly accompanies the glass and is observed close to the edges of the chondrules and fragments. 1 of the fragments is dominated by glass and silica. 8 of the chondrules and fragments contain rounded FeS. This indicates that the FeS formed during chondrule formation. The FeS can occur in the center or at the edges of the chondrules and fragments. Between the chondrules and fragments are aggregates (17 to 65 μm) of FeS and metal. The FeS in the chondrules, fragments, and aggregates range from 4 to 26 μm . The metal ranges from 4 to 57 μm . CrS (4 to 8 μm) is observed in 2 of the aggregates in contact with both FeS and metal.

Site 14 (Figure 2.14) contains 31 identified chondrules and fragments. The diameters of these objects range from 38 to 231 μm . The chondrules and fragments are dominated by low-Ca pyroxene (diameters of 4 to 131 μm). 24 of the chondrules and fragments contain olivine (8 to 115 μm). 4 of the chondrules and fragments are dominated by olivine. Some of the olivines are euhedral and others are anhedral. The anhedral olivines are smaller than the euhedral olivines. Many of the anhedral olivines are surrounded by olivines. This may be an indicator that the anhedral olivines are potentially relict. 24 of the chondrules and fragments contain Na-rich glass (4 to 31 μm). 16 chondrules and fragments contain silica (4 to 23 μm). The silica is mostly observed accompanying the glass at the edges of the chondrules and fragments. 11 of the chondrules and fragments contain FeS. The FeS is mostly rounded and mostly occurs close to the edges of the chondrules and fragments. Between the chondrules and fragments are aggregates (8 to 78 μm) of FeS and metal. The FeS in the chondrules, fragments, and aggregates range from 4 to 35 μm . The metal ranges from 4 to 65 μm .

2.3.2 MET 00783 (EH4)

Site 1 (Figures 2.15) contains 25 identified chondrules and fragments. The diameters of these objects range from 30 to 492 μm . The low-Ca pyroxene in the chondrules and fragments range from 5 to 50 μm in diameter. Olivine is observed only in one chondrule, completely surrounded by low-Ca pyroxene. This grain is anhedral in shape with a diameter of 195 μm . As the olivine is surrounded by low-Ca pyroxene and has an anhedral shape, it may be relict. All chondrules and fragments contain plagioclase infilling between the low-Ca pyroxene and the olivine. 7 of the fragments contain silica, mostly observed at the edges of the fragments and always accompanied by the plagioclase. Most of the chondrules and fragments contain minor FeS (5 to 25 μm). 3 of the fragments contain metal (5 to 25 μm). MgS (4 to 8 μm) is observed at the edges of 2 fragments. Between the chondrules and fragments are aggregates (13 to 148 μm) of FeS (4 to 52 μm) and metal (4 to 52 μm). CaS (4 to 48 μm) is observed in several of the aggregates and is always in contact with FeS. Some of the CaS is in contact with the metal as well.

Site 2 (Figures 2.16) contains 26 identified chondrules and fragments. The diameters of these objects range from 23 to 400 μm . The low-Ca pyroxene in the chondrules and fragments range from 5 to 77 μm in diameter. This site lacks olivine. 23 of the chondrules and fragments contain plagioclase (4 to 62 μm). 6 of the chondrules and fragments contain silica (15 to 23 μm) accompanying the plagioclase at the edges of the chondrules and fragments. FeS (4 to 38 μm) and metal (4 to 54 μm) is observed in 13 of the chondrules and fragments. Aggregates (13 of 257 μm) of FeS (9 to 43 μm) and metal (9 to 257 μm) are observed between the chondrules and fragments. An aggregate at the edge of the largest fragment contains CrS (35 μm). The aggregates around the largest fragment also contain CaS (13 to 43). The CaS is also observed in other aggregates at the edges of other fragments. The largest metal aggregate contains elongated inclusions that are enriched in silica and Ni (9 to 30 μm).

Site 3 (Figures 2.17) contains 45 identified chondrules and fragments. The diameters of these objects range from 15 to 323 μm . The low-Ca pyroxene in the chondrules and fragments range from 4 to 100 μm in diameter. This site lacks olivine. 31 chondrules and fragments contain plagioclase (4 to 46 μm). 12 chondrules and fragments contain silica (8 to 38 μm). The silica is mostly observed accompanying the plagioclase and

often occurs close to the edges of the chondrules and fragments. 3 of the fragments are dominated by glass. Most of the chondrules and fragments contain FeS (4 to 23 μm). MgS (4 to 17 μm) is observed in 2 of the fragments. Between the chondrules and fragments are aggregates (8 to 152 μm) of FeS (4 to 30) and metal (4 to 152 μm). In some of the aggregates are CaS (4 to 22 μm), occurring close to the edges of the chondrules and fragments.

Site 4 (Figures 2.18) contains 37 identified chondrules and fragments. The diameters of these objects range from 15 to 323 μm . The low-Ca pyroxene in the chondrules and fragments range from 4 to 100 μm in diameter. This site lacks olivine. 31 chondrules and fragments contain plagioclase (4 to 46 μm). 17 chondrules and fragments contain silica (8 to 92 μm). The silica is mostly observed accompanying the glass and often occurs close to the edges of the chondrules and fragments. Some silica occurs close to the center of the chondrules and fragments. 2 small fragments are dominated by the silica and 1 is dominated by plagioclase. Most of the chondrules and fragments contain FeS (4 to 38 μm). MgS (4 to 26 μm) is observed in 5 of the fragments. Between the chondrules and fragments are aggregates (8 to 178 μm) of FeS (4 to 96 μm) and metal (4 to 178 μm). In 2 of the aggregates are CaS (13 to 57 μm), occurring close to the edges of the chondrules and fragments. CrS (8 to 43 μm) is observed in 2 aggregates in contact with the FeS only.

Site 5 (Figures 2.19) contains 26 identified chondrules and fragments. The diameters of these objects range from 15 to 500 μm . The low-Ca pyroxene in the chondrules and fragments range from 4 to 123 μm in diameter. This site lacks olivine. 21 chondrules and fragments contain plagioclase (4 to 85 μm). 7 chondrules and fragments contain silica (8 to 46 μm). The silica is mostly observed accompanying the plagioclase and often occurs close to the edges of the chondrules and fragments. Some silica occurs close to the center of the chondrules and fragments. 1 small fragment is dominated by the silica and plagioclase. Most of the chondrules and fragments contain FeS (4 to 31 μm) and metal (4 to 23 μm). MgS (4 to 26 μm) is observed in 5 of the fragments. CaS (4 to 17 μm) is observed in 1 chondrule and 1 fragment. The CaS in the chondrule occurs close to the chondrule edge and is mostly surrounded by low-Ca pyroxene. The CaS in the fragment is in contact with low-Ca pyroxene, plagioclase, and silica. Between the chondrules and fragments are aggregates (8 to 143 μm) of FeS (4 to 65 μm) and metal (4 to 143 μm). In 2 of the aggregates are CaS (8 to 26 μm), occurring close to the edges

of the chondrules and fragments.

Site 6 (Figures 2.20) contains 34 identified chondrules and fragments. The diameters of these objects range from 35 to 250 μm . The low-Ca pyroxene in the chondrules and fragments range from 5 to 50 μm in diameter. Olivine is only observed in 2 chondrules. They have anhedral shapes and range from 17 to 55 μm in diameter. The olivine is surrounded by low-Ca pyroxene. As the olivine is surrounded by low-Ca pyroxene and has an anhedral shape, it may be relict. 22 of the chondrules and fragments contain plagioclase in filling between the low-Ca pyroxene. 13 chondrules and fragments contain silica, usually occurring at the edges of the chondrules and fragments. The silica is always accompanied by plagioclase. Most of the chondrules and fragments contain FeS (5 to 25 μm). 4 chondrules contain metal (5 μm). MgS (4 to 22 μm) is observed in 5 of the fragments. One of the MgS is completely surrounded by glass, the rest are all in contact with low-Ca pyroxene. Between the chondrules and fragments are aggregates (8 to 174 μm) of FeS (4 to 91 μm) and metal (4 to 174 μm). Several of the aggregates contain CaS (13 to 17 μm), occurring close to the edges of the chondrules and fragments. MgS (30 μm) is observed in 1 aggregate between two fragments. An isolated CrS (43 μm) is observed between two fragments and an aggregate of FeS and metal.

Site 7 (Figures 2.21) contains 24 identified chondrules and fragments. The diameters of these objects range from 20 to 250 μm . The low-Ca pyroxene in the chondrules and fragments range from 5 to 50 μm in diameter. Olivine is absent from this site. 20 chondrules and fragments contain plagioclase. One fragment is dominated by the plagioclase. The rest of the plagioclase interfiles between the low-Ca pyroxene. 12 fragments are contain silica, with one fragment dominated by the silica. Inside this fragment are elongated inclusions that enriched in silica and Ni. A second fragment is dominated by silica and plagioclase. The silica is usually accompanied by glass and is often observed at the edges of the chondrules and fragments. FeS (5 to 20 μm) is observed in most of the chondrules and fragments. Metal is observed in only two fragments (5 to 30 μm). In the silica dominated fragment, there are elongated, Ni-rich objects (15 μm). 1 of the fragments contains MgS (17 μm) in an aggregate with FeS. Between the chondrules and fragments are aggregates (8 to 200 μm) of FeS (4 to 43 μm) and metal (4 to 200 μm). Several of the aggregates are CaS (4 to 22 μm), occurring close to the edges of the chondrules and fragments.

Site 8 (Figures 2.22) contains 27 identified chondrules and fragments. The diameters

of these objects range from 15 to 400 μm . The low-Ca pyroxene in the chondrules and fragments range from 4 to 69 μm in diameter. 3 olivines (8 to 146 μm) are observed in the largest chondrule. 24 chondrules and fragments contain plagioclase (4 to 85 μm). 6 chondrules and fragments contain silica (8 to 54 μm). The silica is mostly observed accompanying the plagioclase and often occurs close to the edges of the chondrules and fragments. Some silica occurs close to the center of the chondrules and fragments. 1 small fragment is dominated by glass. Some of the chondrules and fragments contain FeS (4 to 8 μm). MgS (4 to 23 μm) is observed in 5 of the fragments. Between the chondrules and fragments are aggregates (8 to 226 μm) of FeS (4 to 78 μm) and metal (4 to 226 μm). In 3 of the aggregates contain CaS (8 to 43 μm), occurring close to the edges of the chondrules and fragments.

Site 9 (Figures 2.23) contains 34 identified chondrules and fragments. The diameters of these objects range from 31 to 223 μm . The low-Ca pyroxene in the chondrules and fragments range from 4 to 77 μm in diameter. This site lacks olivines. 27 chondrules and fragments contain plagioclase (4 to 92 μm). 15 chondrules and fragments contain silica (8 to 62 μm). The silica is mostly observed accompanying the plagioclase and often occurs close to the edges of the chondrules and fragments. Some silica occurs close to the center of the chondrules and fragments. 1 small fragment is dominated by plagioclase. Some of the chondrules and fragments contain FeS (4 to 8 μm). Between the chondrules and fragments are aggregates (8 to 226 μm) of FeS (4 to 78 μm) and metal (4 to 226 μm). Several of the aggregates contain CaS (8 to 61 μm), occurring close to the edges of the chondrules and fragments.

Site 10 (Figures 2.24) contains 32 identified chondrules and fragments. The diameters of these objects range from 8 to 392 μm . The low-Ca pyroxene in the chondrules and fragments range from 8 to 162 μm in diameter. Olivine (8 to 92 μm) is observed in 1 fragment. 21 chondrules and fragments contain plagioclase (4 to 92 μm). 13 chondrules and fragments contain silica (8 to 69 μm). The silica is mostly observed accompanying the plagioclase and often occurs close to the edges of the chondrules and fragments. Some silica occurs close to the center of the chondrules and fragments. Most of the chondrules and fragments contain FeS (4 to 492 μm). Between the chondrules and fragments are aggregates (8 to 226 μm) of FeS (4 to 131 μm) and metal (4 to 226 μm). Several of the aggregates contain CaS (8 to 46 μm), occurring close to the edges of the chondrules and fragments.

Site 11 (Figures 2.25) contains 31 identified chondrules and fragments. The diameters of these objects range from 23 to 500 μm . The low-Ca pyroxene in the chondrules and fragments range from 8 to 85 μm in diameter. Olivine is observed in a single chondrule (29 μm). 23 chondrules and fragments contain plagioclase (4 to 38 μm). 11 chondrules and fragments contain silica (8 to 54 μm). The silica is mostly observed accompanying the plagioclase and often occurs close to the edges of the chondrules and fragments. Some silica occurs close to the center of the chondrules and fragments. 1 fragment is dominated by silica. 3 fragments are dominated by glass. Most of the chondrules and fragments contain FeS (4 to 38 μm). 1 fragment contains metal (4 μm). MgS (15 to 31 μm) is observed in 2 fragments. Between the chondrules and fragments are aggregates (8 to 204 μm) of FeS (4 to 61 μm) and metal (4 to 204 μm). Several of the aggregates contain CaS (8 to 17 μm), occurring close to the edges of the chondrules and fragments. MgS (8 μm) is observed in 1 aggregate close to the edge of a fragment.

Site 12 (Figures 2.26) contains 43 identified chondrules and fragments. The diameters of these objects range from 23 to 254 μm . The low-Ca pyroxene in the chondrules and fragments range from 8 to 108 μm in diameter. Olivine (23 to 85 μm) is observed in 2 of the chondrules and 1 fragment. 30 chondrules and fragments contain plagioclase (4 to 85 μm). 14 chondrules and fragments contain silica (8 to 69 μm). The silica is mostly observed accompanying the glass and often occurs close to the edges of the chondrules and fragments. Some silica occurs close to the center of the chondrules and fragments. 2 fragments are dominated by silica. 4 fragments are dominated by plagioclase. Most of the chondrules and fragments contain FeS (4 to 23 μm). MgS (15 to 31 μm) is observed in 1 chondrule and 2 fragments. Between the chondrules and fragments are aggregates (8 to 235 μm) of FeS (4 to 65 μm) and metal (4 to 235 μm). Several of the aggregates contain CaS (8 to 26 μm), occurring close to the edges of the chondrules and fragments. Around the rim of the largest chondrule is a discontinuous band of CaS which ranges from 4 to 17 μm thick.

2.3.3 EET 96135 (EH5)

Site 1 (Figures 2.27) contains 21 identified chondrules and fragments. The diameters of these objects range from 38 to 700 μm . The low-Ca pyroxene in the chondrules and fragments range from 8 to 92 μm in diameter. 10 chondrules and fragments contain

plagioclase (4 to 38 μm). 12 chondrules and fragments contain silica (8 to 62 μm). The silica is mostly observed accompanying the plagioclase and often occurs close to the edges of the chondrules and fragments. Some silica occurs close to the center of the chondrules and fragments. 2 fragments are dominated by silica. Most of the chondrules and fragments contain FeS (4 to 54 μm). MgS (15 to 31 μm) is observed in 13 chondrules and fragments. Between the chondrules and fragments are aggregates (8 to 113 μm) of FeS (4 to 26 μm) and metal (4 to 113 μm).

Site 2 (Figures 2.28) contains 26 identified chondrules and fragments. The diameters of these objects range from 31 to 400 μm . The low-Ca pyroxene in the chondrules and fragments range from 8 to 77 μm in diameter. 15 chondrules and fragments contain plagioclase (4 to 38 μm). 9 chondrules and fragments contain silica (8 to 77 μm). The silica is mostly observed accompanying the plagioclase and often occurs close to the edges of the chondrules and fragments. Some silica occurs close to the center of the chondrules and fragments. Most of the chondrules and fragments contain FeS (4 to 54 μm). MgS (8 to 31 μm) is observed in 9 chondrules and fragments. Between the chondrules and fragments are aggregates (8 to 143 μm) of FeS (4 to 35 μm) and metal (4 to 143 μm). 3 of the aggregates contain low-Ca pyroxene and silica inclusions.

Site 3 (Figures 2.29) contains 34 identified chondrules and fragments. The diameters of these objects range from 23 to 254 μm . The low-Ca pyroxene in the chondrules and fragments range from 8 to 77 μm in diameter. 17 chondrules and fragments contain plagioclase (4 to 38 μm). 11 chondrules and fragments contain silica (8 to 69 μm). The silica is mostly observed accompanying the plagioclase and often occurs close to the edges of the chondrules and fragments. Some silica occurs close to the center of the chondrules and fragments. Most of the chondrules and fragments contain FeS (4 to 31 μm). MgS (8 to 23 μm) is observed in 11 chondrules and fragments. Between the chondrules and fragments are aggregates (8 to 109 μm) of FeS (4 to 43 μm) and metal (4 to 74 μm). 5 of the aggregates contain low-Ca pyroxene inclusions.

Site 4 (Figures 2.30) contains 15 identified chondrules and fragments. The diameters of these objects range from 38 to 500 μm . The low-Ca pyroxene in the chondrules and fragments range from 8 to 115 μm in diameter. 13 chondrules and fragments contain plagioclase (4 to 31 μm). 12 chondrules and fragments contain silica (4 to 69 μm). The silica is mostly observed accompanying the plagioclase and often occurs close to the edges of the chondrules and fragments. Some silica occurs close to the center of the

chondrules and fragments. 1 fragment is dominated by silica. Most of the chondrules and fragments contain FeS (4 to 38 μm) and metal (8 to 46 μm). MgS (8 to 23 μm) is observed in 6 chondrules and fragments. Between the chondrules and fragments are aggregates (8 to 91 μm) of FeS (4 to 17 μm) and metal (4 to 91 μm). 5 of the aggregates contain low-Ca pyroxene inclusions.

Site 5 (Figures 2.31) contains 51 identified chondrules and fragments. The diameters of these objects range from 35 to 153 μm . The low-Ca pyroxene in the chondrules and fragments range from 5 to 77 μm in diameter. 28 chondrules and fragments contain plagioclase (4 to 38 μm) interfilling between the low-Ca pyroxene. 16 of the fragments contain silica (4 to 46 μm). The is often accompanied by plagioclase. The silica mostly occurs at the edges of the fragments. 3 fragments are dominated by the silica. All chondrules and fragments contain FeS (5 to 20 μm). 3 fragments contain metal (5 to 30 μm). 10 fragments contain MgS (4 to 23 μm). Between the chondrules and fragments are aggregates (8 to 109 μm) of FeS (4 to 22 μm) and metal (4 to 109 μm). An isolated MgS (31 μm) surrounded by 4 fragments is observed. 3 of the aggregates contain low-Ca pyroxene inclusions. 1 of these aggregates also contains silica inclusions.

Site 6 (Figures 2.32) contains 32 identified chondrules and fragments. The diameters of these objects range from 15 to 315 μm . The low-Ca pyroxene in the chondrules and fragments range from 10 to 75 μm in diameter. 27 chondrules contain plagioclase (8 to 31 μm) interfilling the low-Ca pyroxene. 14 chondrules and fragments contain silica (8 to 62 μm). The silica often occurs close to the edges of the chondrules and fragments, with some of the silica accompanying the glass. 2 small fragments are dominated by silica. These fragments lack low-Ca pyroxene, plagioclase, FeS, and metal. 30 chondrules and fragments contain FeS (5 to 35 μm). 5 chondrules and fragments contain metal (5 to 40 μm). 14 chondrules and fragments contain MgS (8 to 15 μm), often in an aggregate with FeS. Between the chondrules and fragments are aggregates (8 to 91 μm) of FeS (4 to 26 μm) and metal (4 to 91 μm). 4 of the aggregates contain low-Ca pyroxene inclusions.

Site 7 (Figures 2.33) contains 28 identified chondrules and fragments. The diameters of these objects range from 38 to 277 μm . The low-Ca pyroxene in the chondrules and fragments range from 8 to 69 μm in diameter. 17 chondrules and fragments contain plagioclase (4 to 31 μm). 16 chondrules and fragments contain silica (4 to 131 μm). The silica is mostly observed accompanying the plagioclase and often occurs close to

the edges of the chondrules and fragments. Some silica occurs close to the center of the chondrules and fragments. 1 fragment is dominated by silica. Most of the chondrules and fragments contain FeS (4 to 31 μm) and metal (8 to 38 μm). MgS (8 to 31 μm) is observed in 6 chondrules and fragments. Between the chondrules and fragments are aggregates (8 to 151 μm) of FeS (4 to 35 μm) and metal (4 to 151 μm). CaS (4 μm) is observed in two aggregates. 3 of the aggregates contain low-Ca pyroxene inclusions. 1 aggregate contains silica inclusions.

Site 8 (Figures 2.34) contains 41 identified chondrules and fragments. The diameters of these objects range from 23 to 269 μm . The low-Ca pyroxene in the chondrules and fragments range from 8 to 69 μm in diameter. 31 chondrules and fragments contain plagioclase (4 to 38 μm). 18 chondrules and fragments contain silica (4 to 77 μm). The silica is mostly observed accompanying the plagioclase and often occurs close to the edges of the chondrules and fragments. Some silica occurs close to the center of the chondrules and fragments. 1 fragment is dominated by silica. Most of the chondrules and fragments contain FeS (4 to 31 μm) and metal (8 to 23 μm). MgS (8 to 38 μm) is observed in 17 chondrules and fragments. One of the fragments contains CaS (8 μm) in an aggregate with FeS. Between the chondrules and fragments are aggregates (8 to 139 μm) of FeS (4 to 22 μm) and metal (4 to 139 μm). 7 of the aggregates contain low-Ca pyroxene inclusions.

Site 9 (Figures 2.35) contains 28 identified chondrules and fragments. The diameters of these objects range from 23 to 323 μm . The low-Ca pyroxene in the chondrules and fragments range from 8 to 115 μm in diameter. 26 chondrules and fragments contain plagioclase (4 to 38 μm). 15 chondrules and fragments contain silica (4 to 46 μm). The silica is mostly observed accompanying the plagioclase and often occurs close to the edges of the chondrules and fragments. Some silica occurs close to the center of the chondrules and fragments. Most of the chondrules and fragments contain FeS (4 to 31 μm) and metal (8 to 31 μm). MgS (8 to 38 μm) is observed in 18 chondrules and fragments. One of the fragments contains CaS (8 μm) in an aggregate with FeS. Between the chondrules and fragments are aggregates (8 to 109 μm) of FeS (4 to 30 μm) and metal (4 to 74 μm). In an aggregate with FeS is a single CaS (17 μm) observed at the edge of a fragment. 5 of the aggregates contain low-Ca pyroxene inclusions.

Site 10 (Figures 2.36) contains 26 identified chondrules and fragments. The diameters of these objects range from 15 to 255 μm . The low-Ca pyroxene in the chondrules

and fragments range from 15 to 70 μm in diameter. 24 chondrules and fragments contain plagioclase (4 to 69 μm). The plagioclase interfiles the low-Ca pyroxene. The glass close to the edges of the chondrules and fragments are larger than the glass closer to the center of the chondrules and fragments. Silica (8 to 54 μm) is present in 11 chondrules and fragments. 1 fragment is dominated by silica. Most of the silica is accompanied by plagioclase. It is usually observed close to the edges of the chondrules and fragments. 13 chondrules and fragments contain MgS (8 to 31 μm). In 1 fragment there is an aggregate of FeS and CaS (13 μm) observed at the edge of the fragment. Between the chondrules and fragments are aggregates (8 to 109 μm) of FeS (4 to 30 μm) and metal (4 to 109 μm). 4 of the aggregates contain low-Ca pyroxene inclusions.

Site 11 (Figures 2.37) contains 31 identified chondrules and fragments. The diameters of these objects range from 15 to 362 μm . The low-Ca pyroxene in the chondrules and fragments range from 8 to 62 μm in diameter. 28 chondrules and fragments contain plagioclase (4 to 23 μm). The plagioclase interfiles the low-Ca pyroxene. The plagioclase close to the edges of the chondrules and fragments are larger than the plagioclase closer to the center of the chondrules and fragments. Silica (8 to 54 μm) is present in 16 chondrules and fragments. 1 fragment is dominated by silica. Most of the silica is accompanied by plagioclase. It is usually observed close to the edges of the chondrules and fragments. 16 chondrules and fragments contain MgS (4 to 23 μm). In 1 fragment there is an aggregate of FeS and CaS (4 to 13 μm) observed at the edge of the fragment. Between the chondrules and fragments are aggregates (8 to 92 μm) of FeS (4 to 39 μm) and metal (4 to 57 μm). 3 of the aggregates contain low-Ca pyroxene inclusions.

Site 12 (Figures 2.38) contains 33 identified chondrules and fragments. The diameters of these objects range from 31 to 554 μm . The low-Ca pyroxene in the chondrules and fragments range from 4 to 85 μm in diameter. 28 chondrules and fragments contain plagioclase (4 to 54 μm). The plagioclase interfiles the low-Ca pyroxene. The plagioclase close to the edges of the chondrules and fragments are larger than the plagioclase closer to the center of the chondrules and fragments. Silica (8 to 77 μm) is present in 15 chondrules and fragments. 1 fragment is dominated by silica. Most of the silica is accompanied by plagioclase. It is usually observed close to the edges of the chondrules and fragments. 14 chondrules and fragments contain MgS (4 to 23 μm). Between the chondrules and fragments are aggregates (8 to 123 μm) of FeS (4 to 30 μm) and metal (4 to 96 μm). 4 aggregates contain CaS (4 to 22 μm) in contact with FeS and metal. 3 of

the aggregates contain low-Ca pyroxene inclusions. 2 of these aggregates also contain silica inclusions.

2.3.4 QUE 94204 (EH7)

Site 1 (Figures 2.39) does not contain any chondrules or chondrule fragment like objects. The site is dominated by 3 large low-Ca pyroxene grains (485 to 1062 μm). Contained in these bodies are isolated FeS (8 to 15 μm) and metal grains (8 to 23 μm). 3 aggregates are observed at the edges of the sides and are likely completely surrounded by the low-Ca pyroxenes. The aggregates are comprised of FeS (22 to 131 μm) and metal (8 to 52 μm). Two of the aggregates contain CrS (9 to 22 μm). A large irregularly shaped metal grain (808 μm) is observed in contact with all 3 of the low-Ca pyroxenes. 3 of the metal have silica inclusions (4 to 38 μm). These inclusions occur in bands at the edges of 2 the metal grains. In one of these grains the inclusions are also concentrated in the center of the grain. 3 plagioclase grains (69 to 154 μm) are observed. The plagioclase are all in contact with metal, with 2 of them also in contact with FeS.

Site 2 (Figures 2.40) contains 4 low-Ca pyroxene grains (31 to 1038 μm). The 3 smaller low-Ca pyroxene bodies are mostly surrounded by metal. Contained in the largest low-Ca pyroxene grain are 9 plagioclase inclusions (8 to 46 μm). 2 aggregates (38 to 338 μm) of FeS (23 to 192 μm) and metal (15 to 169 μm) are observed contained in the largest low-Ca pyroxene grain. The metal in one of these aggregates contains a silica inclusion at the grain edge. The FeS in this aggregate contains a cluster of small CrS inclusions. A number of cracks are observed in this grain. These cracks are filled in by metal. 5 grains of metal (15 to 38 μm) are also observed contained in the largest low-Ca pyroxene grain. Additional metal grains (15 to 277 μm) are observed outside of the low-Ca pyroxene. 1 of these has a complete band of silica inclusions close to the edge of the grain. 3 plagioclase grains are observed in contact the metal grains. 2 of these contain metal inclusions (8 to 31 μm). All 3 plagioclase grains are cracked. These cracks are filled in by metal.

Site 3 (Figures 2.41) contains 4 low-Ca pyroxene grain (131 to 554 μm). These grain contain cracks that are filled in by metal, metal grains (8 to 31 μm) and FeS (4 to 15 μm). All 4 grain contain at least 1 aggregate of FeS (4 to 92 μm) and metal (8 to 162 μm). One of the aggregates had metal containing a silica inclusion (46 μm). 3 of the

low-Ca pyroxenes contain plagioclase inclusions (8 to 108 μm). The plagioclase (38 to 77 μm) are also observed outside of the low-Ca pyroxenes. A K-rich-plagioclase grain (38 μm) is observed at the edge of one of the low-Ca pyroxenes. 3 aggregates (43 to 139 μm) of FeS (17 to 109 μm) and metal (8 to 35 μm) are observed outside of the low-Ca pyroxenes. The FeS at this site is observed to often contain CrS (4 to 43 μm). A cluster of silica grains (23 to 38 μm) are observed in contact with the low-Ca pyroxene. One of the silica grains is in contact with 1 of the plagioclase grains. Throughout the site are several cracks that are filled in by metal.

Site 4 (Figures 2.42) contains 3 large low-Ca pyroxene grains. The diameters of these objects range from 120 to 445 μm . 2 of the objects have plagioclase grains (23 to 115 μm) accompanied by silica (8 to 77 μm) at the edges. All 3 low-Ca pyroxene bodies contain plagioclase (8 to 62 μm). 1 of the low-Ca pyroxenes contains K-rich-plagioclase grains (8 to 46 μm). The largest object also contains K-rich plagioclase. All 3 objects contain FeS (5 to 100 μm) and metal (5 to 60 μm). All 3 objects contain cracks that are filled in by metal (<5 to 15 μm). A large metal grain (462 μm) is observed between all 3 low-Ca pyroxenes. Below this grain an aggregate (115 μm) of FeS (115 μm) and CrS (22 μm).

Site 5 (Figures 2.43) contains 3 large low-Ca pyroxene grains. The diameters of these objects range from 108 to 385 μm . 1 of the low-Ca pyroxenes contains K-rich plagioclase (4 to 23 μm). All 3 low-Ca pyroxenes contain FeS (5 to 15 μm) and metal (5 to 23 μm). All 3 low-Ca pyroxenes contain cracks that are filled in by metal (<5 to 15 μm). 2 K-rich plagioclase grains (154 to 192 μm) are observed outside of the low-Ca pyroxenes. Metal bodies (15 to 346 μm) are observed in contact with the low-Ca pyroxenes. 1 of these metal bodies contains clusters of very small silica inclusions. The second metal body contains 2 larger silica inclusions (8 to 15 μm). The third metal body contains a low-Ca pyroxene inclusion (15 μm).

Site 6 (Figures 2.44) contains 6 identified low-Ca pyroxene grains. The diameters of the low-Ca pyroxene range from 20 to 500 μm . Two of the low-Ca pyroxenes contain plagioclase. One of these objects also contains K-rich plagioclase (69 μm) at its edge. Between some of the objects is a large plagioclase grain. 2 objects contain FeS (5 to 10 μm). Metal is observed in all objects except 1. The metal is mostly observed filling in cracks (<5 to 15 μm). Two objects contain metal grains (5 to 70 μm). The metal grains outside of the low-Ca pyroxenes were found be 154 to 385 μm in size. 1 of these

grains contains silica inclusions close to the edge of the grain. This grain also contains an aggregate (69 μm) of FeS and CrS. 3 K-rich-glass-like bodies (31 to 69 μm) are also observed in this grain.

Site 7 (Figures 2.45) contains a single large low-Ca pyroxene aggregate. This object is heavily cracked. The cracks are <5 to 23 micron in width and filled in by metal. Contained in this grain are plagioclase (8 to 38 μm), K-rich plagioclase (8 to 131 μm), and silica (46 μm) inclusions. Also contained in the low-Ca pyroxene are individual grains of FeS (5 to 23 μm) and metal (5 to 31 μm), along with aggregates (31 to 154 μm) of FeS (23 to 77 μm) and metal (23 to 77 μm). 2 of the metal grains in the aggregates contain clusters of very small silica inclusions. The FeS in the aggregates contains CrS (8 to 23 μm).

Site 8 (Figures 2.46) contains 10 identified low-Ca pyroxene grain. The diameters of these objects range from 20 to 245 μm . 2 objects contain plagioclase (8 to 77 μm), and 1 contains K-rich plagioclase (8 μm). 2 objects contain FeS (20 to 120 μm). Metal inside the objects is limited to filled in cracks (<5 to 10 μm). Large plagioclase grains (85 to 400 μm) are present outside of the objects, often accompanied by silica (8 to 92 μm). 2 of the low-Ca pyroxene contain aggregates (38 to 92 μm) comprised of FeS (31 to 92 μm) and CrS (8 to 23 micron). 1 of these aggregates also contains silica bearing metal (54 μm). A larger metal grain (200 μm) is observed surrounded by plagioclase, silica and low-Va pyroxene. This grain contains small silica inclusions at the edges of the grain.

Site 9 (Figures 2.47) contains a single large low-Ca pyroxene body. This body is heavily cracked. The cracks are <5 to 23 μm in width and filled in by metal. Contained in this body are plagioclase inclusions (8 to 77 μm) attached to 3 aggregates. Also contained in the low-Ca pyroxene are individual grains of FeS (5 to 13 μm) and metal (5 to 13 μm), along with aggregates (13 to 139 μm) of FeS (9 to 109 μm), CrS (4 to 30 μm), and metal (4 to 78 μm). Several of the metal grains in the aggregates contain clusters of very small silica inclusions.

Site 10 (Figures 2.48) contains 5 identified low-Ca pyroxene grains. The diameters of these objects range from 38 to 546 μm . 2 objects contain plagioclase grains (4 to 46 μm). The smallest low-Ca pyroxene is completely surrounded by a plagioclase (423 μm). 1 of the low-Ca pyroxenes contains 2 K-rich plagioclase (8 μm). The low-Ca pyroxenes contains small grains of FeS (4 to 31 μm) and metal (4 to 31 μm), along with

aggregates (15 to 85 μm) of FeS (15 to 23 μm) and metal (8 to 77 μm). The largest plagioclase grain is accompanied by silica (38 and 223 μm). A large metal body (500 μm) is observed between 2 of the low-Ca pyroxenes and in contact with the plagioclase.

Site 11 (Figures 2.49) is dominated by 2 low-Ca pyroxene grain (115 to 923 μm), separated by a metal filled crack (69 μm). The larger low-Ca pyroxene contains 2 plagioclase (23 to 46 μm) and K-rich plagioclase (23 to 54 μm) inclusions. The low-Ca pyroxenes contain small grains of FeS (4 to 13 μm) and metal (4 to 104 μm), along with aggregates (22 to 130 μm) of FeS (13 to 43 μm) and metal (13 to 109 μm). 2 of the aggregates contain CrS (4 to 48 μm). Both low-Ca pyroxenes are cracked (<5 to 8 μm). These cracks are filled in by metal.

Site 12 (Figures 2.50) is dominated by 4 low-Ca pyroxene grains (38 to 846 μm). Large plagioclase grains are observed around the outside of the low-Ca pyroxenes (231 μm). Between 3 of the low-Ca pyroxenes is a metal grain (262 μm), with filled in cracks (<5 to 54 μm) leading away from it. Inside this body is a number of low-Ca pyroxene (4 to 15 μm) and silica inclusions (8 to 92 μm). All 3 of the low-Ca pyroxenes contain plagioclase (4 to 54 μm). All 3 of the low-Ca pyroxenes contain metal (8 to 31 μm), with 2 of low-Ca pyroxene containing FeS (8 to 38 μm).

Site 13 (Figures 2.51) is dominated by 4 low-Ca pyroxene grain (54 to 462 μm). A large plagioclase grain is observed between the low-Ca pyroxenes (231 μm). A large crack (62 μm) separates 1 of the low-Ca pyroxenes from the others. This crack is filled in by metal. In this crack is a low-Ca pyroxene inclusion (15 μm) and a silica inclusion (15 μm). All 3 low-Ca pyroxenes and the plagioclase are cracked (5 to 31 μm). These cracks are filled in by metal. 2 metal inclusions (31 to 38 μm) are observed in the plagioclase grains. 1 of the low-Ca pyroxenes contains 2 plagioclase inclusions (8 to 62 μm). The largest low-Ca pyroxene contains silica inclusions (8 to 23 μm) and an aggregate (108 μm) of FeS (15 to 23 μm), metal (108 μm) and CrS (23 μm).

Site 14 (Figures 2.52) is dominated by a single low-Ca pyroxene grain, with a Na-rich-glass-like body (154 μm), and a 2 FeS grain (146 to 154 μm). The low-Ca pyroxene grain contains small FeS (4 to 23 μm), metal (4 to 38 μm), and plagioclase inclusions (4 to 8 μm). In the plagioclase body is a silica inclusion (23 μm). The low-Ca pyroxene and plagioclase are cracked (<5 to 31 μm). The cracks are filled in by metal. The FeS fills in a space in the low-Ca pyroxene. It contains CrS (4 to 54 μm) inclusions. The FeS is surrounded by discontinuous metal that varies in thickness from 8 to 31 μm).

2.3.5 LAP 02225 (EH impact melt)

Site 1 (Figures 2.53) contains 19 low-Ca pyroxene grains (8 to 877 μm). No chondrules are observed in this meteorite. 4 of these grains contain plagioclase (4 to 46 μm), 1 had silica inclusions (4 to 8 μm), and 6 contain FeS (8 to 77 μm) and metal inclusions (8 to 38 μm). Plagioclase outside of the low-Ca pyroxenes are observed. These grains are accompanied by silica (15 to 38 μm), FeS (4 to 74 μm), and metal (4 to 213 μm). The metal is observed to contain low-Ca pyroxene (8 to 38 μm) inclusions and silica inclusions (8 to 31 μm). Some of the silica inclusions are enriched in Ni. 6 CrS grains are observed. The CrS (4 to 26 μm) is only observed in contact with the FeS.

Site 2 (Figures 2.54) contains 16 low-Ca pyroxene grains (23 to 592 μm). Some of the low-Ca pyroxenes are elongated rather than rounded. 1 of these contains a silica inclusion (8 μm). 4 of the low-Ca pyroxene contain FeS (4 to 43 μm) and metal (4 to 52 μm) inclusions. A plagioclase outside of the low-Ca pyroxenes are observed. This grain is accompanied by FeS (13 to 43 μm), and metal (8 to 152 μm). A single low-Ca pyroxene (8 μm) inclusion is observed in the plagioclase. The metal body is observed to contain low-Ca pyroxene (31 to 38 μm) and silica inclusions (8 to 31 μm). Some of the silica inclusions are enriched in Ni.

Site 3 (Figures 2.55) contains 13 low-Ca pyroxene grains (8 to 585 μm). Some of the low-Ca pyroxenes are elongated rather than rounded. 3 of these contains a silica inclusion (4 to 15 μm). 3 of the low-Ca pyroxene grains contain plagioclase (8 to 69 μm) inclusions. 5 of the low-Ca pyroxene contain FeS (4 to 92 μm) and metal (4 to 54 μm) inclusions. A plagioclase outside of the low-Ca pyroxenes are observed. This body contains small metal (4 to 13 μm) inclusions. The metal body is observed to contain low-Ca pyroxene (4 to 38 μm), silica (8 to 92 μm), plagioclase (4 to 46 μm) inclusions. Some of the silica inclusions are enriched in Ni. 5 CrS (4 to 13 μm) grains are observed. 4 of these are observed in contact with FeS, with the last CrS in contact with metal.

Site 4 (Figures 2.56) contains 33 low-Ca pyroxene grains (8 to 269 μm). Some of the low-Ca pyroxenes are elongated rather than rounded. 1 of these contains a silica inclusion (4 μm). 3 of the low-Ca pyroxene grains contain plagioclase (4 to 38 μm) inclusions. 3 of the low-Ca pyroxene contain FeS (8 to 38 μm) and metal (4 to 38 μm) inclusions. A large aggregate of silica and plagioclase material dominates the center of the site. The silica ranges from 8 to 154 μm . The glass-like material ranges from 8 to

154 μm . Numerous low-Ca pyroxene (4 to 62 μm), with some FeS (4 to 46 μm), metal (4 to 77 μm), and 1 CrS (8 μm) inclusions. 3 metal grains (46 to 223 μm) and one FeS (54 μm) body are observed. The both the metal and FeS contain low-Ca pyroxene (8 to 62 μm). The metal also contains silica (8 to 38 μm) inclusions that are enriched in Ni. The largest metal body also contains plagioclase (4 to 92 μm) inclusions. 2 CrS grains are (4 to 13 μm) observed accompanying the FeS body.

Site 5 (Figures 2.57) contains 15 low-Ca pyroxene grains (8 to 577 μm). Some of the low-Ca pyroxenes are elongated rather than rounded. 3 of these contains a silica inclusions (8 μm). 3 of the low-Ca pyroxene grains contain plagioclase (8 to 77 μm) inclusions. No FeS or metal inclusions are present in the low-Ca pyroxene. The low-Ca pyroxene is possibly chemically zoned, however this was not observed in the individual element maps. 2 silica grains (8 to 231 μm) are observed. These grains are accompanied by plagioclase (8 to 54 μm). Both the silica and the plagioclase contain low-Ca pyroxene (4 to 62 μm) and FeS (8 to 77 μm) inclusions. CrS (4 to 65 μm) is mostly observed accompanying the FeS. However, 2 isolated grains are observed. 6 metal grains (22 to 30 μm) are observed. These are observed in contact with the low-Ca pyroxene and don't have any contacts with the FeS or CrS.

Site 6 (Figures 2.58) contains 15 low-Ca pyroxene grains (8 to 631 μm). Some of the low-Ca pyroxenes are elongated rather than rounded. 1 of these contains a silica inclusions (4 to 8 μm). 3 of the low-Ca pyroxene grains contain plagioclase (4 to 23 μm) inclusions. 3 low-Ca pyroxene contain FeS (8 to 30 μm) inclusions. 1 low-Ca pyroxene contains a CrS (22 μm) inclusion. 1 low-Ca pyroxene contains a metal (30 μm) inclusion. Plagioclase grains (23 to 77 μm) are present in the center of the site, along with silica (8 to 69 μm), metal (13 to 130 μm), FeS (8 to 87 μm), and CrS (4 to 22 μm). The plagioclase and silica contain low-Ca pyroxene (8 to 23 μm) inclusions. The metal contains plagioclase inclusions that contain silica (8 to 23 μm).

Site 7 (Figures 2.59) contains 20 identified low-Ca pyroxene grains (8 to 538 μm). Some of the low-Ca pyroxenes are elongated rather than rounded. Several low-Ca pyroxene grains cut through each other indicating that after re-melting there were multiple generations of crystal formation. The low-Ca pyroxene grains contain FeS (9 to 22 μm), CrS (9 to 13 μm), and metal (9 to 30 μm) inclusions. Bodies of FeS (13 to 130 μm) and metal (9 to 173 μm) are observed surrounding the low-Ca pyroxenes. CrS (9 to 52 μm) is observed accompanying the FeS. Silica (15 to 92 μm) and plagioclase grains (15 to

77 μm) are observed infilling between the low-Ca pyroxene, metal, and FeS.

Site 8 (Figures 2.60) contains 14 low-Ca pyroxene grains (8 to 377 μm). Some of the low-Ca pyroxenes are elongated rather than rounded. 4 low-Ca pyroxenes contain plagioclase (4 to 77 μm) inclusions. 1 low-Ca pyroxene contains silica (8 μm) inclusions. 4 metal grains (13 to 30 μm) are observed in the largest low-Ca pyroxene. Plagioclase grains are observed close to low-Ca pyroxene. 6 silica grains (8 to 115 μm) not contained in the plagioclase grains or low-Ca pyroxenes are observed. 2 of these silica grains contain low-Ca pyroxene (8 to 15 μm) inclusions. Between the low-Ca pyroxenes are grains of FeS (13 to 113 μm). 3 metal grains (17 to 109 μm) are observed close to FeS or CrS. The CrS ranges from 9 to 130 μm .

Site 9 (Figures 2.61) contains 14 identified low-Ca pyroxene grains (8 to 385 μm). 10 low-Ca pyroxenes contain plagioclase inclusions (8 to 23 μm). 1 low-Ca pyroxene contains a silica inclusion (23 μm). 5 of the low-Ca pyroxenes contain metal (22 μm), FeS (9 to 35 μm), and CrS (4 μm) inclusions. Plagioclase grain (23 to 215 μm) are observed filling in spaces between the low-Ca pyroxenes and the aggregates. The plagioclase are often accompanied by silica (15 to 277 μm). FeS (9 to 109 μm) is more prevalent than metal (13 to 87 μm) at this site, with CrS (13 to 39 μm) having a similar modal abundance to the metal.

Site 10 (Figures 2.62) contains 5 bodies identified bodies of low-Ca pyroxene (8 to 408 μm). Some of the low-Ca pyroxenes are elongated rather than rounded. 4 of the low-Ca pyroxenes contain plagioclase (8 to 46 μm), FeS (8 to 77 μm), and metal (15 to 23 μm) inclusions. The spaces between the low-Ca pyroxenes are filled by plagioclase (15 to 115 μm), silica (23 to 31 μm), FeS (13 to 130 μm), metal (8 to 43 μm), and CrS (8 to 65 μm). Some of the metal is surrounded by the glass-like material, which also contains low-Ca pyroxene inclusions (4 to 15 μm).

Site 11 (Figures 2.63) contains 18 bodies identified bodies of low-Ca pyroxene (8 to 346 μm). Some of the low-Ca pyroxenes are elongated rather than rounded. 6 of the low-Ca pyroxenes contain plagioclase inclusions (8 to 38 μm). 3 low-Ca pyroxenes contain silica inclusions (4 to 8 μm). 3 low-Ca pyroxenes contain FeS (9 to 26 μm), CrS (9 to 22 μm), and metal (13 to 43 μm) inclusions. Between the low-Ca pyroxenes are plagioclase (8 to 108 μm), silica (8 to 277 μm), FeS (8 to 117 μm), metal (8 to 87 μm), and CrS (13 to 30 μm). Some FeS inclusions (4 to 26 μm) are observed in the glass-like bodies and silica. The silica also contains CrS inclusions (4 to 9 μm). Low-Ca pyroxene

inclusions (4 to 31 μm) are observed in the plagioclase.

Site 12 (Figure 2.64) contains 12 identified bodies of low-Ca pyroxene (8 to 354 μm). Some of the low-Ca pyroxenes are elongated rather than rounded. None of the low-Ca pyroxenes contain plagioclase or silica inclusions. Metal (4 to 39 μm) and FeS (4 to 35 μm) inclusions are observed in 6 of the low-Ca pyroxenes. This site lacks a silica body. However, between the low-Ca pyroxenes are plagioclases (15 to 223 μm) and metal (9 to 122 μm). The Na-rich-glass-like bodies contain low-Ca pyroxene (8 μm), metal (4 to 39 μm), FeS (4 to 43 μm), and CrS (4 to 35 μm) inclusions. The metal contains low-Ca pyroxene (8 to 38 μm) and Si-Ni enriched (4 to 65 μm) inclusions.

2.4 EL chondrites

2.4.1 MAC 02837 (EL3)

Site 1 (Figure 2.65) contains 9 identified chondrules and fragments. The diameters of these objects range from 131 to 415 μm . All of the chondrules and fragments are dominated by low-Ca pyroxene (4 to 131 μm). All of the chondrules and fragments contain Na-rich glass (8 to 77 μm) and 5 of them contain silica (4 to 23 μm). Some of the low-Ca pyroxenes are elongated rather than rounded. These grains are similar to the elongated grains in the EH impact melt sample. One of the fragments has a large number of these grains. This indicates that localized partial re-melting may have occurred. Some of the Na-rich glass contains low-Ca pyroxene inclusions (4 to 15 μm). 5 chondrules and fragments contain silica (6 to 8 μm) accompanying the glass. All of the chondrules and fragments contain metal (4 to 74 μm) and/or FeS (4 to 30 μm) inclusions. 3 of the fragments contain CrS (4 to 17 μm) in aggregates with FeS. One metal grain (204 μm) is observed outside of the chondrules and fragments. 7 schreibersite grains (4 to 104 μm) are observed. 6 of these are in aggregates with metal. The largest schreibersite is an isolated grain.

Site 2 (Figure 2.66) contains 13 identified chondrules and fragments. The diameters of these objects range from 54 to 400 μm . All of the chondrules and fragments are dominated by low-Ca pyroxene (4 to 131 μm). 1 fragment contains an olivine grain (11 μm). All of the chondrules and fragments contain Na-rich glass (8 to 77 μm) and 5 of them contain silica (4 to 31 μm). Some of the Na-rich glass contains low-Ca pyroxene

inclusions (4 to 15 μm). All of the chondrules and fragments contain FeS (4 to 31 μm) inclusions. 6 of the fragments contain CrS (4 to 46 μm) in aggregates with FeS. Metal inclusions (5 to 61 μm) are observed in 3 fragments. Schreibersite grains (4 to 61 μm) are observed in 2 aggregates with metal (100 μm), 1 aggregate with FeS, and 1 with an aggregate of FeS and CrS.

Site 3 (Figure 2.67) contains 13 identified chondrules and fragments. The diameters of these objects range from 69 to 438 μm . All of the chondrules and fragments are dominated by low-Ca pyroxene (4 to 92 μm). 3 fragments contain olivine (6 to 11 μm). All of the chondrules and fragments contain Na-rich glass (8 to 77 μm) and 5 of them contain silica (4 to 108 μm). All of the chondrules and fragments contain FeS (4 to 62 μm) inclusions. 4 of the fragments contain CrS (4 to 13 μm) in aggregates with FeS. Metal inclusions (4 to 17 μm) are observed in 3 fragments. 1 metal grain (143 μm) and 3 aggregates (87 to 213 μm) are observed outside of the chondrules and fragments. In the aggregates there is a large metal:FeS ratio. One of the aggregates contains CrS (4 to 17 μm). Schreibersite grains (4 to 26 μm) are observed as inclusions in the chondrules and fragments.

Site 4 (Figure 2.68) contains 15 identified chondrules and fragments. The diameters of these objects range from 54 to 562 μm . All of the chondrules and fragments are dominated by low-Ca pyroxene (4 to 108 μm). 1 fragment contains olivine (6 μm). All of the chondrules and fragments contain Na-rich glass (8 to 38 μm) and 7 of them contain silica (4 to 31 μm). Some of the Na-rich glass contains low-Ca pyroxene inclusions (4 to 15 μm). Apart from 1 exception, all of the chondrules and fragments contain FeS (4 to 54 μm) inclusions. 4 of the fragments contain CrS (4 to 13 μm) in aggregates with FeS. At the edge of one of the fragments is a CaS grain (4 μm) in an aggregate of metal and Ni-rich material. Metal inclusions (4 to 65 μm) are observed in 5 fragments. Schreibersite grains (4 to 30 μm) are observed in 3 aggregates with metal, 2 aggregates with FeS, and 1 isolated grain. 2 metal grains (100 to 177 μm) outside of the chondrules and fragments are observed. These grains and those inside the chondrules and fragments contain low-Ca pyroxene (4 to 15 μm), glass (4 to 8 μm), and silica (4 to 15 μm) inclusions.

Site 5 (Figure 2.69) contains 7 identified chondrules and fragments. The diameters of these objects range from 92 to 485 μm . All of the chondrules and fragments are dominated by low-Ca pyroxene (4 to 77 μm). All of the chondrules and fragments

contain Na-rich glass (8 to 31 μm) and 2 of them contain silica (4 to 38 μm). Some of the Na-rich glass contains low-Ca pyroxene inclusions (4 to 15 μm). All of the chondrules and fragments contain FeS (4 to 54 μm) inclusions. CaS (4 to 30 μm) is observed in aggregates with FeS and/or metal, in 1 of the fragments. 5 of the fragments contain CrS (4 to 13 μm) in aggregates with FeS. Metal inclusions (4 to 70 μm) are observed in 3 fragments. Schreibersite grains (4 to 13 μm) are observed in 2 aggregates with metal and 1 aggregate with FeS. 1 metal aggregate (163 μm) is observed outside of the chondrules and fragments.

Site 6 (Figure 2.70) contains 8 identified chondrules and fragments. The diameters of these objects range from 138 to 385 μm . All of the chondrules and fragments are dominated by low-Ca pyroxene (4 to 138 μm). Some of the low-Ca pyroxenes are elongated rather than rounded. These grains are similar to the elongated grains in the EH impact melt sample. One of the fragments has a large number of these grains. This indicates that localized partial re-melting may have occurred. 3 fragments contains 3 olivine grains (6 to 23 μm). The olivines are anhedral and completely surrounded by low-Ca pyroxene. This may be an indicator that the olivines are potentially relict. All of the chondrules and fragments contain Na-rich glass (8 to 77 μm) and 3 of them contain silica (4 to 38 μm). Some of the Na-rich glass contains low-Ca pyroxene inclusions (4 μm). All of the chondrules and fragments contain FeS (4 to 62 μm) inclusions. 6 of the fragments contain CrS (4 to 13 μm) in aggregates with FeS. Metal inclusions (4 to 43 μm) are observed in 3 fragments. Schreibersite grains (4 to 26 μm) are observed in 3 aggregates with metal, 2 aggregate with FeS, and 1 individual grain. 1 metal grain (239 μm) outside of the chondrules and fragments is observed. Many of the metal grains contain low-Ca pyroxene (4 to 31 μm) and/or glass (4 to 31 μm) inclusions.

Site 7 (Figure 2.71) contains 7 identified chondrules and fragments. The diameters of these objects range from 38 to 385 μm . All of the chondrules and fragments are dominated by low-Ca pyroxene (4 to 77 μm). Olivine (15 μm) is observed in 1 fragment. The olivine is anhedral and shares contacts low-Ca pyroxene, Na-rich glass, and silica. There is no evidence to suggest that this grain is relict. All of the chondrules and fragments contain Na-rich glass (8 to 38 μm) and 3 of them contain silica (4 to 38 μm). Some of the Na-rich glass contains low-Ca pyroxene inclusions (4 to 15 μm). All of the chondrules and fragments contain FeS (4 to 77 μm) inclusions. 4 of the fragments contain CrS (4 to 43 μm) in aggregates with FeS. Metal inclusions (4 to 174 μm) are

observed in 3 fragments. Schreibersite grains (4 to 30 μm) are observed in 3 aggregates with metal and 1 aggregate with FeS. 1 metal grain (448 μm) is observed outside of the chondrules and fragments.

Site 8 (Figure 2.72) contains 7 identified chondrules and fragments. The diameters of these objects range from 92 to 538 μm . All of the chondrules and fragments are dominated by low-Ca pyroxene (4 to 138 μm). All of the chondrules and fragments contain Na-rich glass (8 to 77 μm) and 4 of them contain silica (4 to 15 μm). Some of the low-Ca pyroxenes are elongated rather than rounded. These grains are similar to the elongated grains in the EH impact melt sample. One of the fragments has a large number of these grains. This indicates that localized partial re-melting may have occurred. Some of the Na-rich glass contains low-Ca pyroxene inclusions (4 to 15 μm). All of the chondrules and fragments contain metal (4 to 115 μm) and/or FeS (4 to 38 μm) inclusions. 5 of the fragments contain CrS (4 to 13 μm) in aggregates with FeS. One metal grain (152 μm) is observed outside of the chondrules and fragments. 7 grains of schreibersite (4 to 43 μm) is observed in aggregates with metal and/or FeS.

Site 9 (Figure 2.73) contains 16 identified chondrules and fragments. The diameters of these objects range from 38 to 346 μm . All of the chondrules and fragments are dominated by low-Ca pyroxene (4 to 138 μm). All of the chondrules and fragments contain Na-rich glass (8 to 38 μm) and 5 of them contain silica (4 to 38 μm). Some of the low-Ca pyroxenes are elongated rather than rounded. These grains are similar to the elongated grains in the EH impact melt sample. This indicates that localized partial re-melting may have occurred. 1 of the fragments contains anhedral olivines (4 to 22 μm) that are mostly surrounded by low-Ca pyroxene. This may be an indicator that the olivines are relict. 14 of the chondrules and fragments contain metal (4 to 46 μm) and/or FeS (4 to 62 μm) inclusions. A large aggregate of metal (395 μm), FeS (4 to 13 μm), and schreibersite (4 to 196 μm) is observed dominating the center of the site. In this aggregate is a small CaS (4 μm) grain. A larger CaS (30 μm) is observed in an aggregate with FeS close to two fragments. 3 fragments contain CrS (4 to 22 μm) in aggregates with FeS and the large metal aggregate.

2.4.2 PCA 91020 (EL3)

Site 1 (Figure 2.74) contains 6 identified chondrules and fragments. The diameters of these objects range from 246 to 492 μm . All of the chondrules and fragments are dominated by low-Ca pyroxene (8 to 69 μm). 1 of the fragments contains low-Ca pyroxenes that are elongated rather than rounded. These grains are similar to the elongated grains in the EH impact melt sample. This indicates that localized partial re-melting may have occurred. 2 of the fragments contain spinel (8 to 54 μm). These grains are anhedral in shape and are surrounded by elongated and euhedral low-Ca pyroxenes. 1 fragment contains olivine (6 μm). All of the chondrules and fragments contain Na-rich glass (4 to 38 μm). Contain in some of the glass is low-Ca pyroxene inclusions (4 to 15 μm). Silica (4 to 38 μm) is observed in 5 of the chondrules and fragments. The silica is often observed accompanying the glass. The location of the glass and silica within the chondrules and fragments is random. CaS is observed in an aggregate with FeS sandwiched between 2 fragments. All of the chondrules and fragments contain FeS (4 to 54 μm), with 5 of the fragments containing metal (4 to 46 μm). A small number of FeS grains contain low-Ca pyroxene (4 μm) inclusions. 2 metal bodies (115 to 238 μm) are observed between the chondrules and fragments. Both of these bodies contains low-Ca pyroxene inclusions (8 to 15 μm).

Site 2 (Figure 2.75) contains 17 identified chondrules and fragments. The diameters of these objects range from 77 to 346 μm . All of the chondrules and fragments are dominated by low-Ca pyroxene (8 to 208 μm). This site lacks olivine and spinel. All of the chondrules and fragments contain Na-rich glass (4 to 46 μm). Contain in some of the glass is low-Ca pyroxene inclusions (4 to 15 μm). Silica (4 to 15 μm) is observed in 6 of the chondrules and fragments. The silica is often observed accompanying the glass. The location of the glass and silica within the chondrules and fragments is random. An aggregate of CaS (4 to 39 μm) is observed between 3 fragments. All of the chondrules and fragments contain FeS (4 to 30 μm), with 5 of the fragments containing metal (4 to 22 μm). Several aggregates (31 to 308 μm) of FeS (4 to 46 μm) and metal (31 to 308 μm) are observed outside of the chondrules and fragments. In these aggregates, the ratio of FeS to metal is significantly smaller compared to their counter parts in the EH3 chondrite. These aggregates contain a small number of low-Ca pyroxene (4 to 8 μm), glass (4 and 8 μm) and silica (4 to 23 μm) inclusions. The inclusions are all observed at

the edges of the aggregates.

Site 3 (Figure 2.76) contains 13 identified chondrules and fragments. The diameters of these objects range from 85 to 277 μm . All of the chondrules and fragments are dominated by low-Ca pyroxene (8 to 54 μm). 2 olivine grains 5 μm are observed in 1 of the fragments. 1 of the fragments contain a spinel grain (8 to 54 μm). This grain is subhedral in shape and are surrounded by euhedral low-Ca pyroxenes. All of the chondrules and fragments contain Na-rich glass (4 to 54 μm). Silica (4 to 31 μm) is observed in 6 of the chondrules and fragments. The silica is often observed accompanying the glass. The location of the glass and silica within the chondrules and fragments is random. Contain in some of the glass is low-Ca pyroxene (4 to 15 μm) and silica (inclusions 4 to 31 μm). All of the chondrules and fragments contain FeS (4 to 38 μm), with 6 of the fragments containing metal (4 to 46 μm). Several aggregates (43 to 274 μm) of FeS (4 to 22 μm) and metal (9 to 274 μm) are observed outside of the chondrules and fragments. In these aggregates, the ratio of FeS to metal is significantly smaller compared to their counter parts in the EH3 chondrite. These aggregates contain a small number of low-Ca pyroxene (4 to 15 μm), glass (4 and 23 μm) and silica (4 to 15 μm) inclusions.

Site 4 (Figure 2.77) contains 13 identified chondrules and fragments. The diameters of these objects range from 23 to 538 μm . All of the chondrules and fragments are dominated by low-Ca pyroxene (8 to 62 μm). 1 fragment contains both euhedral and anhedral olivine (4 to 35 μm). The olivines aren't surrounded by low-Ca pyroxene. There is currently no evidence to support these grains being relict. This site lacks spinel. 9 of the chondrules and fragments contain Na-rich glass (4 to 46 μm) and silica (4 to 31 μm). Both the glass and silica contain low-Ca pyroxene inclusions (4 to 8 μm). Several aggregates (22 to 143 μm) of FeS (4 to 39 μm) and metal (9 to 126 μm) are observed outside of the chondrules and fragments. In these aggregates, the ratio of FeS to metal is significantly smaller compared to their counter parts in the EH3 chondrite. These aggregates contain a small number of low-Ca pyroxene (4 to 38 μm), glass (8 μm) and silica (4 μm) inclusions. Al-rich material is observed in holes.

Site 5 (Figure 2.78) contains 16 identified chondrules and fragments. The diameters of these objects range from 23 to 431 μm . All of the chondrules and fragments are dominated by low-Ca pyroxene (8 to 77 μm). 2 fragments contain anhedral olivines (4 to 38 μm) surrounded by low-Ca pyroxene. This may be an indicator that the olivines in this site are potentially relict. This site lacks spinel. All of the chondrules and fragments

contain Na-rich glass (4 to 23 μm). 6 of the chondrules and fragments contain silica (4 to 69 μm). The silica is often observed accompanying the glass. 1 silica grain contains a glass inclusion (8 μm). The largest silica grain contains low-Ca pyroxene inclusions (4 to 8 μm). All of the chondrules and fragments contain FeS (4 to 35 μm). 8 of the chondrules and fragments contain metal (4 to 30 μm). 7 aggregates (38 to 423 μm) outside of the chondrules and fragments are observed. These fragments are primarily comprised of FeS (38 to 423 μm), with 3 being dominated by metal (31 to 215 μm). Several of the aggregates contain low-Ca pyroxene (4 to 23 μm), glass (4 to 8 μm), and silica (4 to 8 μm) inclusions. Two the aggregates contain MgS (22 to 30 μm). The MgS appears 'faded' on the R-G-B maps. This may be an indicator that the MgS was being removed.

Site 6 (Figure 2.79) contains 10 identified chondrules and fragments. The diameters of these objects range from 46 to 562 μm . All of the chondrules and fragments are dominated by low-Ca pyroxene (8 to 69 μm). 3 fragments contain anhedral olivines (4 to 23 μm) surrounded by low-Ca pyroxene. This may be an indicator that the olivines in this site are potentially relict. This site lacks spinel. 9 of the chondrules and fragments contain Na-rich glass (4 to 85 μm). Some the glass contains low-Ca pyroxene inclusions (4 to 8 μm). 8 of the chondrules and fragments contain silica (4 to 31 μm). One of the fragments contains an elongated bar of silica. All of the chondrules and fragments contain FeS (4 to 57 μm). 6 of the chondrules and fragments contain metal (4 to 74 μm). 5 aggregates (13 to 187 μm) outside of the chondrules and fragments are observed. These aggregates are dominated by metal. The aggregates both inside and outside of the chondrules and fragments contain low-Ca pyroxene (4 to 8 μm), glass (4 to 23 μm), and silica (4 to 8 μm) inclusions.

Site 7 (Figure 2.80) contains 4 identified chondrules and fragments. The diameters of these objects range from 92 to 669 μm . All of the chondrules and fragments are dominated by low-Ca pyroxene (8 to 100 μm). One of the chondrules contains a subhedral olivines (4 to 23 μm). The olivines are surrounded by low-Ca pyroxene. There is no evidence to indicate that these grains are potentially relict. This site lacks spinel. All chondrules and fragments contain Na-rich glass (4 to 54 μm). The glass contains low-Ca pyroxene inclusions (4 to 8 μm). 3 of the chondrules and fragments contain silica (4 to 46 μm). All of the chondrules and fragments contain FeS (4 to 48 μm), and the 2 chondrules contain metal (2 to 35 μm). Between the chondrules and fragments are

two aggregates (52 and 287 μm). The larger of the 2 is dominated by metal, and the smaller 1 is dominated by FeS. The metal and FeS inside and outside of the chondrules and fragments contain low-Ca pyroxene (4 to 8 μm), glass (4 to 8 μm), and silica (4 to 23 μm) inclusions.

Site 8 (Figure 2.81) contains 13 identified chondrules and fragments. The diameters of these objects range from 31 to 415 μm . All of the chondrules and fragments are dominated by low-Ca pyroxene (8 to 54 μm). 3 of the chondrules and fragments contain subhedral olivines (4 to 15 μm). The olivines are surrounded by low-Ca pyroxene. There is no evidence to indicate that these grains are potentially relict. This site lacks spinel. Apart from 1 exception, all chondrules and fragments contain Na-rich glass (4 to 46 μm). The glass contains low-Ca pyroxene inclusions (4 to 8 μm). 11 of the chondrules and fragments contain silica (4 to 23 μm). All of the chondrules and fragments contain FeS (4 to 52 μm), and the 9 chondrules contain metal (4 to 22 μm). Between the chondrules and fragments are 6 aggregates (77 and 408 μm). 1 of these aggregates is dominated by FeS, the rest are dominated by metal. The metal and FeS inside and outside of the chondrules and fragments contain low-Ca pyroxene (4 to 8 μm), glass (4 to 31 μm), and silica (4 to 31 μm) inclusions.

Site 9 (Figure 2.82) contains 10 identified chondrules and fragments. The diameters of these objects range from 92 to 538 μm . All of the chondrules and fragments are dominated by low-Ca pyroxene (8 to 54 μm). 3 of the chondrules and fragments contain olivines (4 to 8 μm). 1 of the olivines is euhedral and surrounded by Na-rich glass. The other olivines are anhedral and surrounded by low-Ca pyroxene. This may be an indicator that both relict and non-relict olivines are present. The largest fragment contains a subhedral spinel grain (54 μm). This grain is surrounded by Na-rich glass, FeS, and low-Ca pyroxene. All of the chondrules and fragments contain Na-rich glass (4 to 46 μm). 6 of the chondrules and fragments contain silica (4 to 38 μm). In 1 fragment, some of the glass is enriched in Al compared to the rest of the glass. All of the fragments contain FeS (4 to 43 μm) and 5 of the chondrules and fragments contain metal (4 to 74 μm). 4 aggregates (39 to 261 μm) are observed outside of the chondrules and fragments. The metal and FeS inside and outside of the chondrules and fragments contain low-Ca pyroxene (4 to 23 μm), glass (4 to 8 μm), and silica (4 to 8 μm) inclusions. The largest aggregate contains a rounded CaS grain (48 μm) completely surrounded by metal.

Site 10 (Figure 2.83) contains 8 identified chondrules and fragments. The diameters

of these objects range from 92 to 523 μm . All of the chondrules and fragments are dominated by low-Ca pyroxene (8 to 92 μm). 2 of the chondrules and fragments contain anhedral olivines (8 μm). This site lacks spinel. All of the chondrules and fragments contain Na-rich glass (4 to 100 μm). Some of the glass contains low-Ca pyroxene inclusions (4 to 8 μm). 4 of the chondrules and fragments contain silica (4 to 77 μm). Some of the silica contain low-Ca pyroxene inclusions (4 μm). The silica is always observed accompanying glass in this site. All of the fragments contain FeS (4 to 57 μm) and 4 of the chondrules and fragments contain metal (4 to 52 μm). 5 aggregates (56 to 174 μm) outside of the chondrules and fragments are observed. These aggregates are composed primarily of metal. The metal and FeS inside and outside of the chondrules and fragments contain low-Ca pyroxene (4 to 8 μm), glass (4 to 15 μm), and silica (4 to 8 μm) inclusions. The largest aggregate contains a rounded CaS grain (13 μm) completely surrounded by metal. This aggregate also contains FeS inclusions (4 μm).

Site 11 (Figure 2.84) contains 16 identified chondrules and fragments. The diameters of these objects range from 46 to 438 μm . All of the chondrules and fragments are dominated by low-Ca pyroxene (8 to 77 μm). 2 fragments contain anhedral olivine (8 to 23 μm). The olivines are mostly surrounded by low-Ca pyroxenes and may be relict. The olivines in 1 of the fragments are clustered around spinels (15 μm). An additional spinel (23 μm) is observed at the edge of the fragment. All of the chondrules and fragments contain Na-rich glass (4 to 23 μm). Silica (4 to 31 μm) is observed in 9 chondrules and fragments. The largest silica grains are independent of the glass. However, the smaller silica grains tend to accompany the glass. In 1 fragment most of the silica clusters in 2 groups, with one of the grains having an elongated, bar-like shape. 15 of the chondrules and fragments contain FeS. 6 chondrules and fragments contain metal (4 to 17 μm). 10 aggregates (22 to 130 μm) are observed outside of the chondrules and fragments. The metal and FeS inside and outside of the chondrules and fragments contain low-Ca pyroxene (4 to 8 μm), glass (4 to 31 μm), and silica (4 to 8 μm) inclusions.

Site 12 (Figure 2.85) contains 12 identified chondrules and fragments. The diameters of these objects range from 31 to 538 μm . All of the chondrules and fragments are dominated by low-Ca pyroxene (8 to 100 μm). Olivine (4 to 15 μm) is observed in 2 fragments. The olivines are anhedral and surrounded by low-Ca pyroxene. This may be an indicator that the olivines are potentially relict. This site lacks spinel. 11 chondrules and fragments contain Na-rich glass (4 to 38 micron). 7 chondrules and fragments con-

tain silica (4 to 23 μm). The silica is mostly observed accompanying the glass. All of the chondrules and fragments contain FeS (4 to 35 micron). 5 of the chondrules and fragments contain metal (4 to 57 μm). 3 fragments contain CaS (4 to 22 μm) as independent grains. 7 aggregates (are observed outside of the chondrules and fragments. 1 of these aggregates is dominated by FeS, the rest are dominated by metal. The metal contains low-Ca pyroxene (4 to 15 micron), glass (4 to 8 micron), and silica (4 to 8 μm) inclusions.

Site 13 (Figure 2.86) contains 11 identified chondrules and fragments. The diameters of these objects range from 31 to 423 μm . All of the chondrules and fragments are dominated by low-Ca pyroxene (8 to 92 μm). Olivine (4 to 62 μm) is observed in 3 fragments. The olivines are anhedral and surrounded by low-Ca pyroxene. This may be an indicator that the olivines are potentially relict. This site lacks spinel. All of the chondrules and fragments contain Na-rich glass (4 to 31 μm). 9 chondrules and fragments contain silica (4 to 31 μm). Both the glass and silica contain low-Ca pyroxene inclusions (4 to 8 micron). All of the chondrules and fragments contain FeS (4 to 52 micron). 7 of the chondrules and fragments contain metal (4 to 35 μm). 1 fragments contain CaS (9 μm) as an independent grain. Metal contains low-Ca pyroxene (4 to 23 μm) and glass (4 to 8 μm) inclusions. FeS only contains low-Ca pyroxene (4 to 8 μm) inclusions. Several aggregates (15 to 190 μm) comprised of FeS and metal are observed outside of the chondrules and fragments.

Site 14 (Figure 2.87) contains 13 identified chondrules and fragments. The diameters of these objects range from 46 to 446 μm . 12 of the chondrules and fragments are dominated by low-Ca pyroxene (8 to 86 μm). 1 fragment is dominated by spinel (23 to 77 μm). The spinels are mostly clustered in the center of the fragment. Anhedral olivines (15 to 38 μm) are observed in 3 fragments. The olivines are surrounded by low-Ca pyroxene. It is possible that the olivines are relict. All of the chondrules and fragments contain Na-rich glass (4 to 38 μm). Silica (4 to 38 μm) is observed in 5 chondrules and fragments. The silica often accompanies the glass. Some silica have elongated, bar like-shapes. All of the chondrules and fragments contain FeS (4 to 30 μm). 5 chondrules and fragments contain metal (4 to 54 μm). 6 aggregates (31 to 77 μm) are observed outside of the chondrules and fragments. Apart from 1 exception, the aggregates are dominated by FeS. The FeS contains low-Ca pyroxene (4 to 8 μm) and glass (4 μm) inclusions, the metal only contains low-Ca pyroxene (4 to 8 μm) inclusions.

2.4.3 MAC 02747 (EL4)

Site 1 (Figure 2.88) contains 18 identified chondrules and fragments. The diameters of these objects range from 23 to 254 μm . All of the chondrules and fragments are dominated by low-Ca pyroxene (8 to 77 μm). 2 chondrules contain subhedral and anhedral olivines (8 to 38 μm). The olivines are surrounded by low-Ca pyroxene. Some of these olivines may be potential relict grains. 15 of the chondrules and fragments contain plagioclase (4 to 69 μm). Some of the plagioclase contains low-Ca pyroxene inclusions (4 to 31 μm). 10 of the chondrules and fragments contain silica (4 to 23 μm). The silica is often observed accompanying the plagioclase. 15 of the chondrules and fragments contain FeS (4 to 26 μm). 5 of the chondrules and fragments contain metal (4 to 17 μm). 3 aggregates (54 to 346 μm) outside of the chondrules and fragments are observed. These aggregates are dominated by metal. One of these aggregates contains a cluster of schreibersite ($[\text{Fe}, \text{Ni}]_3\text{P}$). This cluster is 91 μm in size and completely surrounded by metal. The FeS in 5 fragments contains CrS (4 to 13 μm). 1 fragment has CrS grains (4 to 8 μm) that is independent of FeS. The FeS contains low-Ca pyroxene (4 to 8 μm) and glass (8 μm) inclusions. The metal contains low-Ca pyroxene (4 to 46 μm), plagioclase (4 to 23 μm), and silica (4 to 8 μm) inclusions.

Site 2 (Figure 2.89) contains 22 identified chondrules and fragments. The diameters of these objects range from 31 to 538 μm . 22 of the chondrules and fragments are dominated by low-Ca pyroxene (8 to 154 μm). 3 of the chondrules and fragments contain subhedral and anhedral olivine (8 to 38 μm). The olivines are surrounded by low-Ca pyroxene, other olivines, and plagioclase. There is no evidence to indicate that the olivines are potentially relict grains. All of the chondrules and fragments contain plagioclase (4 to 77 μm). Some of the plagioclase is more enriched in Al than other plagioclase in different and the same chondrules and fragments at this site. Some of the plagioclase contains low-Ca pyroxene inclusions (4 to 15 μm). 7 of the chondrules and fragments contain silica (8 to 38 μm). The silica is mostly observed accompanying the plagioclase at the edges of the chondrules and fragments. 1 fragment is dominated by silica. 21 of the chondrules and fragments contain FeS (4 to 26 μm). 5 of the chondrules and fragments contain metal (4 to 17 μm). 7 aggregates (38 to 231 μm) outside of the chondrules and fragments are observed. 3 of the fragments are dominated by metal, the remaining 4 are dominated by FeS. Some of the FeS dominated aggregates include

CrS (4 to 17 μm). Several of the aggregates (both FeS and metal dominated) contain schreibersite (4 to 26 μm). Some of the FeS and metal contain low-Ca pyroxene (4 to 46 μm) and glass (4 to 8 μm) inclusions.

Site 3 (Figure 2.90) contains 20 identified chondrules and fragments. The diameters of these objects range from 31 to 377 μm . All of the chondrules and fragments are dominated by low-Ca pyroxene (8 to 92 μm). This site lacks olivine. All of the chondrules and fragments contain plagioclase (4 to 115 μm). Some of the plagioclase contains low-Ca pyroxene (4 to 8 μm), silica (4 to 15 μm), and FeS (4 to 23 μm) inclusions. 15 of the chondrules and fragments contain silica (4 to 77 μm). Most of the silica is observed accompanying plagioclase. Some of the silica contain low-Ca pyroxene (4 to 15 μm) and FeS (4 to 8 μm) inclusions. All of the chondrules and fragments contain FeS (4 to 31 μm). 6 of the fragments contain metal (4 to 15 μm). Some of the FeS are in aggregates with CrS (4 to 23 μm). 4 aggregates (26 to 148 μm) are observed outside of the chondrules and fragments. 2 of the aggregates are dominated by metal, 1 is dominated by FeS, and the last aggregate is dominated by schreibersite. Schreibersite (4 to 30 μm) is observed mostly in the aggregates, but is also observed accompanying some of the FeS and metal in the chondrules and fragments. The aggregates also contain low-Ca pyroxene (4 to 31 μm) and glass (4 to 8 μm) inclusions.

Site 4 (Figure 2.91) contains 14 identified chondrules and fragments. The diameters of these objects range from 69 to 485 μm . All of the chondrules and fragments are dominated by low-Ca pyroxene (8 to 100 μm). This site lacks olivine. All of the chondrules and fragments contain plagioclase (4 to 69 μm). Some of the plagioclase contains low-Ca pyroxene (4 to 15 μm), silica (4 to 8 μm), and FeS (4 to 23 μm) inclusions. 10 of the chondrules and fragments contain silica (4 to 38 μm). Some of the silica is observed accompanying plagioclase. Apart from 2 exceptions, the bulk of the silica is observed at the edges of the chondrules and fragments. All of the chondrules and fragments contain FeS (4 to 77 μm). Several of these are in aggregates with CrS (4 to 17 μm). 2 aggregates (77 to 254 μm) outside of the chondrules and fragments are observed. These aggregates are dominated by metal. The larger of the aggregates contains schreibersite (85 μm). The smaller aggregate has an elongated shape and contains FeS (54 μm) and CaS (22 μm). The aggregates also contain low-Ca pyroxene (4 to 8 μm) and silica (4 to 23 μm) inclusions.

Site 5 (Figure 2.92) contains 10 identified chondrules and fragments. The diameters

of these objects range from 38 to 323 μm . All of the chondrules and fragments are dominated by low-Ca pyroxene (8 to 146 μm). 1 of the fragments contains an anhedral olivine grain (15 μm) surrounded by low-Ca pyroxene. This may be an indicator that the olivine is potentially a relict grain. All of the chondrules and fragments contain plagioclase (4 to 62 μm). Some of the plagioclase contains low-Ca pyroxene (4 to 46 μm) and FeS (4 to 13 μm) inclusions. 9 of the chondrules and fragments contain silica (4 to 77 μm). Most of the silica is observed accompanying glass. Some of the silica contains low-Ca pyroxene (4 to 12 μm). All of the chondrules and fragments contains FeS (4 to 17 μm). Some of the FeS is accompanied by CrS (4 to 13 μm). Metal (4 to 43 μm) is observed in 6 of the chondrules and fragments. Some of the FeS and metal are accompanied by schreibersite (4 to 17 μm). 5 aggregates (35 to 183 μm) are observed outside of the chondrules and fragments. 4 of these are dominated by metal, 1 is dominated by FeS. The aggregates contain low-Ca pyroxene (4 to 15 μm) and glass (4 to 15 μm) inclusions.

Site 6 (Figure 2.93) contains 11 identified chondrules and fragments. The diameters of these objects range from 38 to 323 μm . All of the chondrules and fragments are dominated by low-Ca pyroxene (8 to 146 μm). All of the chondrules and fragments contain plagioclase (4 to 77 μm). Some of the plagioclase contains low-Ca pyroxene (4 to 38 μm) and FeS (4 to 23 μm) inclusions. All of the chondrules and fragments contain silica (4 to 38 μm). The silica is mostly observed accompanying the plagioclase and with 1 exception, always appears close to the chondrule and fragment edges. All of the chondrules and fragments contain FeS (4 to 39 μm). 6 of the chondrules and fragments contain metal (4 to 48 μm). 7 aggregates (38 to 254 μm) are observed outside of the chondrules and fragments. 5 of the aggregates are dominated by metal, and the remaining 2 are dominated by FeS. Schreibersite (4 to 39 μm) is observed in 5 of the aggregates and in 4 of the fragments often accompanying metal or FeS. The aggregates contain low-Ca pyroxene (4 to 8 μm), plagioclase (4 to 15 μm), and silica (4 to 8 μm) inclusions.

Site 7 (Figure 2.94) contains 8 identified chondrules and fragments. The diameters of these objects range from 69 to 577 μm . 7 of the chondrules and fragments are dominated by low-Ca pyroxene (8 to 146 μm). 1 of the fragments is dominated by both low-Ca pyroxene and metal (292 μm). Anhedral olivine (4 to 15 μm) is observed in 1 fragment. The olivines are surrounded by low-Ca pyroxene. The olivines in this site

are potentially relict grains. All of the chondrules and fragments contain plagioclase (4 to 77 μm). Some of the plagioclase contains low-Ca pyroxene (4 to 8 μm) and FeS (4 to 8 μm) inclusions. 7 of the chondrules and fragments contain silica (4 to 54 μm). The silica is mostly observed accompanying plagioclase close to the edges of the chondrules and fragments. All of the chondrules and fragments contain FeS (4 to 22 μm). Some of the FeS is accompanied by CrS (4 to 13 μm). A CaS grain (13 μm) is observed accompanying FeS in 1 fragment. 5 aggregates (23 to 138 μm) outside of the chondrules and fragments are observed. These aggregates are dominated by metal and contain schreibersite (4 to 17 μm). Schreibersite is also observed in 4 of the fragments. These schreibersite grains range from 4 to 13 μm). The FeS and metal in the chondrules, fragments, and aggregates contain low-Ca pyroxene (4 to 54 μm), glass (4 to 23 μm), and silica (4 to 15 μm) inclusions.

Site 8 (Figure 2.95) contains 8 identified chondrules and fragments. The diameters of these objects range from 31 to 500 μm . 7 of the chondrules and fragments are dominated by low-Ca pyroxene (8 to 92 μm). 1 of the fragments is dominated by both low-Ca pyroxene and metal (338 μm). All of the chondrules and fragments contain plagioclase (4 to 62 μm). Some of the plagioclase contains low-Ca pyroxene (4 to 15 μm) and FeS (4 to 8 μm) inclusions. 7 of the chondrules and fragments contain silica (4 to 46 μm). The silica is mostly observed accompanying glass. All of the chondrules and fragments contain FeS (4 to 48 μm). Some of the FeS is accompanied by CrS (2 to 26 μm). 6 aggregates (38 to 246 μm) outside of the chondrules and fragments are observed. 4 of these are dominated by metal, 1 is dominated by FeS and CrS. Schreibersite (4 to 38 μm) is present in 3 of the aggregates and in 5 of the chondrules and fragments accompanying FeS and metal. The FeS and metal in the chondrules, fragments, and aggregates contain low-Ca pyroxene (4 to 31 μm), glass (4 to 23 μm), and silica (4 to 15 μm) inclusions.

Site 9 (Figure 2.96) contains 4 identified chondrules and fragments. The diameters of these objects range from 231 to 654 μm . All of the chondrules and fragments are dominated by low-Ca pyroxene (8 to 123 μm). 1 of the fragments contains an anhedral olivine grain (8 μm) surrounded by low-Ca pyroxene. This grain is possibly relict. All of the chondrules and fragments contain plagioclase (4 to 92 μm). Some of the plagioclase contains low-Ca pyroxene (4 to 8 μm) and FeS (4 to 8 μm) inclusions. 2 of the chondrules and fragments contain silica (4 to 8 μm). The silica is observed accompanying plagioclase. All of the chondrules and fragments contain FeS (4 to 43

μm). Some of the FeS is accompanied by CrS (2 to 22 μm). 5 aggregates (31 to 515 μm) are observed outside of the chondrules and fragments. These are all dominated by metal. Schreibersite (4 to 13 μm) is present in 1 of the aggregates and in 2 of the chondrules and fragments accompanying FeS and metal. The FeS and metal in the chondrules, fragments, and aggregates contain low-Ca pyroxene (4 to 31 μm) and plagioclase (4 to 23 μm).

Site 10 (Figure 2.97) contains 13 identified chondrules and fragments. The diameters of these objects range from 46 to 438 μm . All of the chondrules and fragments are dominated by low-Ca pyroxene (8 to 154 μm). 1 fragment contains 2 anhedral olivines (5 to 10 μm). All of the chondrules and fragments contain plagioclase (4 to 77 μm). Some of the plagioclase contains low-Ca pyroxene (4 to 8 μm) and FeS (4 to 15 μm) inclusions. 9 of the chondrules and fragments contain silica (4 to 23 μm). The silica is observed accompanying plagioclase. All chondrules and fragments contain FeS (4 to 46 μm). 6 aggregates (38 to 154 μm) are observed outside of the chondrules and fragments. These are all dominated by metal. Schreibersite (4 to 9 μm) is present in 2 of the aggregates and in 6 of the chondrules and fragments accompanying FeS and metal. The FeS and metal in the chondrules, fragments, and aggregates contain low-Ca pyroxene (4 to 15 μm) and plagioclase (4 to 31 μm).

Site 11 (Figure 2.98) contains 6 identified chondrules and fragments. The diameters of these objects range from 31 to 654 μm . All of the chondrules and fragments are dominated by low-Ca pyroxene (8 to 92 μm). 1 chondrule contains anhedral and euhedral olivine (4 to 31 μm). The anhedral olivines are mostly surrounded by low-Ca pyroxene and the euhedral olivines are surrounded by plagioclase or low-Ca pyroxene. It is possible that some of these olivines are relict. All of the fragments contain plagioclase. Some of the plagioclase contains low-Ca pyroxene (4 to 23 μm) and FeS (4 to 15 μm) inclusions. Silica (4 to 38 μm) is observed in 3 of the chondrules and fragments. The silica is mostly observed accompanying the plagioclase. All of the chondrules and fragments contain FeS (4 to 23 μm). 3 of the chondrules and fragments contain CrS (4 to 22 μm) accompanying FeS. 2 aggregates (154 to 577 μm) dominated by metal are observed outside of the chondrules and fragments. Schreibersite (4 to 17 μm) is present in the 2 aggregates and in 4 of the chondrules and fragments accompanying FeS. The FeS and metal in the chondrules, fragments, and aggregates contain low-Ca pyroxene (4 to 31 μm) and plagioclase (4 to 31 μm).

Site 12 (Figure 2.99) contains 9 identified chondrules and fragments. The diameters of these objects range from 46 to 577 μm . All of the chondrules and fragments are dominated by low-Ca pyroxene (8 to 85 μm). 1 fragment contains subhedral olivines (4 to 54 μm) surrounded by low-Ca pyroxene and plagioclase. There is currently no evidence to indicate that the olivines in this site are relict. All of the chondrules and fragments contain plagioclase (4 to 77 μm). Some of the plagioclase contains low-Ca pyroxene (4 to 23 μm) and FeS (4 to 8 μm) inclusions. Silica (4 to 62 μm) is observed in 7 of the chondrules and fragments. The silica is mostly observed accompanying the plagioclase. All of the chondrules and fragments contain FeS (4 to 30 μm). 4 of the chondrules and fragments contain CrS (4 to 28 μm) accompanying FeS. 3 aggregates (46 to 100 μm) dominated by metal are observed outside of the chondrules and fragments. Schreibersite (4 to 30 μm) is present in the 1 aggregate and in 4 of the chondrules and fragments accompanying FeS. The FeS and metal in the chondrules, fragments, and aggregates contain low-Ca pyroxene (4 to 9 μm) and plagioclase (4 to 30 μm).

2.4.4 TIL 91714 (EL5)

Site 1 (Figure 2.100) lacks chondrules and chondrule like fragments. The site contains 10 identified low-Ca pyroxene bodies (31 to 569 μm). 9 of the enstatite bodies contain plagioclase (8 to 162 μm), with 2 plagioclase grains (23 to 223 μm) observed outside of the enstatite grains. Some of the plagioclase contain low-Ca pyroxene inclusions (8 to 15 μm). Silica (8 to 31 μm) is observed in 2 of the enstatite grains. 3 of the enstatite bodies contain FeS (4 to 30 μm). 4 of the enstatite grains contain metal (4 to 57 μm). 8 aggregates (31 to 638 μm) are observed outside of the enstatite bodies. 5 of these are dominated by metal, the rest are dominated by FeS. In 1 fragments and 1 aggregate CaS is observed (4 to 9 μm). 3 aggregates contain CrS (4 to 43 μm). An alabandite ([Mg,Fe]MnS) grain (65 μm) is observed in one of the largest aggregate, sandwiched between FeS and metal. Schreibersite (17 μm) is also observed in the largest aggregate. Some of the aggregates contain low-Ca pyroxene (4 to 8 μm), plagioclase (4 to 8 μm), and silica (4 to 8 μm) inclusions. Several metal filled cracks are observed (<4 to 8 μm).

Site 2 (Figure 2.101) lacks chondrules and chondrule like fragments. The site contains 15 identified enstatite bodies (23 to 446 μm). 8 of the enstatite grain contain plagioclase (4 to 69 μm). 6 of the enstatite grains contain silica (4 to 31 μm). The

silica mostly occurs close to the edges of the enstatite grains and/or accompanying the plagioclase grains. 5 of the enstatite bodies contain FeS (4 to 26 μm). 9 of the enstatite bodies contain metal (4 to 62 μm). Outside of the enstatite grains are 15 aggregates (15 to 308 μm). 11 of these are dominated by metal, the rest are dominated by FeS. 3 of the aggregates contain CaS (4 to 13 μm). CrS (4 to 26 μm) is also observed in 3 of the aggregates. The FeS and metal contain low-Ca pyroxene inclusions (8 μm). Several metal filled cracks are observed (<4 to 8 μm).

Site 3 (Figure 2.102) lacks chondrules and chondrule like fragments. The site contains 13 identified enstatite grain (42 to 438 μm). 11 of the enstatite grain contain plagioclase (4 to 154 μm). Some the plagioclase contain low-Ca pyroxene (4 to 15 μm) inclusions. 1 of the plagioclase inclusions contains a silica inclusion (15 μm). Silica (4 to 23 μm) is observed in 8 of the enstatite grains. 3 of the enstatite grains contain FeS (4 to 17 μm) and 6 contain metal (4 to 35 μm). 11 aggregates (17 to 148 μm) are observed outside of the enstatite grains. 6 of these are dominated by metal, the rest are dominated by FeS. 2 aggregates (1 metal and 1 FeS) contain CaS (4 to 22 μm). 3 FeS aggregates contain CrS (4 to 17 μm). 1 metal aggregate contains a low-Ca pyroxene inclusion (12 μm). a different metal aggregate contains silica inclusions (4 to 8 μm). Several metal filled cracks are observed (<4 to 8 μm).

Site 4 (Figure 2.103) lacks chondrules and chondrule like fragments. The site contains 15 identified enstatite grains (35 to 473 μm). 12 enstatite grains contain plagioclase (4 to 77 μm). 1 plagioclase grain is observed outside of the enstatite grains (177 μm). Some of the plagioclase grains contain low-Ca pyroxene inclusions (4 to 31 μm). Silica (4 to 31 μm) is observed in 8 enstatite grains. The silica is mostly observed close to the edge of the enstatite grains and/or accompanying the plagioclase. This is not the case in 2 enstatite grains. 4 of the enstatite grains contain FeS (4 to 23 μm) and 12 of the enstatite grains contain metal (4 to 31 μm). 12 aggregates (54 to 169 μm) are observed between the low-Ca pyroxenes. 8 of these are dominated by metal and the rest are dominated by FeS. 2 of the aggregates contain low-Ca pyroxene inclusions (4 to 15 μm). 1 of the FeS aggregates contains CaS (22 μm). 3 of the FeS aggregates contain CrS (4 to 35 μm). Most of the enstatite bodies contain metal filled cracks (<4 to 23 μm).

Site 5 (Figure 2.104) lacks chondrules and chondrule like fragments. The site contains 17 identified enstatite grains (54 to 523 μm). 14 of the enstatite grains contain plagioclase (4 to 231 μm). Some of the plagioclase contains low-Ca pyroxene (4 to 23

μm), silica ($8\ \mu\text{m}$), and metal (4 to $31\ \mu\text{m}$) inclusions. 1 plagioclase grain ($92\ \mu\text{m}$) is observed outside of the enstatite grains. 10 of the enstatite grains contain silica (4 to $38\ \mu\text{m}$). The silica is mostly observed close to the edge of the enstatite bodies and/or accompanying the plagioclase. This is not always the case. 5 of the enstatite grains contain FeS (4 to $23\ \mu\text{m}$). Metal (4 to $54\ \mu\text{m}$) is observed in 7 of the enstatite grains. The plagioclase outside of the enstatite grains also contains FeS ($31\ \mu\text{m}$) and metal (4 to $38\ \mu\text{m}$). 7 aggregates (31 to $215\ \mu\text{m}$) between the enstatite grains are observed. 4 are dominated by metal and the rest are dominated by FeS. One of the enstatite grains contains a CaS ($13\ \mu\text{m}$) grain in an aggregate with metal. CrS (4 to $22\ \mu\text{m}$) is observed in aggregates with FeS.

Site 6 (Figure 2.105) lacks chondrules and chondrule like fragments. The site contains 10 identified enstatite bodies (54 to $431\ \mu\text{m}$). 8 of the low-Ca pyroxene grains contain plagioclase (4 to $92\ \mu\text{m}$). 1 plagioclase grain ($385\ \mu\text{m}$) is observed outside of the low-pyroxene grain. The plagioclase contains low-Ca pyroxene (4 to $31\ \mu\text{m}$) inclusions. 5 of the low-Ca pyroxene bodies contain silica (4 to $38\ \mu\text{m}$). 9 of the low-Ca pyroxene bodies contain metal (4 to $38\ \mu\text{m}$). FeS is absent from this site. 4 metal aggregates (69 to $300\ \mu\text{m}$) are observed outside of the low-Ca pyroxene grains.

Site 7 (Figure 2.106) lacks chondrules and chondrule like fragments. The site contains 15 identified low-Ca pyroxene grains (23 to $365\ \mu\text{m}$). 10 of the enstatite grains contain plagioclase grains (4 to $77\ \mu\text{m}$). 1 of the plagioclase grains contains a low-Ca pyroxene ($8\ \mu\text{m}$) inclusion. 8 enstatite low-Ca pyroxene contain silica (4 to $38\ \mu\text{m}$). 7 enstatite bodies contain FeS (4 to $35\ \mu\text{m}$). 5 of the enstatite bodies contain metal (4 to $26\ \mu\text{m}$). 12 aggregates (31 to $285\ \mu\text{m}$) between the enstatite bodies are observed. 5 of the aggregates are dominated by metal, 4 of the aggregates are dominated by FeS, 2 of the aggregates are dominated by both metal and FeS, and the last aggregates is dominated by metal and schreibersite. 2 other aggregates contain schreibersite, with a single schreibersite grain observed in 1 of the low-Ca pyroxene bodies. Schreibersite ranges from 9 to $30\ \mu\text{m}$. CrS (4 to $13\ \mu\text{m}$) is observed in aggregates with FeS. 2 of the CrS are also in aggregates with metal.

Site 8 (Figure 2.107) lacks chondrules and chondrule like fragments. The site contains 12 identified enstatite grains (200 to $400\ \mu\text{m}$). 11 of the enstatite grains contain plagioclase grains. Silica (4 to $46\ \mu\text{m}$) is observed in 10 of the low-Ca pyroxene grains. Most of the silica occurs at the edges of the enstatite grains and/or accompanying the

plagioclase. This is not always the case. 8 of the enstatite grains contain FeS (4 to 138 μm). All of the enstatite grains contain metal (4 to 62 μm). 4 aggregates (54 to 165 μm) between the low-Ca pyroxene grains are observed. All of these aggregates are dominated by metal. One of the aggregates contain schreibersite (13 to 22 μm). 2 of the low-Ca pyroxene grains contain CaS (4 to 17 μm). 3 of the low-Ca pyroxene grains contain CrS (4 to 13 μm) in aggregates with FeS. 1 of the aggregates contains low-Ca pyroxene (4 to 23 μm) and silica (4 to 8 μm) inclusions.

Site 9 (Figure 2.108) lacks chondrules and chondrule like fragments. The site contains 14 identified enstatite grains (23 to 423 μm). 8 of the enstatite grains contain plagioclase (8 to 69 μm). 1 of the plagioclase contains low-Ca pyroxene (8 μm) inclusions. Silica (4 to 19 μm) is observed in 9 of the low-Ca pyroxene grains. Most of the silica occurs at the edges of the enstatite grains and/or accompanying the plagioclase. This is not always the case. 6 of the low-Ca pyroxene grains contain FeS (4 to 42 μm). Metal (4 to 17 μm) is observed in 9 of the low-Ca pyroxene bodies. 13 aggregates (15 to 423 μm) are observed between the low-Ca pyroxene grains. 3 aggregates are dominated by FeS, 8 are dominated by metal, the rest are dominated by both FeS and metal. CaS (4 to 13 μm) is observed in 2 aggregates and 2 low-Ca pyroxene grains. CrS (4 to 22 μm) is observed in aggregates with FeS.

Site 10 (Figure 2.109) lacks chondrules and chondrule like fragments. The site contains 12 identified enstatite bodies (23 to 354 μm). 8 of the enstatite bodies contain Na-rich-glass-like bodies (8 to 115 μm). 2 glass-like bodies are observed outside of the low-Ca pyroxene bodies. These bodies are 54 and 100 μm in size. Some of the glass-like bodies contain low-Ca pyroxene (4 to 23 μm) inclusions. 8 of the low-Ca pyroxene bodies contain silica (4 to 23 μm). 6 of the low-Ca pyroxene bodies contain FeS (4 to 46 μm) and 10 contain metal (4 to 77 μm). 8 aggregates (38 to 192 μm) are observed between the low-Ca pyroxene bodies. 4 of the aggregates are dominated by metal, and 4 are dominated by FeS. CaS (4 to 30 μm) is observed in aggregates with metal, FeS, and as independent grains. CrS (4 to 13 μm) is observed in aggregates with FeS. The aggregates contain low-Ca pyroxene (8 to 31 μm), glass-like (4 to 8 μm), and silica (8 μm) inclusions. Several cracks (<4 to 38 μm) filled in by metal are observed.

Site 11 (Figure 2.110) lacks chondrules and chondrule like fragments. The site contains 14 identified enstatite grains (62 to 462 μm). 13 of the low-Ca pyroxene grains contain plagioclase (8 to 92 μm). Some of the plagioclase contain low-Ca pyroxene (4

to 15 μm) inclusions. 13 of the low-Ca pyroxene grains contain silica (4 to 38 μm). The silica is mostly observed close to the edges of the low-Ca pyroxene grains. Some of the silica accompanies the plagioclase. 6 of the low-Ca pyroxene grains contain FeS (4 to 46 μm) and 11 of the low-Ca pyroxene grains contain metal (4 to 38 μm). 5 aggregates (31 to 115 μm) are observed between the low-Ca pyroxene grains. 3 of the aggregates are dominated by metal and 2 are dominated by FeS. 1 low-Ca pyroxene grain and 1 aggregate contain CaS (17 to 26 μm) accompanying FeS. 2 low-Ca pyroxene grain and 3 aggregate contain CrS (4 to 30 μm) accompanying FeS. 1 of the FeS aggregates contains a low-Ca pyroxene (8 μm) inclusion and a silica (8 μm) inclusion.

Site 12 (Figure 2.111) lacks chondrules and chondrule like fragments. The site contains 16 identified low-Ca pyroxene grains (46 to 377 μm). 10 of the low-Ca pyroxene grains contain plagioclase (8 to 69 μm). 2 plagioclase grains (31 to 46 μm) are observed outside of the low-Ca pyroxene grains. 7 of the low-Ca pyroxene grains contain silica (4 to 15 μm). The silica is mostly observed close to the edges of the low-Ca pyroxene grains and sometimes accompanies the plagioclase. 7 of the low-Ca pyroxene grains contain FeS (4 to 31 μm) and 11 of the low-Ca pyroxene grains contain metal (4 to 31 μm). 11 aggregates (69 to 162 μm) are observed between the low-Ca pyroxene grains. 8 of the aggregates are dominated by metal, the rest are dominated by FeS. 1 low-Ca pyroxene grains contain a CaS (9 μm) grain accompanied by metal. CrS (4 to 39 μm) is observed in the FeS aggregates and in 2 low-Ca pyroxene grains accompanied by FeS. Several cracks (<4 to 27 μm) are observed filled in by metal.

Site 13 (Figure 2.112) lacks chondrules and chondrule like fragments. The site contains 13 identified enstatite grains (54 to 554 μm). 7 of the low-Ca pyroxene grains contain plagioclase (8 to 138 μm). Some of the plagioclase contain low-Ca pyroxene inclusions (8 to 15 μm). 6 of the low-Ca pyroxene grains contain silica (4 to 31 μm). The occurrence of the silica appears to be random. 4 of the enstatite grains contain FeS (4 to 15 μm). 11 of the low-Ca pyroxene grains contain metal (4 to 15 μm). 10 aggregates (38 to 154 μm) are observed between the low-Ca pyroxene. 8 of these are dominated by metal, 2 are dominated by FeS. This site lacks CaS and CrS. 1 of the aggregates contains a low-Ca pyroxene inclusion (8 μm) and a second aggregate has silica inclusions (4 to 8 μm).

Site 14 (Figure 2.113) lacks chondrules and chondrule like fragments. The site contains 15 identified enstatite grains (31 to 500 μm). 4 of the low-Ca pyroxene grains

contain plagioclase (8 to 38 μm). 6 of the low-Ca pyroxene grains contain silica (8 to 85 μm). The silica is often observed close to metal. All low-Ca pyroxene grains contain metal (4 to 38 μm) and 4 contain FeS (4 to 8 μm). 11 aggregates (38 to 162 μm) are observed between the low-Ca pyroxene grains. 7 are dominated by metal, 2 are dominated by metal and FeS, 1 is dominated by schreibersite, and the last is dominated by both metal and schreibersite. CrS (13 to 22 μm) is observed in 2 aggregates accompanying FeS. Additional schreibersite (4 to 17 μm) is observed in two of the metal aggregates and accompanying metal in 1 low-Ca pyroxene grain.

2.4.5 ALHA 81021 (EL6)

Site 1 (Figure 2.114) lacks chondrules and chondrule like fragments. The site contains 17 identified low-Ca pyroxene grains (31 to 462 μm). 6 of the low-Ca pyroxene grains contain plagioclase (4 to 77 μm). Some of the plagioclase contain low-Ca pyroxene (4 to 31 μm) inclusions. Silica (4 to 54 μm) is observed in 6 of low-Ca pyroxene grains. The silica is often observed accompanying the plagioclase close to the edges of the low-Ca pyroxene grains. 6 of the low-Ca pyroxene grains contain FeS (4 to 17 μm) and 7 contain metal (4 to 65 μm). 6 aggregates (31 to 331 μm) are observed between the low-Ca pyroxene grains. 4 of these are dominated by metal, 1 is dominated by FeS, and the last is dominated by both FeS and metal. In the largest aggregate alabandite is observed accompanying the metal and FeS (9 to 38 μm). 3 of the aggregates contain low-Ca pyroxene inclusions (31 to 115 μm). The largest inclusion is an aggregate of low-Ca pyroxene, plagioclase, and silica.

Site 2 (Figure 2.115) lacks chondrules and chondrule like fragments. The site contains 15 identified low-Ca pyroxene grains (31 to 462 μm). One of these grains is surrounded by a metal aggregate. 9 of the low-Ca pyroxene grains contain plagioclase (4 to 77 μm). 6 of the low-Ca pyroxene bodies contain silica (4 to 15 μm). The silica occurrence appears random. 5 of the low-Ca pyroxene grains contain FeS (2 to 4 μm). 13 of the low-Ca pyroxene grains contain metal (2 to 38 μm). 9 aggregates (31 to 169 μm) are observed between the low-Ca pyroxene grains. 8 of these are dominated by metal and 1 by FeS. Cr-bearing alabandite (4 to 48 μm) is observed in two aggregates with FeS.

Site 3 (Figure 2.116) lacks chondrules and chondrule like fragments. The site con-

tains 20 identified low-Ca pyroxene grains (15 to 400 μm). 8 of the low-Ca pyroxene grains are surrounded by plagioclase. 9 of the low-Ca pyroxene grains contain plagioclase (8 to 77 μm), this included 2 of the low-Ca pyroxenes surrounded by plagioclase. 3 plagioclase grains are observed outside of the low-Ca pyroxene grains. The low-Ca pyroxene inclusions in the plagioclase (both inside and outside the low-Ca pyroxene grains) ranges from 8 to 62 μm . 4 of the low-Ca pyroxene grains contain silica (8 to 38 μm). Some of the silica is observed accompanying the plagioclase, often close to the edge of the low-Ca pyroxene grains. 3 of the low-Ca pyroxene grains contain FeS (4 to 35 μm). 6 of the low-Ca pyroxene grains contain metal (4 to 43 μm). 8 aggregates (27 to 142 μm) are observed between the low-Ca pyroxenes and plagioclase. 3 aggregates are dominated by metal and 5 are dominated by FeS. Alabandite (35 μm) is observed in an aggregate with FeS and CrS (4 to 26 μm) is observed in 6 other aggregates with FeS.

Site 4 (Figure 2.117) lacks chondrules and chondrule like fragments. The site contains 17 identified low-Ca pyroxene grains (15 to 492 μm). The smallest of these grains is completely surrounded by metal and 3 other small low-Ca pyroxene grains are surrounded by plagioclase. 8 of the low-Ca pyroxene bodies contain plagioclase (4 to 88 μm). 5 plagioclase (54 to 165 μm) are observed between the low-Ca pyroxene grains. The low-Ca pyroxene inclusions in the plagioclase (both inside and outside the low-Ca pyroxene grains) ranges from 8 to 46 μm . 4 of the low-Ca pyroxene grains contain silica (8 to 31 μm). The silica is mostly observed at the edges of the low-Ca pyroxene grains, sometimes accompanying the plagioclase. 5 of the low-Ca pyroxene grains contain FeS (4 to 22 μm). 6 of the low-Ca pyroxene grains contain metal (4 to 43 μm). 10 aggregates (23 to 300 μm) are observed between the low-Ca pyroxene grains. 5 of the aggregates are dominated by metal, 4 are dominated by FeS, and 1 is dominated by FeS and metal. CrS (4 to 13 μm) is observed in 4 aggregates with FeS.

Site 5 (Figure 2.118) lacks chondrules and chondrule like fragments. The site contains 26 identified low-Ca pyroxene grains (15 to 392 μm). 9 of the low-Ca Pyroxene grains are surrounded by plagioclase. 11 of the low-Ca pyroxene grains contain plagioclase inclusions (8 to 54 μm). 3 plagioclase grains (88 to 408 μm) are observed between the low-Ca pyroxene grains. All 3 of the plagioclase grains contain low-Ca pyroxene inclusions (8 to 46 μm). Silica (4 to 8 μm) is observed in 3 of the low-Ca pyroxenes. 1 of the plagioclase grains contains silica (4 to 8 μm). 4 of the low-Ca pyroxene grains contain FeS (2 to 39 μm). 4 of the low-Ca pyroxene grains contain metal (2 to 13 μm).

2 of the plagioclase also contain FeS (2 to 15 μm) and metal (2 to 46 μm). 7 aggregates (38 to 235 μm) are observed between the low-Ca pyroxene and plagioclase. 4 are dominated by metal and 3 are dominated by FeS. CrS (4 to 17 μm) is observed in 6 aggregates with FeS (inside and outside of the low-Ca pyroxene grains).

Site 6 (Figure 2.119) lacks chondrules and chondrule like fragments. The site contains 13 identified low-Ca pyroxene grains (62 to 477 μm). 9 of the low-Ca pyroxene grains contain plagioclase (4 to 62 μm). 2 plagioclase grains (77 to 100 μm) are observed between low-Ca pyroxene grains. The plagioclase (in and outside of the low-Ca pyroxene grains) contain low-Ca pyroxene inclusions (8 to 15 μm). 7 of the low-Ca pyroxene grains contain silica (4 to 23 μm). The silica generally occurs close to the edges of the low-Ca pyroxene grains. 4 of the low-Ca pyroxene grains contain FeS (4 to 35 μm), and 7 contain metal (4 to 39 μm). 8 aggregates (31 to 269 μm) are observed between the low-Ca pyroxene grains. 3 are dominated by FeS, 4 are dominated by metal, and 1 is dominated by both FeS and metal. CrS (4 to 43 μm) is observed in aggregates with FeS.

Site 7 (Figure 2.120) lacks chondrules and chondrule like fragments. The site contains 16 identified low-Ca pyroxene grains (15 to 354 μm). 8 of the low-Ca pyroxene grains contain plagioclase inclusions (8 to 69 μm). 7 plagioclase grains (15 to 292 μm) are observed between low-Ca pyroxene grains. Some of the plagioclase grains and inclusions contain low-Ca pyroxene inclusions (8 to 38 μm). Silica is observed in 5 of the low-Ca pyroxene grains (8 to 38 μm) and 2 of the plagioclase grains (8 μm). 3 of the low-Ca pyroxene grains contain FeS (2 to 13 μm) and 6 contain metal (2 to 30 μm). 6 aggregates (38 to 177 μm) between the low-Ca pyroxene grains are observed. 2 are dominated by FeS and 4 are dominated by metal. CrS (4 to 39 μm) is observed in aggregates with FeS.

Site 8 (Figure 2.121) lacks chondrules and chondrule like fragments. The site contains 10 identified low-Ca pyroxene grains (31 to 577 μm). 5 of the low-Ca pyroxene grains contain plagioclase inclusions (8 to 200 μm). Some of the plagioclase contains low-Ca pyroxene inclusions (8 to 23 μm) and 1 contains a silica inclusion (15 μm). 4 of the low-Ca pyroxene grains contain silica (8 to 38 μm). 5 of the low-Ca pyroxene bodies contain FeS (4 to 20 μm) and 5 contain metal (4 to 65 μm). 9 aggregates (15 to 469 μm) are observed between the low-Ca pyroxene grains. 2 aggregates are dominated by FeS, the rest are dominated by metal. The largest aggregate contains a low-Ca pyroxene

inclusion (15 μm). Schreibersite (9 to 22 μm) is observed in the largest aggregate with the metal.

Site 9 (Figure 2.122) lacks chondrules and chondrule like fragments. The site contains 13 identified low-Ca pyroxene grains (50 to 550 μm). 1 of these grains (54 μm) is completely surrounded by a metal aggregate. 6 of the low-Ca pyroxene grains contain plagioclase (8 to 54 μm). 2 plagioclase grains (138 μm) are observed between low-Ca pyroxene grains. Both of these contain low-Ca pyroxene inclusions (4 to 23 μm). 6 of the low-Ca pyroxene grains contain silica (4 to 35 μm). 5 of the low-Ca pyroxene grains contain FeS (4 to 62 μm). 8 of the low-Ca pyroxene grains contain metal (4 to 50 μm). 11 aggregates are observed between the low-Ca pyroxene grains. 2 of the aggregates are dominated by FeS, the rest are dominated by metal. Schreibersite (4 to 22 μm) is observed in aggregates with the metal.

Site 10 (Figure 2.123) lacks chondrules and chondrule like fragments. The site contains 27 identified low-Ca pyroxene grains (6 to 276 μm). 11 low-Ca pyroxene grains contain plagioclase (5 to 41 μm). 9 plagioclase grains (18 to 341 μm) are observed between the low-Ca pyroxene grains. These grains contain low-Ca pyroxene inclusions (6 to 59 μm). 1 of the plagioclase grains contain silica inclusions (12 μm). Silica (6 to 18 μm) is observed in 10 of the low-Ca pyroxene grains. 4 of the low-Ca pyroxene grains contain FeS (5 to 14 μm) and 6 contain metal (5 to 24 μm). 15 aggregates are observed between the low-Ca pyroxene (18 to 265 μm). 10 are dominated by metal and 5 by FeS. Schreibersite (5 to 19 μm) is observed in aggregates with the metal. CrS (5 to 14 μm) is observed in aggregates with FeS.

Site 11 (Figure 2.124) lacks chondrules and chondrule like fragments. The site contains 14 identified low-Ca pyroxene grains (41 to 335 μm). 7 low-Ca pyroxene grains contain plagioclase (3 to 24 μm). Silica (3 to 24 μm) is observed in 4 of the low-Ca pyroxene grains. 5 of the low-Ca pyroxene grains contain FeS (5 to 14 μm) and 6 contain metal (5 to 29 μm). 11 aggregates are observed between the low-Ca pyroxene (18 to 206 μm). 9 are dominated by metal and 3 by FeS. Schreibersite (5 to 14 μm) is observed in aggregates with the metal.

Site 12 (Figure 2.125) lacks chondrules and chondrule like fragments. The site contains 17 identified low-Ca pyroxene grains (24 to 312 μm). 9 low-Ca pyroxene grains contain plagioclase (3 to 94 μm). 4 plagioclase grains (29 to 159 μm) are observed between the low-Ca pyroxene grains. These grains contain low-Ca pyroxene

inclusions (3 to 24 μm). Silica (3 to 12 μm) is observed in 5 of the low-Ca pyroxene grains. The silica is often observed accompanying the plagioclase but this is not always the case. 6 of the low-Ca pyroxene grains contain FeS (2 to 29 μm) and 5 contain metal (2 to 29 μm). 13 aggregates (6 to 135 μm) are observed between the low-Ca pyroxene grains. 4 are dominated by FeS, 8 are dominated by metal, and 1 is dominated by both FeS and metal. Schreibersite (14 μm) is observed in an aggregate with the metal. CrS (2 to 14 μm) is observed in aggregates with FeS.

Site 13 (Figure 2.126) lacks chondrules and chondrule like fragments. The site contains 17 identified low-Ca pyroxene grains (24 to 312 μm). 11 low-Ca pyroxene bodies contain plagioclase (3 to 112 μm). 8 plagioclase grains (94 to 118 μm) are observed between the low-Ca pyroxene grains. The plagioclase (both inside and outside of the low-Ca pyroxene grains) contain low-Ca pyroxene inclusions (6 to 24 μm). Silica (6 to 18 μm) is observed in 5 low-Ca pyroxene bodies. 4 low-Ca pyroxene grains contain FeS (2 to 18 μm) and 5 contain metal (2 to 21 μm). 12 aggregates (25 to 229 μm) are observed between the low-Ca pyroxene grains. 4 of the aggregates are dominated by FeS and 8 are dominated by metal. CaS (10 μm) are observed in 1 aggregate with FeS and CrS (5 to 52 μm) is observed in 9 aggregates with FeS.

Site 14 (Figure 2.127) lacks chondrules and chondrule like fragments. The site contains 14 identified low-Ca pyroxene grains (26 to 544 μm). 6 low-Ca pyroxene grains contain plagioclase (3 to 38 μm). 3 plagioclase grains (18 to 94 μm) are observed between the low-Ca pyroxene grains. The plagioclase (both inside and outside of the low-Ca pyroxene grains) contain low-Ca pyroxene inclusions (6 μm). 3 of the low-Ca pyroxene grains contain silica (6 to 29 μm) accompanying the plagioclase. 4 low-Ca pyroxene grains contain FeS (2 to 24 μm) and 6 contain metal (2 to 48 μm). 12 aggregates (12 to 129 μm) are observed between the low-Ca pyroxene grains. 3 are dominated by FeS, 7 are dominated by metal, and 2 are dominated by FeS and metal. 1 of the aggregates houses a low-Ca pyroxene inclusion (29 μm). CrS (5 to 14 μm) is in 7 aggregates with FeS.

Site 15 (Figure 2.128) lacks chondrules and chondrule like fragments. The site contains 12 identified low-Ca pyroxene grains (29 to 376 μm). 5 low-Ca pyroxene grains contain plagioclase (3 to 47 μm). 1 plagioclase grain (24 μm) is observed between the low-Ca pyroxene grain. 1 of the plagioclase in the low-Ca pyroxene grain contains a low-Ca Pyroxene inclusion (6 μm). 3 of the low-Ca pyroxene grains contain silica (3

to 12 μm). Some of the silica accompanies plagioclase close to the edge of the low-Ca pyroxene grains. 7 of the low-Ca pyroxene grains contain FeS (2 to 52 μm) and 7 contain metal (2 to 100 μm). 10 aggregates (24 to 147 μm) are observed between the low-Ca pyroxene grains. 5 are dominated by metal, the rest are dominated by FeS. CrS (2 to 24 μm) is observed in aggregates with FeS. Schreibersite (2 to 33 μm) is observed in aggregates with the metal and as an independent grain.

2.5 Enstatite-rich achondrites

2.5.1 Zakłodzie (Enstatite-rich-achondrite ungrouped)

Site 1 (Figure 2.129) lacks chondrules and chondrule like fragments and is located at the edge of the edge of the thin section. The site contains 8 identified low-Ca pyroxene grains (29 to 376 μm). Some of the low-Ca pyroxene grains contain metal (3 to 12 μm). 5 plagioclase grains (24 to 176 μm) are observed between the low-Ca pyroxene grains. 3 metal grains are observed between the low-Ca pyroxenes. 1 of these contains a silica inclusion (12 μm). Contained in the metal is an Al-rich inclusion (88 μm).

Site 2 (Figure 2.130) lacks chondrules and chondrule like fragments and is located at the edge of the edge of the thin section. The upper 2 thirds of the site is dominated by a single low-Ca pyroxene grain (85 μm), 2 plagioclase grains (23 to 48 μm), and a metal grain (69 μm). 2 plagioclase inclusions (1 to 3 μm) are observed in the metal body.

Site 3 (Figure 2.131) lacks chondrules and chondrule like fragments. The site is dominated by 4 low-Ca pyroxene grains (3 to 22 μm). The lower third and left hand side are dominated by metal (8 to 13 μm).

Site 4 (Figure 2.132) lacks chondrules and chondrule like fragments. This site is also observed close to the edge of the thin section. The site contains 4 low-Ca pyroxene grains (12 to 42 μm). The rest of the site is dominated by metal (56 μm). Contained in the metal is an Al-rich inclusion (37 μm). Silica inclusions (3 to 8 μm) are observed at the edge of the metal.

Site 5 (Figure 2.133) lacks chondrules and chondrule like fragments. This site is also observed close to the edge of the thin section. The site contains 18 low-Ca pyroxene grains (19 to 176 μm). 6 plagioclase grains (21 to 177 μm) are observed between the low-Ca pyroxene. These are often accompanied by silica (14 to 21 μm). Between the

low-Ca pyroxenes, plagioclase, and silica bodies are aggregates of FeS and metal (14 to 102 μm). In these aggregates, the FeS is concentrated on the edge and the metal is concentrated in the center.

Site 6 (Figure 2.134) lacks chondrules and chondrule like fragments. This site contains 4 low-Ca pyroxene grains (13 to 45 μm) around the top and bottom of the site. One of the low-Ca pyroxene grains contains FeS (3 μm) and metal (2 to 4 μm) inclusions, but 2 of the others only contain metal inclusions. In the center of the site is a metal grain (3 to 57 μm), with an FeS border (3 to 8 μm). Surrounding these are silica grains (4 to 21 μm). The silica contains 1 FeS inclusion (2 μm) and 1 metal inclusion (3 μm).

Site 7 (Figure 2.135) lacks chondrules and chondrule like fragments. The site is dominated by 4 low-Ca pyroxene grains (16 to 88 μm). Contained in the low-Ca pyroxene grains are metal (1 to 2 μm) and Al-rich (1 to 2 μm) inclusions. Between the low-Ca pyroxenes is an aggregate of silica (2 to 82 μm) and plagioclase (2 to 18 μm). This aggregate is dominated by the silica. A small number of plagioclase (1 to 4 μm) and metal (1 to 4 μm) are observed in the silica. A metal grain (8 μm) is observed in the top left of the site, surrounded by FeS (5 μm) and accompanied by an Al-rich inclusion (3 μm). Throughout the site are cracks (1 to 6 μm) in filled by FeS.

Site 8 (Figure 2.136) lacks chondrules and chondrule like fragments. The site contains 9 low-Ca pyroxene grains (4 to 46 μm). 1 of these grains contains metal (3 μm) and Al-rich (1 to 3 μm) inclusions. Between the low-Ca pyroxenes is a aggregate comprised of silica (3 to 28 μm) and plagioclase (8 to 12 μm). FeS (3 to 4 μm) and metal (1 to 6 μm) inclusions are observed in the silica-plagioclase aggregate. In addition to the silica and plagioclase, aggregates (10 to 65 μm) of FeS and metal are also observed between the low-Ca pyroxene. In these aggregates contain an Al-rich inclusion (5 μm) and a silica inclusion (9 μm). The silica-plagioclase aggregate contains cracks (1 to 2 μm) filled in by FeS. MgS (10 μm) is observed accompanying 1 of the metal aggregates.

Site 9 (Figure 2.137) lacks chondrules and chondrule like fragments. The site contains 23 low-Ca pyroxene grains (21 to 300 μm). 12 of the low-Ca pyroxene grains contain metal (3 to 12 μm). 3 of the low-Ca pyroxene grains contain silica inclusions (6 to 12 μm). Between the low-Ca pyroxenes are plagioclase (15 to 141 μm). Within the plagioclase are metal aggregates (3 to 82 μm). 1 silica grain (88 μm) is also observed between 5 of the low-Ca pyroxenes. 3 other metal aggregates (47 to 159 μm) are observed. 2 of these aggregates contain silica inclusions (6 to 112 μm).

Site 10 (Figure 2.138) lacks chondrules and chondrule like fragments. The site contains 5 low-Ca pyroxene grains (34 to 109 μm). 3 of the low-Ca pyroxene grains contain metal inclusions (2 to 5 μm). Between the low-Ca pyroxene grains are silica (16 to 64 μm), plagioclase (19 μm), and metal (78 μm). The silica contains a metal inclusion (11 μm) and low-Ca pyroxene inclusions (2 μm). Several metal filled cracks (2 to 7 μm) are observed through the site.

Site 11 (Figure 2.139) lacks chondrules and chondrule like fragments. This site is close to the edge of the thin section. The site contains 13 low-Ca pyroxene grains (45 to 263 μm). 5 of the low-Ca pyroxene grains contain FeS inclusions (5 to 16 μm) and 5 contain metal inclusions (5 to 16 μm). Between the low-Ca pyroxene grains are plagioclase (21 to 205 μm) and metal (26 to 137 μm). 1 of the plagioclase grains contains a low-Ca pyroxene inclusion (5 μm). 3 of the metal grains contain silica inclusions (3 to 5 μm). Several cracks (3 to 26 μm) filled in by FeS are observed.

Site 12 (Figure 2.140) lacks chondrules and chondrule like fragments. The site contains 12 low-Ca pyroxene grains (10 to 314 μm). 10 of the contain metal inclusions (5 to 10 μm). 2 of the low-Ca pyroxene grains contain Al-rich inclusions (5 μm). Between the low-Ca pyroxene grains are plagioclase (10 to 190 μm) and metal (5 to 24 μm). Some of the plagioclase contain metal inclusions (5 to 14 μm). 1 silica (10 μm) is observed sandwiched between plagioclase and a low-Ca pyroxene. Some of the metal grains contain silica inclusions (2 to 10 μm). Some metal filled cracks (5 μm) are observed.

Site 13 (Figure 2.141) lacks chondrules and chondrule like fragments. The site contains 17 low-Ca pyroxene grains (11 to 224 μm). 2 of the low-Ca pyroxene grains contain FeS (4 μm). 10 of the low-Ca pyroxene grains contain metal (4 to 17 μm). Between the low-Ca pyroxene are silica (11 to 126 μm), plagioclase (9 to 78 μm), and metal (4 to 87 μm). 1 of the metal bodies contains a low-Ca pyroxene inclusion (7 μm). MgS is observed in an aggregate (17 μm) with metal. Some of the metal is surrounded by a FeS border (2 to 7 μm). Metal inclusions (4 to 26 μm) are observed in the silica and plagioclase. Some of the metals contain Al-rich inclusions (4 to 9 μm). Some metal and FeS filled cracks (2 to 11 μm) are observed.

Site 14 (Figure 2.142) lacks chondrules and chondrule like fragments. The site contains 9 low-Ca pyroxene grains (4 to 69 μm). Some of the low-Ca pyroxene grains contain FeS (1 to 4 μm) and metal (1 to 5 μm) inclusions. Between the low-Ca pyroxenes are silica (4 to 13 μm), plagioclase (4 to 21 μm), and metal (9 to 107 μm). Sandwiched

between a silica and a plagioclase grain is a metal inclusion (5 μm). MgS (20 μm) is observed in an aggregate with a metal body. Silica (1 to 9 μm) and Al-rich (2 to 4 μm) inclusions are observed in the metal. Some metal and FeS filled cracks (1 to 8 μm) are observed. Schreibersite (18 to 19 μm) is observed in aggregates with the metal and as an independent grain. 1 of the metal aggregates contains a metal grain (18 μm) that is enriched in Fe relative to the other metal bodies at this site.

Site 15 (Figure 2.143) lacks chondrules and chondrule like fragments. The site contains 10 low-Ca pyroxene grains (5 to 108 μm). 7 of the low-Ca pyroxene grains contain metal inclusions (3 to 8 μm) and 1 contains a silica inclusion (5 μm). Al-rich inclusions (3 μm) are observed in 2 of the low-Ca pyroxene grains. Between the low-Ca pyroxene grains are silica (8 to 138 μm), plagioclase (13 to 80 μm), and metal (15 to 120 μm). Metal inclusions are observed in both the silica (3 to 25 μm) and the plagioclase. 1 of the silica bodies contains a low-Ca pyroxene inclusion (3 μm). Silica inclusions (3 to 15 μm) are observed in the plagioclase. The metal bodies contain a plagioclase inclusion (5 μm) and Al-rich inclusions (3 to 5 μm). Some cracks (1 to 5 μm) filled in by FeS and metal are observed.

2.5.2 NWA4301 (Enstatite-rich-achondrite ungrouped)

Site 1 (Figure 2.144) lacks chondrules and chondrule like fragments. The site contains 20 low-Ca pyroxene grains (18 to 215 μm). 7 of the low-Ca pyroxene grains contain metal inclusions (3 to 18 μm). The site is dominated by plagioclase (6 to 541 μm). 6 metal aggregates (29 to 88 μm) are observed, connected by cracks (3 to 59 μm) filled in by metal. The aggregates contain clusters of very small silica inclusions (3 μm) and some plagioclase inclusions (3 to 12 μm). The cracks contain some low-Ca pyroxene (3 to 12 μm) and plagioclase (3 to 9 μm) inclusions.

Site 2 (Figure 2.145) lacks chondrules and chondrule like fragments. The site contains 13 low-Ca pyroxene grains (24 to 255 μm). 9 of the low-Ca pyroxene grains contain metal inclusions (3 to 16 μm). Between the low-Ca pyroxene grains are plagioclase grains (11 to 68 μm) and a metal aggregate (400 μm). The aggregate contains a low-Ca pyroxene inclusion (11 μm) and plagioclase inclusions (5 to 47 μm). In the aggregate are clusters of very small silica inclusions (3 to 5 μm). Connected to the aggregate are several cracks (5 to 55 μm) filled in by metal. In the cracks are low-Ca pyroxene (5 μm)

and plagioclase (5 to 11 μm) inclusions.

Site 3 (Figure 2.146) lacks chondrules and chondrule like fragments. This site is dominated by metal aggregates that are difficult to separate from each other. The aggregates contain clusters of tightly packed very small silica inclusions (1 to 6 μm). A number of possible scratches are observed (see Figure 2.146d).

Site 4 (Figure 2.147) lacks chondrules and chondrule like fragments. The site contains 13 low-Ca pyroxene grains (28 to 413 μm). 7 of the low-Ca pyroxene grains contain metal inclusions (6 to 19 μm). Between the low-Ca pyroxene grains are 2 plagioclase grains (44 to 200 μm). In the middle of the site are two metal aggregates (356 to 375 μm). Both aggregates contain clusters of very small silica inclusions (3 to 6 μm). Both have been affected by terrestrial weathering, with 1 grain (49 to 59 μm) in the smaller aggregate that are less affected by the weathering. Sandwiched between the larger aggregate and the low-Ca pyroxene grains are 2 plagioclase grains (13 to 19 μm). Also contained in this aggregate is a low-Ca pyroxene inclusion (6 μm). Connected to the aggregates are a number of metal filled cracks. 1 of these contains a plagioclase inclusion (13 μm).

Site 5 (Figure 2.148) lacks chondrules and chondrule like fragments. The site contains 6 low-Ca pyroxene grains (41 to 350 μm). 3 of the low-Ca pyroxene grains contain metal inclusions (6 to 16 μm). The low-Ca pyroxene grains are separated by metal aggregates (88 to 288 μm). 3 of the low-Ca pyroxene grains are cut by metal filled cracks (3 to 38 μm).

Site 6 (Figure 2.149) lacks chondrules and chondrule like fragments. The site contains 12 low-Ca pyroxene grains (20 to 188 μm). 11 of the low-Ca pyroxene grains contain metal inclusions (2 to 20 μm). Between the low-Ca pyroxene grains are 5 plagioclase grains (5 to 78 μm). 1 of these grains contains metal inclusions (7 to 15 μm). The center of the site is dominated by a metal and FeS aggregate (415 μm). This aggregate contains clusters of silica grains (2 to 24 μm) that are mostly concentrated at the aggregate edges, but some are closer to the center. Several metal and FeS filled cracks (2 to 39 μm) are observed leading off of the aggregate.

Site 7 (Figure 2.150) lacks chondrules and chondrule like fragments. The site contains 13 low-Ca pyroxene grains (17 to 272 μm). 11 low-Ca pyroxene grains contain metal inclusions (3 to 14 μm). Between the low-Ca pyroxene grains are metal and FeS aggregates (28 to 317 μm). The aggregates contain clusters of silica inclusions (3 to

6 μm), low-Ca pyroxene inclusions (3 to 6 μm), and Al-rich inclusions (6 to 28 μm). Several cracks (3 to 53 μm) filled with metal and FeS are observed connecting to the aggregates.

Site 8 (Figure 2.151) lacks chondrules and chondrule like fragments. The site contains 10 low-Ca pyroxene grains (21 to 369 μm). 7 of the low-Ca pyroxene grains contain metal inclusions (3 to 23 μm). 3 of the low-Ca pyroxene grains contain plagioclase inclusions (5 to 46 μm). 6 plagioclase grains (41 to 149 μm) are observed between the low-Ca pyroxenes, a metal and FeS aggregate (282 μm), and a large metal and FeS filled crack with several branches (3 to 118 μm). Contained in the aggregate are clusters of silica (3 to 10 μm) inclusions and low-Ca pyroxene inclusions (5 μm). Low-Ca pyroxene (3 to 15 μm) and plagioclase (3 to 41 μm) inclusions are observed in the cracks.

Site 9 (Figure 2.152) lacks chondrules and chondrule like fragments. The site contains 12 low-Ca pyroxene grains (6 to 328 μm). 9 of the low-Ca pyroxene grains contain metal inclusions (3 to 11 μm). 1 of the low-Ca pyroxene grains contains a plagioclase inclusion (33 μm). Between the low-Ca pyroxene grains are plagioclase grains (25 to 139 μm). 2 metal aggregates (100 to 122 μm) are observed between the low-Ca pyroxene and plagioclase grains. The aggregates contain clusters of silica inclusions (3 to 11 μm) concentrated around the edge of the aggregates. Close to the edge of the largest aggregate is an elongated plagioclase inclusion (22 μm). Several metal filled cracks (3 to 39 μm) are observed. Small low-Ca pyroxene inclusions (3 to 6 μm) are observed in the largest crack.

Site 10 (Figure 2.153) lacks chondrules and chondrule like fragments. The site contains 12 low-Ca pyroxene grains (17 to 444 μm). 10 of the low-Ca pyroxene grains contain metal inclusions (3 to 44 μm). 1 of the low-Ca pyroxene contains a plagioclase inclusion (28 μm). Between the low-Ca pyroxenes are plagioclase grains (72 to 183 μm). Some of these grains contain metal inclusions (6 to 17 μm). 2 metal grains are observed between the low-Ca pyroxene grains (67 to 294 μm). These contain clusters of silica inclusions (3 to 6 μm). Several metal filled cracks (3 to 44 μm) are observed.

Site 11 (Figure 2.154) lacks chondrules and chondrule like fragments. The site contains 13 low-Ca pyroxene grains (28 to 240 μm). 10 of the low-Ca pyroxene grains contain metal inclusions (3 to 25 μm). Between the low-Ca pyroxenes are plagioclase grains (20 to 200 μm). Some of these grains contain metal inclusions (3 to 13 μm). 2

aggregates (190 to 270 μm) of metal are observed between the low-Ca pyroxene grains. The aggregates contain clusters of silica inclusions (3 to 10 μm). Metal filled cracks (3 to 10 μm) are observed, often connecting to the aggregates. FeS (8 μm) is observed in an aggregate with metal.

Site 12 (Figure 2.155) lacks chondrules and chondrule like fragments. The site contains 12 low-Ca pyroxene grains (17 to 272 μm). 7 of the low-Ca pyroxene grains contain metal inclusions (3 to 39 μm). 4 plagioclase grains (56 to 67 μm) are observed between the low-Ca pyroxenes. The plagioclase contain a small number of metal inclusions (6 to 11 μm) and 1 has a low-Ca pyroxene inclusion (11 μm). 2 metal filled cracks with branches (3 to 56 μm) are observed. Low-Ca pyroxene and plagioclase inclusions are observed in the cracks, both range from 3 to 6 μm .

Site 13 (Figure 2.156) lacks chondrules and chondrule like fragments. The site contains 12 low-Ca pyroxene grains (59 to 235 μm). 10 of the low-Ca pyroxene grains contain metal inclusions (3 to 26 μm). 6 metal aggregates (29 to 206 μm) are observed between the low-Ca pyroxene grains. All of the aggregates contain clusters of silica inclusions (3 to 6 μm). Cracks (3 to 29 μm) filled with metal are observed connecting the aggregates. Some of the cracks contain low-Ca pyroxene inclusions (3 to 35 μm).

Site 14 (Figure 2.157) lacks chondrules and chondrule like fragments. The site contains 6 low-Ca pyroxene grains (16 to 263 μm). 3 plagioclase grains (142 to 184 μm) are observed between the low-Ca pyroxene grains. Metal inclusions (5 to 32 μm) are observed in the plagioclase. 1 large metal and FeS aggregate (416 μm) is observed. Silica inclusions (3 to 5 μm) are observed in the aggregate. Several metal and FeS filled cracks (3 to 47 μm) are observed. Both low-Ca pyroxene (3 to 11 μm) and plagioclase (3 to 11 μm) inclusions are observed in the cracks.

Site 15 (Figure 2.158) lacks chondrules and chondrule like fragments. The site contains 20 low-Ca pyroxene grains (17 to 217 μm). 11 of the low-Ca pyroxene grains contain metal inclusions (3 to 33 μm). 1 body contains a plagioclase inclusion (50 μm). The low-Ca-pyroxene grains are embedded in an aggregate of plagioclase (761 μm). This aggregate contains metal inclusions (3 to 94 μm). A metal and FeS aggregate is observed next to the plagioclase grains (347 μm). This aggregate contains low-Ca pyroxene (6 to 22 μm) and plagioclase (6 to 19 μm) inclusions. Metal and FeS filled cracks (3 to 78 μm) are observed with several smaller cracks branching off of the largest crack. In the largest crack are low-Ca pyroxene (6 to 8 μm) and plagioclase (3 to 11

μm) inclusions.

2.5.3 NWA8173 (Enstatite-rich-achondrite ungrouped)

section a

Site 1 (Figure 2.159) lacks chondrules and chondrule like fragments. The site contains 4 low-Ca pyroxene grains (43 to 239 μm). 3 of the low-Ca pyroxene grains contain plagioclase inclusions (3 to 18 μm). 1 also contains silica inclusions (3 to 29 μm) and a schreibersite inclusion (18 μm). Between the low-Ca pyroxenes are plagioclase grains (24 to 88 μm) and silica (12 to 41 μm). 1 of the plagioclase grains contain low-Ca pyroxene inclusions (6 to 12 μm). 5 metal grains are also observed (12 to 471 μm), 4 of which are in contact with the low-Ca pyroxene grains. The largest metal body contains a silica inclusion (12 μm). Filling the space between the other phases are 3 grains of alabandite (41 to 206 μm). 2 schreibersite grains (13 to 43 μm) are observed in contact with low-Ca pyroxene, plagioclase grains, and alabandite. 1 is also in contact with silica.

Site 2 (Figure 2.160) lacks chondrules and chondrule like fragments. The site contains 23 low-Ca pyroxene grains (9 to 273 μm). 4 of the low-Ca pyroxene grains contain silica inclusions (5 to 23 μm), 2 contain plagioclase inclusions (5 to 9 μm), and 1 contains alabandite inclusions (5 to 18 μm). Between the low-Ca pyroxene grains are plagioclase grains (7 to 55 μm), silica (5 to 23 μm), metal (7 to 418 μm), and alabandite (9 to 68 μm). The plagioclase grains contain low-Ca pyroxene inclusions (2 to 5 μm). Some of the alabandite contains a low-Ca pyroxene inclusion (5 μm) and a plagioclase inclusion (9 μm).

Site 3 (Figure 2.161) lacks chondrules and chondrule like fragments. The site contains 19 low-Ca pyroxene grains (9 to 211 μm). 3 of the low-Ca pyroxene grains contain plagioclase inclusions (2 to 9 μm). 2 contain silica inclusions (5 to 9 μm). Between the low-Ca pyroxene grains are plagioclase grains (9 to 109 μm), silica (7 to 45 μm), metal (18 to 123 μm), and alabandite (11 to 118 μm). The plagioclase and silica contain low-Ca pyroxene inclusions (5 to 9 μm). 2 alabandite inclusions (5 to 9 μm) are observed in the plagioclase. 1 metal aggregate contains low-Ca pyroxene inclusions (9 to 20 μm).

Site 4 (Figure 2.162) lacks chondrules and chondrule like fragments. The site contains 30 low-Ca pyroxene grains (5 to 308 μm). Some of the low-Ca pyroxene grains

contain silica inclusions (5 to 15 μm) and 1 contains an alabandite inclusion (25 μm). Between the low-Ca pyroxene grains are plagioclase grains (10 to 55 μm), silica (5 to 35 μm), metal (15 to 50 μm), and alabandite (5 to 260 μm). 1 of the plagioclase grains contains low-Ca pyroxene inclusions (3 to 5 μm). 1 low-Ca pyroxene grain (10 μm) is observed sandwiched between silica, plagioclase, and alabandite.

Site 5 (Figure 2.163) lacks chondrules and chondrule like fragments. The site contains 6 low-Ca pyroxene grains (23 to 182 μm). 2 of the low-Ca pyroxenes contains silica inclusions (5 to 9 μm). A second low-Ca pyroxene grain contains alabandite inclusions (5 to 14 μm). Between the low-Ca pyroxenes are plagioclase grains (9 to 82 μm), metal (9 to 441 μm), and alabandite (19 to 89 μm). 1 plagioclase grain contains low-Ca pyroxene inclusions (2 to 5 μm). 2 of the metal grains contain plagioclase inclusions (2 to 23 μm). An isolate schreibersite grain (10 μm) is observed sandwiched between plagioclase and a alabandite aggregate.

Site 6 (Figure 2.164) lacks chondrules and chondrule like fragments. The site contains 20 low-Ca pyroxene grains (9 to 268 μm). 4 low-Ca pyroxene grains contain plagioclase inclusions (5 to 9 μm) and 3 contains silica inclusions (5 to 9 μm). Between the low-Ca pyroxene grains are plagioclase grains (18 to 86 μm), silica (9 to 36 μm), and alabandite (14 to 68 μm). Some low-Ca pyroxene (5 to 9 μm) and alabandite (2 to 5 μm) inclusions are observed in the plagioclase and silica. Contained in the center of the site are two aggregates of metal (93 to 241 μm). Contained in a low-Ca pyroxene grain, is a plagioclase, a silica, and schreibersite inclusions (5 μm).

Site 7 (Figure 2.165) lacks chondrules and chondrule like fragments. The site contains 11 low-Ca pyroxene grains (17 to 224 μm). The low-Ca pyroxene grains contain plagioclase (5 to 67 μm), silica (5 to 14 μm), and alabandite (10 μm) inclusions. At the edge of 1 of the low-Ca pyroxene grains is a spinel grain (26 μm). Between the low-Ca pyroxene grains are plagioclase (2 to 24 μm), metal (10 to 190 μm), and alabandite (19 to 243 μm). 2 grains of Fe,Ni,P (48 to 57 μm) are observed, 1 in an aggregate with metal. Between 2 of the low-Ca pyroxene grains are Al-rich material (5 to 29 μm). The metal aggregate contains low-Ca pyroxene inclusions (5 μm). A crack is observed in the alabandite with a silica inclusion (5 μm) in it. The crack does not cut through the metal, indicating that the crack is older than the metal.

Site 8 (Figure 2.166) lacks chondrules and chondrule like fragments. The site contains 15 low-Ca pyroxene grains (18 to 295 μm). 2 low-Ca pyroxene grains contain

silica inclusions (5 μm). 1 of the low-Ca pyroxene grains contains a alabandite inclusion (9 μm). Between the low-Ca pyroxene grains are plagioclase grains (9 to 66 μm), silica (5 to 30 μm), alabandite (14 to 145 μm), and metal (5 to 77 μm). The plagioclase and silica contain low-Ca pyroxene (5 to 59 μm) and alabandite (5 μm) inclusions.

Site 9 (Figure 2.167) lacks chondrules and chondrule like fragments. The site contains 14 low-Ca pyroxene grains (5 to 171 μm). The low-Ca pyroxene grains contain plagioclase (5 μm), silica (5 to 14 μm), and alabandite (10 μm) inclusions. Between the low-Ca pyroxene grains are plagioclase grains (5 to 81 μm), silica (5 to 33 μm), alabandite (10 to 314 μm), and metal (5 to 119 μm). The plagioclase and silica contain low-Ca pyroxene (5 to 14 μm), alabandite (10 to 14 μm) and metal (5 to 19 μm) inclusions. alabandite contains low-Ca pyroxene (5 μm), plagioclase (5 to 10 μm), and silica (7 to 21 μm) inclusions.

Site 10 (Figure 2.168) lacks chondrules and chondrule like fragments. The site contains 32 low-Ca pyroxene grains (11 to 206 μm). The low-Ca pyroxene grains contain plagioclase (6 to 17 μm), silica (6 to 11 μm), and alabandite (11 to 17 μm) inclusions. Between the low-Ca pyroxene grains are plagioclase grains (6 to 178 μm), silica (6 to 56 μm), alabandite (17 to 261 μm), and metal (6 to 119 μm). Schreibersite (4 to 54 μm) is observed in aggregates with metal. Metal inclusions (3 to 22 μm) are observed in the plagioclase and silica. A crack is observed in the largest alabandite which is not present in the other phases. 2 of the metal aggregates contains a plagioclase inclusions (3 to 11 μm).

section b

Site 1 (Figure 2.169) lacks chondrules and chondrule like fragments. The site contains 10 low-Ca pyroxene grains (3 to 266 μm). Contained in the largest low-Ca pyroxene grain are plagioclase (3 to 45 μm), silica (3 μm), and Al-rich (3 to 7 μm) inclusions. Approximately half of the site is dominated by a large metal aggregate (328 μm). Contained in this aggregate are low-Ca pyroxene (3 to 45 μm) and plagioclase (2 to 24 μm) inclusions.

Site 2 (Figure 2.170) lacks chondrules and chondrule like fragments. The site contains 8 low-Ca pyroxene grains (12 to 247 μm). Contained in the low-Ca pyroxene grains are plagioclase (6 to 35 μm), silica (6 to 59 μm), metal (6 to 12 μm), and ala-

bandite (6 to 12 μm) inclusions. In the center of the site is an aggregate (317 μm) of metal (266 μm) and alabandite (7 to 93 μm). Both the metal and the alabandite contain low-Ca pyroxene (2 to 45 μm) and plagioclase (3 to 22 μm) inclusions.

Site 3 (Figure 2.171) lacks chondrules and chondrule like fragments. The site contains 10 low-Ca pyroxene grains (10 to 190 μm). The low-Ca pyroxene grains contain plagioclase (10 to 14 μm), silica (5 to 14 μm), and alabandite (5 to 33 μm) inclusions. Between the low-Ca pyroxene grains are plagioclase grains (24 to 110 μm) and an aggregate (238 μm) of metal (21 to 167 μm) and schreibersite (114 μm). Contained in 1 plagioclase grain are 2 low-Ca pyroxene inclusions (5 to 10 μm). The metal contains Al-rich inclusions (14 to 126 μm).

Site 4 (Figure 2.172) lacks chondrules and chondrule like fragments. The site contains 10 low-Ca pyroxene grain (5 to 89 μm). The low-Ca pyroxene grain contain plagioclase (4 to 8 μm) and silica (4 μm) inclusions. Between the low-Ca pyroxene grains are plagioclase grains (5 to 74 μm), silica (5 to 42 μm), alabandite (5 to 289 μm), metal aggregates (5 to 89 μm), and Al-rich material (5 to 32 μm). The silica is always observed accompanying the plagioclase. Low-Ca pyroxene (5 to 37 μm) and plagioclase (5 to 37 μm) inclusions are observed in the MgS. The metal and Al-rich material contains a low-Ca pyroxene (16 μm), plagioclase (5 to 26 μm), and silica (5 to 45 μm) inclusions.

Site 5 (Figure 2.173) lacks chondrules and chondrule like fragments. The site contains 16 low-Ca pyroxene grains (4 to 164 μm). The low-Ca pyroxene grains contain plagioclase (6 μm), silica (4 to 8 μm), alabandite (4 to 8 μm), and Al-rich (4 to 8 μm) inclusions. Between the low-Ca pyroxenes are plagioclase (10 to 180 μm), silica (4 to 40 μm), alabandite (4 to 16 μm), and metal aggregates (22 to 206 μm). The plagioclase and silica contain low-Ca pyroxene inclusions (4 μm). The plagioclase grains also contain alabandite inclusions (4 to 8 μm). 1 of the metal aggregates contains a low-Ca pyroxene inclusion (4 μm). Part of a plagioclase grain is cut-off from the rest of the body by a hole. This gives the effect of a plagioclase inclusion in a metal aggregate, but this is not the case.

Site 6 (Figure 2.174) lacks chondrules and chondrule like fragments. The site contains 8 low-Ca pyroxene grains (6 to 238 μm). The largest low-Ca pyroxene grain dominates the site. It contains plagioclase (3 to 58 μm), silica (3 to 6 μm), metal (3 to 6 μm), and Al-rich (3 to 12 μm) inclusions. The largest plagioclase inclusion contains

low-Ca pyroxene inclusions (1 to 3 μm). Throughout the largest low-Ca pyroxene grain are metal filled cracks (1 to 3 μm). 2 metal aggregates (23 to 280 μm) dominated the rest of the site. The metal aggregates contain low-Ca pyroxene inclusions (9 to 29 μm).

Site 7 (Figure 2.175) lacks chondrules and chondrule like fragments. The site contains 5 low-Ca pyroxene grains (9 to 371 μm). The largest low-Ca pyroxene grain contains silica inclusions (4 to 13 μm). The silica inclusions are mostly concentrated near the center of the low-Ca pyroxene grain. A crack (4 to 9 μm) is observed in the largest low-Ca pyroxene grain. Between the low-Ca pyroxene grain is a large metal aggregate (374 μm). Contained in the aggregate are low-Ca pyroxene (4 to 13 μm) and plagioclase (9 to 15 μm) inclusions.

Site 8 (Figure 2.176) lacks chondrules and chondrule like fragments. The site contains 26 low-Ca pyroxene grains (7 to 214 μm). 6 of the low-Ca pyroxene grains contain plagioclase inclusions (2 to 14 μm), 6 contain silica inclusions (2 to 14 μm), and 5 contain alabandite inclusions (2 to 10 μm). Between the low-Ca pyroxene grains are plagioclase grains (14 to 119 μm), silica (12 to 29 μm), alabandite (5 to 43 μm), and metal aggregates (17 to 233 μm). The plagioclase, alabandite, and metal contain low-Ca pyroxene inclusions (2 to 48 μm). The metal also contains plagioclase inclusions (5 to 19 μm).

Site 9 (Figure 2.177) lacks chondrules and chondrule like fragments. The site is dominated by a single large low-Ca pyroxene grain (863 μm). The low-Ca pyroxene grain contains plagioclase (6 to 88 μm), silica (6 to 22 μm), and Al-rich (3 to 19 μm) inclusions.

Site 10 (Figure 2.178) lacks chondrules and chondrule like fragments. The site contains 10 low-Ca pyroxene grains (5 to 400 μm). 8 of the low-Ca pyroxene grains contain plagioclase inclusions (5 to 10 μm), 6 contain silica inclusions (3 to 8 μm), 2 contain alabandite inclusions (3 to 15 μm), and Al-rich inclusions (3 to 5 μm). Between the low-Ca pyroxene grains are plagioclase grains (5 to 120 μm) and an aggregate (215 μm) of alabandite (215 μm) and metal (45 μm). 2 of the plagioclase grains contain low-Ca pyroxene inclusions (3 to 10 μm). The alabandite contains a low-Ca pyroxene (25 μm) and 4 plagioclase (3 to 15 μm) inclusions.

Site 11 (Figure 2.179) lacks chondrules and chondrule like fragments. The site is dominated by a single large low-Ca pyroxene grain (622 μm). The low-Ca pyroxene grain contains plagioclase (5 to 7 μm), silica (2 to 5 μm), metal (2 to 105 μm), and Al-

rich (2 to 14 μm) inclusions. The largest metal inclusion is an aggregate that contains a low-Ca pyroxene inclusion (9 μm).

Site 12 (Figure 2.180) lacks chondrules and chondrule like fragments. The site is dominated by a single large low-Ca pyroxene grain (622 μm). The low-Ca pyroxene grain contains plagioclase (5 to 55 μm), silica (5 to 32 μm), metal (2 to 55 μm), alabandite (9 to 68 μm), and Al-rich (2 to 5 μm) inclusions. Next to the low-Ca pyroxene grain are a plagioclase grains (5 to 14 μm) and an aggregate (132 μm) of metal (109 μm) and alabandite (23 μm).

Site 13 (Figure 2.181) lacks chondrules and chondrule like fragments. The site contains 11 low-Ca pyroxene grains (14 to 268 μm). Contained in 3 of the low-Ca pyroxene grains are plagioclase inclusions (5 to 27 μm), 2 contain silica inclusions (5 to 27 μm), and 4 contain alabandite inclusions (5 μm). Beside the low-Ca pyroxene grains are large alabandite aggregate (307 μm) and a metal grain (36 μm). A small plagioclase grain (9 μm) is observed sandwiched between the metal grain and a low-Ca pyroxene grain. A glass-like inclusion (32 μm) is observed in the alabandite.

Site 14 (Figure 2.182) lacks chondrules and chondrule like fragments. The site contains 9 low-Ca pyroxene grains (5 to 495 μm). 4 of the low-Ca pyroxene grains contain plagioclase inclusions (3 to 20 μm), 3 contain silica inclusions (3 to 20 μm), 2 contain metal inclusions (3 to 20 μm), and 1 contains alabandite inclusions (3 to 15 μm). Between the low-Ca pyroxene grains are plagioclase grains (25 to 110 μm) and a metal aggregate (235 μm). 2 of the plagioclase grains contain silica inclusions (5 to 10 μm) and 1 contains low-Ca pyroxene inclusions (5 μm).

Site 15 (Figure 2.183) lacks chondrules and chondrule like fragments. The site contains 11 low-Ca pyroxene grains (7 to 367 μm). 3 of the low-Ca pyroxene grains contain silica inclusions (3 to 33 μm) and 1 contains spinel (7 to 27 μm) inclusions. Between the low-Ca pyroxene grains are plagioclase grains (7 to 153 μm), silica (7 to 73 μm), and alabandite (7 to 313 μm). Some of the plagioclase and silica contain low-Ca pyroxene (3 to 27 μm) and alabandite (7 to 93 μm) inclusions. Low-Ca pyroxene (13 to 27 μm) and glass-like (7 to 67 μm) inclusions are observed in the alabandite.

Site 16 (Figure 2.184) lacks chondrules and chondrule like fragments. The site contains 16 low-Ca pyroxene grains (17 to 208 μm). 6 low-Ca pyroxene grains are observed to contain plagioclase inclusions (3 to 33 μm). 3 of the low-Ca pyroxene grains contain silica inclusions (3 to 33 μm). 9 of the low-Ca pyroxene grains contain alabandite

inclusions (3 to 14 μm). Between the low-Ca pyroxene grains are plagioclase grains (17 to 139 μm), silica (3 to 161 μm), alabandite (6 to 206 μm), and metal aggregates (14 to 272 μm). The plagioclase contain low-Ca pyroxene inclusions (3 to 6 μm). 1 plagioclase grain contains a silica inclusion (6 μm). The silica outside of the low-Ca pyroxene grains are always observed accompanying the plagioclase, with 2 silica containing plagioclase inclusions (6 to 11 μm). The alabandite contains low-Ca pyroxene (6 μm) and plagioclase (3 to 17 μm) inclusions. 2 of the metal aggregates contains clusters of Al-rich inclusions (3 to 28 μm) and 1 contains plagioclase inclusions (3 to 6 μm).

Site 17 (Figure 2.185) lacks chondrules and chondrule like fragments. The site contains 11 low-Ca pyroxene grains (6 to 341 μm). 2 of the low-Ca pyroxene grains plagioclase (12 μm), alabandite (3 μm) and Al-rich (3 to 6 μm) inclusions. 1 contains silica inclusions (6 to 12 μm). In addition to the low-Ca pyroxene grains, plagioclase grains (6 to 76 μm), silica (6 to 53 μm), alabandite (21 to 388 μm), and metal (47 μm) are also observed. The silica is observed accompanying the plagioclase. 4 of the plagioclase grains contain silica inclusions (3 to 6 μm). 1 plagioclase grain contains a low-Ca pyroxene inclusion (3 μm). The alabandite contains low-Ca pyroxene (18 to 29 μm), plagioclase (6 to 65 μm), and silica (15 to 24 μm) inclusions.

Site 18 (Figure 2.186) lacks chondrules and chondrule like fragments. The site contains 22 low-Ca pyroxene grains (15 to 396 μm). 7 of the low-Ca pyroxene grains contain plagioclase inclusions (4 to 31 μm), 7 contain silica inclusions (4 to 23 μm). Between the low-Ca pyroxene grains are plagioclase grains (8 to 162 μm), silica (8 to 69 μm), and alabandite (8 to 77 μm). The silica accompanies the plagioclase grains. They both contain low-Ca pyroxene (4 to 46 μm) and alabandite (4 to 15 μm) inclusions. 1 plagioclase contains a metal inclusion (15 μm). The alabandite contains 1 low-Ca pyroxene inclusion (8 μm) and 3 plagioclase inclusions (4 to 15 μm).

Site 19 (Figure 2.187) lacks chondrules and chondrule like fragments. The site contains 33 low-Ca pyroxene grains (9 to 500 μm). 7 of the low-Ca pyroxene grains contain plagioclase inclusions (9 to 27 μm), 14 contain silica (9 to 18 μm), and 4 contain alabandite (5 to 9 μm). Between the low-Ca pyroxene grains are plagioclase grains (18 to 200 μm), silica (9 to 109 μm), metal (45 to 55 μm), and alabandite (9 to 255 μm). The silica accompanies the plagioclase. They both contain low-Ca pyroxene (5 to 36 μm) and alabandite (5 to 9 μm) inclusions. The alabandite contains low-Ca pyroxene (5 to 18 μm), plagioclase (9 to 82 μm), and silica (9 to 36 μm) inclusions. 1 of the metal grains

contains Al-rich inclusions (5 to 14 μm). A hole in the thin section contains low-Ca pyroxene (5 μm), silica (18 μm) and Al-rich material (5 to 27 μm).

Site 20 (Figure 2.188) lacks chondrules and chondrule like fragments. The site contains 12 low-Ca pyroxene grains (59 to 541 μm). 6 of the low-Ca pyroxene grains contain plagioclase inclusions (12 to 47 μm), 9 contain silica (6 to 12 μm) inclusions, and 2 contain metal inclusions (6 to 12 μm). Between the low-Ca pyroxene grains are plagioclase grains (12 to 71 μm), silica (35 to 94 μm), and alabandite (35 to 171 μm). 1 plagioclase grain contains a low-Ca pyroxene (6 μm) and 2 alabandite (6 to 12 μm) inclusions.

Site 21 (Figure 2.189) lacks chondrules and chondrule like fragments. The site contains 34 low-Ca pyroxene grains (8 to 323 μm). 14 of the low-Ca pyroxene grains contain plagioclase inclusions (4 to 31 μm), 13 contain silica inclusions (4 to 38 μm). 1 low-Ca pyroxene grain contains an alabandite inclusion (8 μm). 3 of the low-Ca pyroxene grains contain metal inclusions (8 to 15 μm). Between the low-Ca pyroxene grains are plagioclase grains (8 to 177 μm), silica (8 to 54 μm), alabandite (8 to 96 μm), and metal (23 to 154 μm). The plagioclase grains contain low-Ca pyroxene (4 to 8 μm) and silica (8 to 12 μm) inclusions. The silica outside of the low-Ca pyroxene grains is always observed accompanying the plagioclase. 1 alabandite and 1 metal aggregate contains low-Ca pyroxene (4 to 8 μm) and plagioclase (4 to 8 μm) inclusions.

Site 22 (Figure 2.190) lacks chondrules and chondrule like fragments. The site contains 29 low-Ca pyroxene grains (14 to 186 μm). 12 low-Ca pyroxene grains contain plagioclase inclusions (7 to 21 μm), 12 contain silica inclusions (7 to 14 μm), 4 contain alabandite inclusions (7 to 29 μm). 16 of the low-Ca pyroxene grains contain Al-rich inclusions (4 to 7 μm), especially in cracks (4 to 7 μm). 2 low-Ca pyroxene grains contain metal inclusions (11 to 29 μm). Between the low-Ca pyroxene grains are plagioclase grains (7 to 321 μm), silica (7 to 107 μm), alabandite (7 to 143 μm), and metal (7 to 29 μm). The plagioclase grains and silica contains low-Ca pyroxene inclusions (4 to 186 μm). The plagioclase and silica also contain alabandite inclusions (7 to 36 μm). The silica and alabandite both contain plagioclase inclusions (7 to 14 μm).

Site 23 (Figure 2.191) lacks chondrules and chondrule like fragments. This site is dominated by a single low-Ca pyroxene grain (809 μm). This grain contains plagioclase (6 to 71 μm), silica (6 to 9 μm), metal (6 to 41 μm), and Al-rich (3 to 6 μm) inclusions.

Site 24 (Figure 2.192) lacks chondrules and chondrule like fragments. The site con-

tains 7 low-Ca pyroxene grains (10 to 171 μm). The largest low-Ca pyroxene contains plagioclase (2 to 5 μm), silica (2 to 5 μm), metal (2 to 5 μm), and Al-rich (2 to 5 μm) inclusions. The metal inclusions are connected by metal filled cracks (2 to 5 μm). 1 of the other low-Ca pyroxene grains also contains Al-rich inclusions (2 to 5 μm). Between the low-Ca pyroxene grains is a plagioclase grain (43 μm) and a metal aggregate (462 μm). Sandwiched between the plagioclase and the aggregate is a low-Ca pyroxene grain (7 μm). Contained in the aggregate are 2 plagioclase inclusions (5 to 10 μm) and a low-Ca pyroxene inclusion (5 μm). The aggregate also contains clusters of Al-rich inclusions (2 to 10 μm).

Site 25 (Figure 2.193) lacks chondrules and chondrule like fragments. The site contains 10 low-Ca pyroxene grains (12 to 350 μm). 1 low-Ca pyroxene grains contains plagioclase inclusion (6 to 12 μm), 1 contains silica inclusions (3 to 18 μm), 3 contain alabandite (3 to 6 μm), and 4 contain Al-rich inclusions (3 to 6 μm). Between the low-Ca pyroxene grains are plagioclase grains (9 to 41 μm), silica (6 to 165 μm), alabandite (12 to 571 μm), and metal (282 μm). A plagioclase and silica contain low-Ca pyroxene inclusions (3 to 6 μm). The plagioclase contains silica inclusions (3 μm) and the silica contains plagioclase inclusions 3 to 12 μm . The alabandite contains low-Ca pyroxene (6 to 100 μm), plagioclase (3 to 26 μm), and metal (3 to 12 μm) inclusions, along with Al-rich material filled cracks (3 to 6 μm).

Site 26 (Figure 2.194) lacks chondrules and chondrule like fragments. The site contains 12 low-Ca pyroxene grains (14 to 255 μm). 8 of the low-Ca pyroxene grains contain plagioclase grains (5 to 23 μm). 3 of the low-Ca pyroxene grains contain silica inclusions (5 to 27 μm). 5 of the low-Ca pyroxene grains contain metal inclusions (2 to 5 μm). 2 of the low-Ca pyroxene grains contains alabandite inclusions (5 to 27 μm). Between the low-Ca pyroxene grains are plagioclase grains (14 to 98 μm), silica (5 to 34 μm), alabandite (11 to 18 μm), and metal (9 to 272 μm). The silica contains low-Ca pyroxene inclusions (2 to 5 μm). Low-Ca pyroxene (3 to 5 μm) and plagioclase (14 μm) inclusions are observed in the metal.

Site 27 (Figure 2.195) lacks chondrules and chondrule like fragments. The site contains 13 low-Ca pyroxene grains (5 to 250 μm). 3 low-Ca pyroxene grains contain plagioclase inclusions (5 to 14 μm), 1 contains silica inclusion (7 μm), 1 contain a alabandite inclusion (14 μm). Between the low-Ca pyroxene grains are plagioclase grains (14 to 236 μm) and alabandite (14 to 136 μm). 2 plagioclase grains contains

low-Ca pyroxene inclusions (2 to 5 μm). Both the plagioclase and 1 alabandite contain silica inclusions (2 to 14 μm).

Site 28 (Figure 2.196) lacks chondrules and chondrule like fragments. The site contains 3 low-Ca pyroxene grains (56 to 491 μm). The low-Ca pyroxene grains contain plagioclase (6 μm), silica (6 to 19 μm), and metal (6 to 13 μm) inclusions. Between the low-Ca pyroxene grains are plagioclase grains and alabandite aggregates (6 to 106 μm). Around the edges of the aggregates are borders of metal (3 to 6 μm). The aggregates contain low-Ca pyroxene inclusions (3 to 9 μm).

Site 29 (Figure 2.197) lacks chondrules and chondrule like fragments. The site contains 19 low-Ca pyroxene grains (13 to 238 μm). 5 of the low-Ca pyroxene grains contain plagioclase inclusions (3 to 13 μm), 2 contain silica inclusions (3 to 6 μm), and 2 contain alabandite inclusions (3 to 13 μm). Between the low-Ca pyroxene grains are plagioclase (13 to 269 μm), silica (6 to 94 μm), and aggregates (6 to 150 μm) of alabandite (6 to 59 μm) and metal (9 to 150 μm). The plagioclase grains contain silica inclusions (3 to 25 μm) and metal inclusions (3 to 19 μm). Both the plagioclase and silica contain low-Ca pyroxene inclusions (3 to 6 μm). The aggregates contain plagioclase inclusions (13 to 19 μm).

2.6 Discussion

2.6.1 Variation among EH chondrites

At the first order the EH chondrites are mineralogically similar to each other. It should be noted that only one meteorite from each type was surveyed in this study. Thus additional meteorites should be characterised in future work. There is currently no method to quantitatively define the difference between an E3 and E4 chondrite. However, Prinz et al. (1984) defined the differences between E3 and E4 chondrules as the abundance of chondrules, a wide variation of FeO content in olivine and pyroxene, the abundance of olivine, the presence of glass with a wide Na content, and a relatively large abundance of metals and sulphides. The most noticeable differences between them is the size and abundance of the chondrules and chondrule fragments. The EH3 chondrite tends to have smaller but more abundant chondrules and chondrule fragments compared to the EH4 and EH5 chondrites. The EH7 and EH impact melt do not contain any chondrules

or chondrule fragments. Instead they are comprised of large low-Ca pyroxene with the spaces between them filled in by glass, plagioclase, silica, and metal aggregates. Both also contain FeS, but the with FeS and MgS observed to be significantly more prevalent in the EH impact melt.

The ratio of FeS to metal was observed to decrease from the EH3 to the EH7. As enstatite chondrites formed in a reduced environment, this may be an indicator that the sulphur is lost as H_2S during metamorphism. The MgS may be more abundant in the EH impact melt compared to the EH chondrites because the re-melting may have allowed sulphur to infiltrate the melt and bond with the Mg and the Fe. The abundance of olivine sharply decreases from the EH3 to the EH4 (average number of grains per site decreases from 27 to 1), and is completely absent in the EH5, EH7, and EH impact melt. This may be an indicator that EH3 chondrites cooled faster, preventing the removal of olivine by reacting with added SiO_2 . This is supported by the EH3 and EH4 typically having smaller chondrules and fragments compared to the EH5.

The matrix component of the EH3 is significantly larger compared to that of the EH4 and EH5. The matrix is absent from the EH7 and EH impact melt. This can be attributed to recrystallization during metamorphism and complete or partial re-melting. The abundance of CaS is observed to increase from the EH3 to the EH4, but then decrease from the EH4 to the EH7. However it should be noted that the size and abundance of the CaS grains is limited in these meteorites. The increase from the EH3 to the EH4 may be the result of a spatial and/or temporal variation in relation to a S-rich reservoir. The decrease of CaS from the EH4 to the EH7 can be attributed to the redistribution of Ca into plagioclase, by the breakdown of CaS into Ca and S. The S is then likely lost to the ambient gas. This can also explain the lack of CaS in the EH impact melt. CrS is observed to decrease in abundance from the EH3 to the EH7 and is absent from the EH impact melt. The Cr was likely redistributed during metamorphism and re-melting, attaching to the FeS and metal as an accessory element.

2.6.2 Variation among EL chondrites

At the first order the EL chondrites are also mineralogically similar to each other. The first difference is that the EL3 and EL4 chondrites contain chondrules and chondrule fragments. However, the EL5 and EL6 lack chondrules and fragments. The differ-

ence between EL3 and EL4 according to Van Niekerk and Keil (2011) is a significant decrease in the abundance of olivine and removal of some chondritic textures such as chondrules. The EL5 retains some chondrule like features, such Na-rich-glass-like bodies identified as plagioclase and silica often occurring within the low-Ca pyroxene bodies rather than as separate bodies. However, the EL5 exhibits plagioclase and silica that are separate from the low-Ca pyroxene. The EL6 also has plagioclase and silica contained within the low-Ca pyroxene bodies, but to a lesser extent.

The textural differences between the EL4 and EL5 can be attributed to re-crystallization due to metamorphism. There is no significant difference in the olivine abundance from the EL3 to the EL4 chondrites. However, olivine is absent from the EL5 and EL6 chondrites. The absence of olivine is attributed to secondary processes on the EL asteroid. At the first order, the mineralogies of the EH, EL, and enstatite achondrites are similar. However, in this study spinel is observed in the EL3 chondrites, but is absent in the EL4, EL5, and EL6 chondrites. This can be attributed to Al being redistributed into the Na-rich glass and plagioclase during metamorphism. The size of the FeS aggregates increases, but their abundance decreases from the EL3 to the EL6 chondrites. This results in the ratio of FeS to metal decreasing. As stated earlier, enstatite chondrites formed in a reduced environment. Therefore the sulphur can be interpreted as being lost as H₂S during metamorphism. The abundance of the silica is observed to decrease from the EL4 to the EL5. This may be the result of the bulk of the SiO₂ reacting with olivine to produce low-Ca pyroxene. The remainder may then get redistributed into a few grains/aggregates during metamorphism.

The FeS and metal aggregates become less rounded, with the low-Ca pyroxene bodies in the EL5 and EL6 chondrites containing less FeS and metal compared to the chondrules and fragments in the EL3 and EL4 chondrites. This can be linked to the loss of sulphur and redistribution of both FeS and metal during metamorphism. The low-Ca pyroxenes and plagioclases in the EL5 and EL6 chondrites increased in size compared to the low-Ca pyroxene and Na-rich glass in the chondrules and fragments in the EL3 and EL4 chondrites. This swelling is likely related to re-crystallization during metamorphism. However, this may depend on which E3 is studied as the modal abundance of olivine varies significantly in E3 chondrules. This suggests that some E3's were heated to a higher metamorphic temperature than others.

2.6.3 Variation among enstatite achondrites

The 3 enstatite achondrites show significant differences. Zaklodzie is the only 1 of the 3 that contains FeS as a major phase. NWA4301 only has minor FeS in aggregates with metal. NWA8173 lacks FeS completely. Zaklodzie contains alabandite as a minor phase, NWA8173 contains it as a major phase, and NWA4301 lacks alabandite. This indicates that the 3 achondrites formed in different S-rich environments, or in the same environment but were temporally separated. In NWA4301, silica is observed almost exclusively as inclusions within the metal. This is not the case for the other 2 achondrites. As all 3 lack olivine, their olivine-rich precursors likely completely reacted with the added SiO_2 . Alternatively, their precursors were already enstatite-rich. The silica in Zaklodzie and NWA8173 may have formed from left-over free SiO_2 or formed from the chondrule melt. The silica in NWA4301 likely formed from the reduction of FeO to metal.

NWA8173 contains schreibersite in aggregates with metal. The other 2 achondrites lack schreibersite. The phosphorus may have infiltrated the achondrite melt with sulphur during sulphidation. This would indicate a spacial or temporal variation in terms of the S-rich reservoir in relation to the formation of the other 2 achondrites. Al-rich material is observed in the metal and as inclusions in low-Ca pyroxenes in Zaklodzie and NWA8173. However, NWA4301 lacks this Al-rich material. This may be the result of Al being redistributed during metamorphism or as a result of complete melting. NWA4301 also contains many vein like cracks filled by metal and in some sites minor FeS. These vein like cracks are not observed in the other achondrites. This may indicate that there was an impact prior to or during the production of the metal.

2.6.4 Variation among all three enstatite meteorite groups

The abundance of the olivine is a striking difference between the 3 groups. The EH3 contains a significantly larger abundance of olivine compared to the EL3 and EL4, with the achondrites lacking any olivine. This supports that the EH chondrites cooled more rapidly than the EL chondrites and the achondrites as shown by Zhang et al. (1996) and Zhang and Sears (1996). This may support the typically larger size of the EL chondrules and fragments compared to their counter parts in the EH chondrites. Schneider et al. (2002) reported that intact EH3 and EL3 chondrules range from 45 to 1313 μm

and 85-2125 μm respectively, with averages of 278 ± 229 and 476 ± 357 respectively. The chondrules and fragments in this survey have average ranges of 31 to 304 μm for the EH3 and 69 to 474 μm for the EL3. The larger EL chondrules are buried within the chondrite regolith (Schneider et al., 2002) resulting in them experiencing prolonged heating post peak metamorphism, possibly within the temperature range where ortho-pyroxene is stable (Zhang et al., 1996). Whereas degassing events in the EH chondrite regolith brings EH chondrules closer to the surface where they are less insulated resulting in more rapid cooling (Schneider et al., 2002).

The abundance of the metal and sulphide aggregates is another key difference. The EH chondrites typically have a large abundance of metal and FeS compared to the EL chondrites. However, the size of the aggregates (particularly the metal) is generally larger in the EL chondrites. In the EH3, the average number of metal grains per site is 81, with an average size range of 5 to 110 μm . Whereas the EL3s average 38 metal grains per site with average sizes ranging from 5 to 220 μm . Due to the longer cooling period, the aggregates in the EL chondrites may have had more time to come together into a smaller number of larger aggregates. Wood (2005) suggested that metal is brought into the EH chondrites during chondrule formation events, causing the nebula to be depleted which in turn results in the depletion of metal in EL asteroid.

The aggregates in the EH chondrites tend to be more well rounded compared to their counter parts in the EL chondrites and achondrites. The more rounded shape indicates that they may have been formed in the nebula after a period of melting. The less rounded shapes of the aggregates in the EL chondrites and the achondrites may indicate that they were inherited from a precursor and may not have undergone complete melting. Compared to the EL chondrites, the EH chondrites and the achondrites tend to lack or have very little schreibersite and spinel. This is likely due to the nature of the environment in which they form, indicating heterogeneity in the enstatite meteorite forming region.

The achondrites are less diverse in terms of their sulphide components compared to the EH and EL chondrites. This indicates that if there was a single S-rich reservoir for all 3 groups, then it was likely heterogeneous in its composition due to spatial or temporal variation. Alternatively, all 3 groups had distinct S-rich reservoirs. This may also be the case for the Si-rich reservoir as the silica in all 3 groups varies in its abundance. This may also explain why the EH chondrites tend to have a larger abundance of olivine compared to the other 2 groups.

2.6.5 Occurrence of silicification and sulphidation

The presence of both enstatite, olivine, and sulphides in the E3 and E4 chondrules indicates that silicification and sulphidation occurs during chondrule formation. The lack of olivine in E5 to E7 chondrites indicates that silicification was less likely to have occurred on the enstatite asteroid. However, the presence of sulphides indicates that sulphidation does occur on the asteroid. The silicification reaction involves oxygen in the form of SiO_2 (3.1) and the sulphidation reaction does not (3.2). This implies that sulphidation is an important process in causing reduction in the protosolar nebula and that reduction occurs during enstatite chondrule formation.

The initial survey does not clarify if silicification and sulphidation accompany each other. Nor does it clarify which process is the dominant process in producing enstatite in the enstatite-chondrite forming-region from an olivine-rich precursor. These two issues will be addressed in the next chapter of this study. Weisberg and Kimura (2012) states that the enstatites in heated enstatite chondrites have compositions that are close to pure enstatite. It is uncertain if this is the result of heating on the asteroid or silicification and sulphidation during chondrule formation. This will be addressed by determining the major-element composition of enstatites in EH3 and EH4 chondrules.

2.7 Conclusions

The petrography of the EH and EL meteorites that were surveyed indicates that mineralogy does not change significantly with increasing petrological type. At the first order, the mineralogies of the EH, EL, and enstatite achondrites. The key differences is the abundance and sizes of chondrules and metal grains (or aggregates). The observations in this survey are generally in agreement with the observations of previous studies. A significant variation is that olivine is more common in the EH3 chondrite compared to the EL3 chondrites. The EH4 has a significant drop in the abundance of olivine, where as the EL4 has a similar abundance of olivine compared to the EL3. From the E5 chondrites, olivine is absent from all examined sites.

In addition to the decrease in olivine abundance, the grain sizes increase with petrological type. The removal of olivine, glass turning into plagioclase, and the increasing grain size are likely the result of heating on the asteroids. The presence of sulphides in the chondrules of the E3 and E4 meteorites indicates that sulphidation that resulted

in the production of enstatite from an olivine-rich precursor will have occurred during chondrule formation. There is a lack of evidence to support enstatite production by sulphidation on the enstatite asteroid. Metal is also observed in every E3 and E4 site examined, with many of the chondrules and fragments containing metal. The presence of sulphides and metal in the enstatite chondrules indicates that the Mg/Si ratio and reduced nature of the enstatite chondrites is the result of chondrule formation processes. This supports gas-melt interactions during the last chondrule melting event.

Some of the indicators of the reduced nature of enstatite chondrites include a high abundance of metallic Fe relative to oxidized Fe (Sears, 2004; Jacquet et al., 2018) along with the presence of Ca- and Mg-sulphides and metal that contain Si (Lehner et al., 2010; Wood, 2005; Horstmann et al., 2014; Ringwood, 1960). Based on this and the presence of metal and sulphides observed in the enstatite chondrules in this study, sulphidation is likely plays an important role in the reduction of the enstatite chondrites and that enstatite chondrules formed and accreted in a reduced environment.

Table 2.1: List of enstatite chondrites: “En-rich-achon ung” means “an enstatite-rich achondrite that is ungrouped”. “EH-imp melt” means “an enstatite chondrite of the EH group which has been impact melted”.

sample	classification	type	optical	SEM	EPMA	Raman	sites
EET 87746	EH3	thin section	yes	yes	yes	no	14
Sahara 97103	EH3	thin section	yes	yes	yes	yes	-
MET 00783	EH4	thin section	yes	yes	no	yes	12
EET 96135	EH5	thin section	yes	yes	no	no	12
QUE 94204	EH7	thin section	yes	yes	no	no	14
LAP 02225	EH imp melt	thin section	yes	yes	no	no	12
MAC 02837	EL3	thin section	yes	yes	no	no	9
PCA 91020	EL3	thin section	yes	yes	no	yes	14
MAC 02747	EL4	thin section	yes	yes	no	yes	12
TIL 91714	EL5	thin section	yes	yes	yes	no	14
ALHA 81021	EL6	thin section	yes	yes	no	no	15
Zaklodzie	En-rich-achon ung	thick section	yes	yes	no	yes	15
NWA 4301	En-rich-achon ung	thick section	yes	yes	no	no	15
NWA 8173	En-rich-achon ung	thick section	yes	yes	no	yes	39

Table 2.2: Major and minor phases observed by previous studies. “En-rich-achon ung” means “an enstatite-rich achondrite that is ungrouped”. “EH-imp melt” means “an enstatite chondrite of the EH group which has been impact melted”.

sample	phases	ref
EET 87746 (EH3)	clino-enstatite, olivine, metal, sulphides	Grossman (1994); Izawa et al. (2010)
Sahara 97103 (EH3)	enstatite, olivine, plagioclase, silica, metal, FeS, MgS, high-Ca pyroxene	Tanaka and Nakamura (2017)
MET 00783 (EH4)	enstatite, metal, sulphides	Russell et al. (2003); Izawa et al. (2010)
EET 96135 (EH5)	enstatite, silica, metal, FeS, MgS, (Fe,Cr)S	Grossman (1999); Izawa et al. (2010)
QUE 94204 (EH7)	enstatite, plagioclase, metal, FeS	Grossman and Score (1996); Izawa et al. (2010)
LAP 02225 (EH imp melt)	enstatite, plagioclase, metal, FeS, MgS, (Fe,Cr)S, (Zn,Fe)S, evaporites/salts	Russell et al. (2004); Izawa et al. (2010); Hopp et al. (2021)
PCA 91020 (EL3)	enstatite, olivine, metal, sulphides	Wlotzka (1994); Izawa et al. (2010)
MAC 02837 (EL3)	enstatite, olivine, metal, evaporites/salts	Russell et al. (2004); Izawa et al. (2010)
MAC 02747 (EL4)	enstatite, metal, sulphides	Russell et al. (2005); Izawa et al. (2010)
TIL 91714 (EL5)	enstatite, metal, sulphides	Wlotzka (1994); Izawa et al. (2010)
ALHA 81021 (EL6)	enstatite, metal, plagioclase, sinoite	Wlotzka (1994); Izawa et al. (2010)
Zaklodzie (En-rich-achon ung)	ortho-enstatite, silica, metal, feldspathic impurities, FeS, Fe ₃ P, CaS, MnS, amphibole, graphite	Grossman (2000); Uribe et al. (2017)
NWA 4301 (En-rich-achon ung)	enstatite, silica, metal, FeS, other sulphides, plagioclase, graphite	Uribe et al. (2017)
NWA 8173 (En-rich-achon ung)	ortho-enstatite, silica, metal, feldspathic impurities, FeS, (Fe,Mg)S	Uribe et al. (2017)

Table 2.3: Major and minor phases observed in this study: “En-rich-achon ung” means “an enstatite-rich achondrite that is ungrouped”. “EH-imp melt” means “an enstatite chondrite of the EH group which has been impact melted”.

sample	major phases	minor phases
EET 87746 (EH3)	enstatite, olivine, Na-rich glass, silica, metal, FeS	MgS, CaS, CrS
Sahara 97103 (EH3)	enstatite, olivine, Na-rich glass	silica, K-rich glass, metal, FeS, MgS, CaS, high-Ca pyroxene, FeO-rich pyroxene
MET 00783 (EH4)	enstatite, Na-rich glass, silica, metal, FeS	olivine, silica, MgS, CaS, CrS
EET 96135 (EH5)	enstatite, Na-rich plagioclase, silica, metal, FeS	MgS, CaS
QUE 94204 (EH7)	enstatite, Na-rich plagioclase, metal, FeS	silica, K-rich plagioclase, CrS
LAP 02225 (EH impact melt)	enstatite, Na-rich plagioclase, silica, metal, FeS	Si,Ni-rich material, MgS, CrS, schreibersite
MAC 02837 (EL3)	enstatite, Na-rich glass, metal, FeS	olivine, silica, MgS, CaS, schreibersite
PCA 91020 (EL3)	enstatite, Na-rich glass, silica, metal, FeS	olivine, spinel, MgS, CaS, schreibersite
MAC 02747 (EL4)	enstatite, Na-rich glass, silica, metal, FeS	olivine, CaS, CrS, schreibersite
TIL 91714 (EL5)	enstatite, Na-rich plagioclase, metal, FeS	silica, alabandite, CaS, CrS, schreibersite
ALHA 81021 (EL6)	enstatite, Na-rich plagioclase, metal, FeS	silica, alabandite, CaS, CrS, schreibersite
Zaklodzie (Enstatite-achondrite ungrouped)	enstatite, Na-rich plagioclase, metal, FeS	silica, alabandite, Al-rich material
NWA 4301 (Enstatite-achondrite ungrouped)	enstatite, Na-rich plagioclase, metal	silica, FeS
NWA 8173 (Enstatite-achondrite ungrouped)	enstatite, Na-rich plagioclase, metal, alabandite	silica, schreibersite, Al-rich material

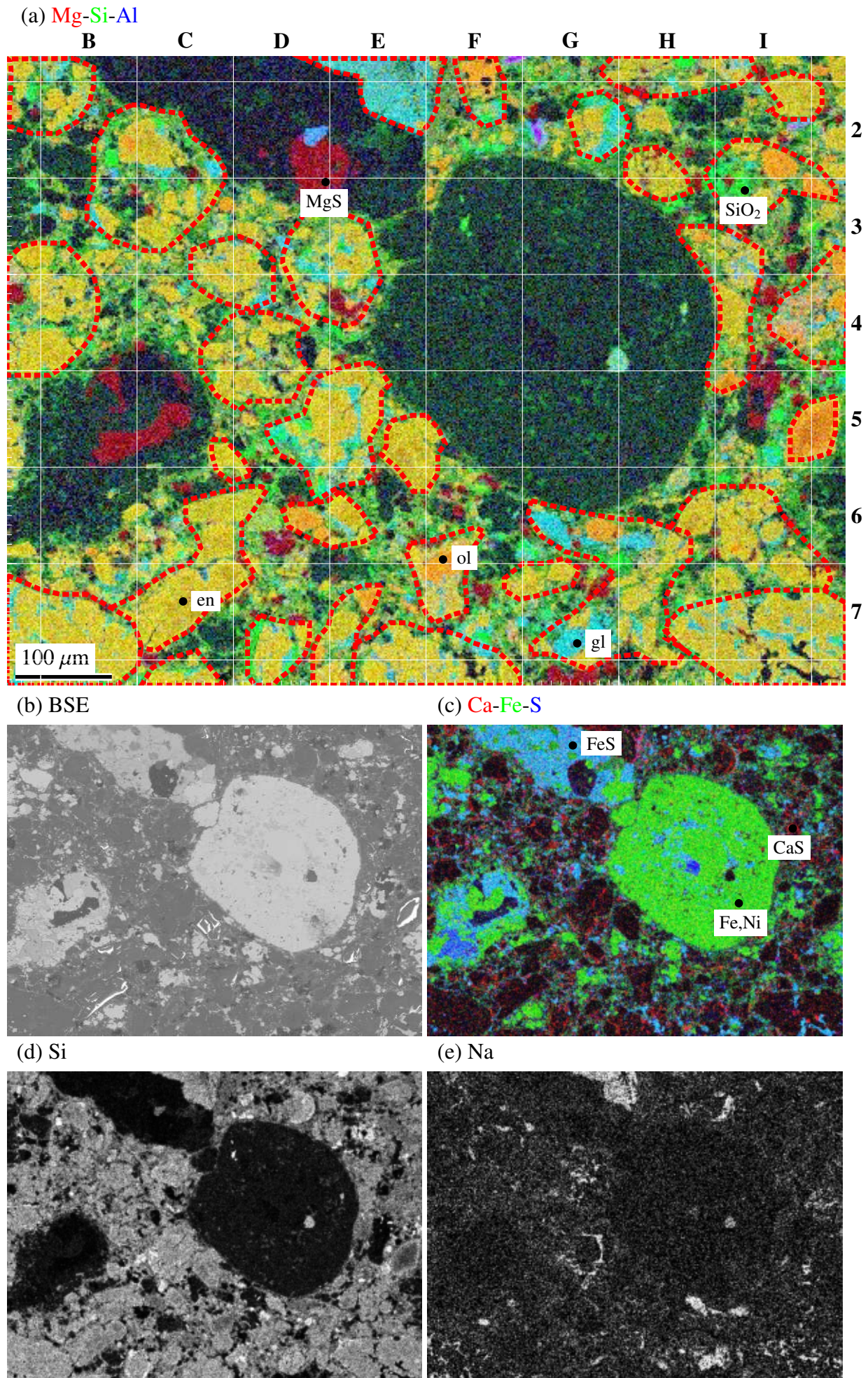


Figure 2.1: Site-1 of EET 87746 (EH3). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown.

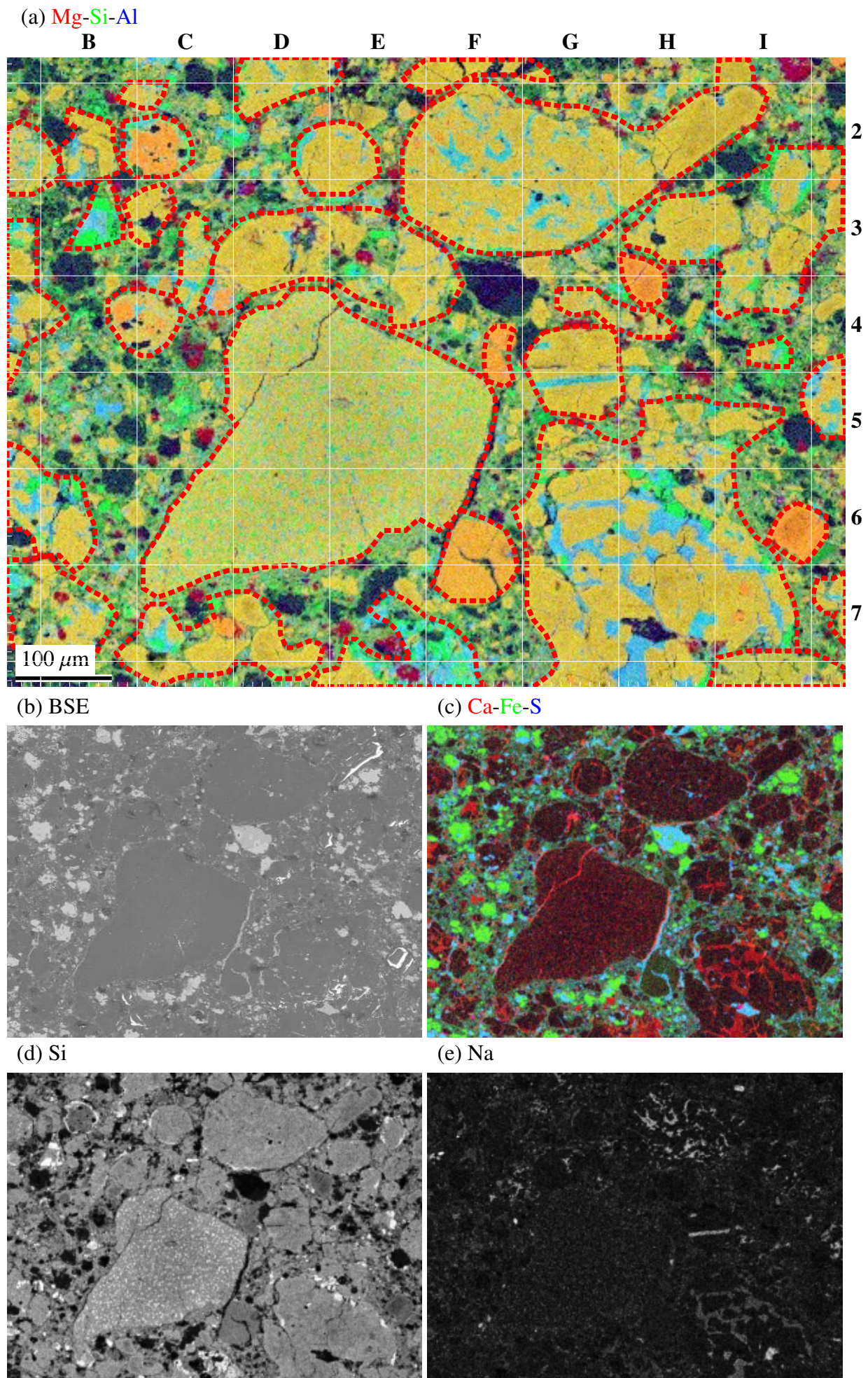


Figure 2.2: Site-2 of EET87746 (EH3). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.1.

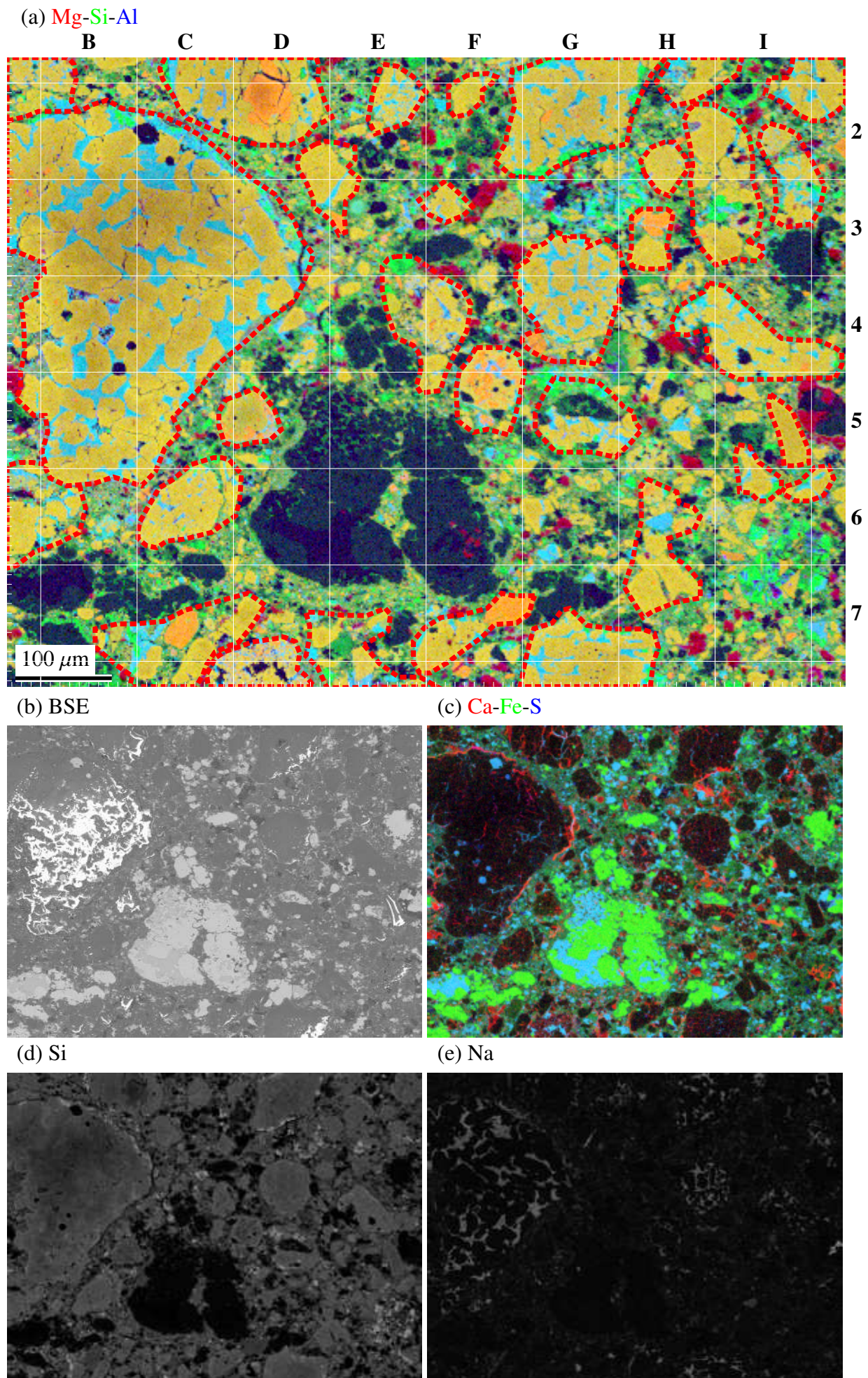


Figure 2.3: Site-3 of EET87746 (EH3). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.1.

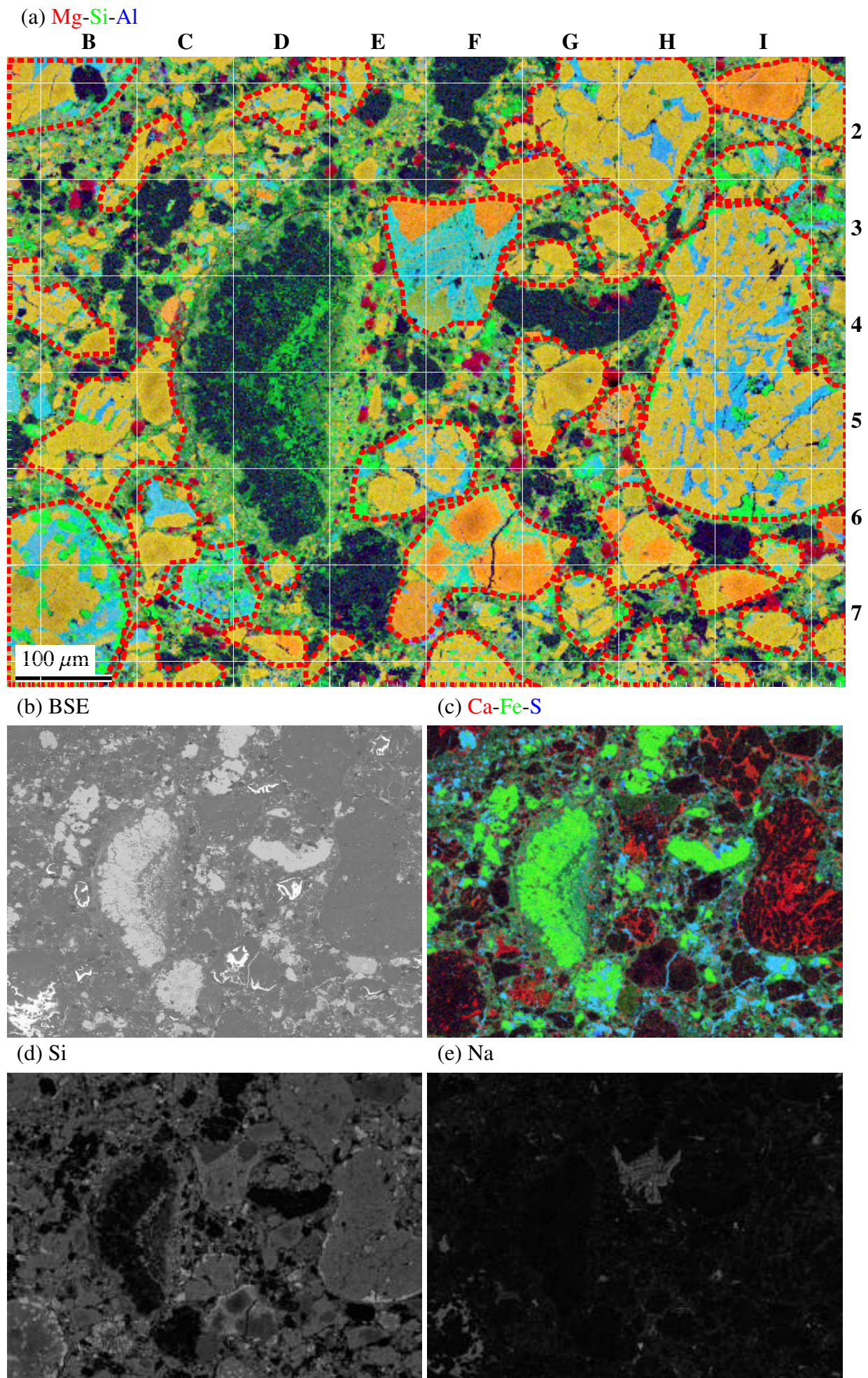


Figure 2.4: Site-4 of EET87746 (EH3). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.1.

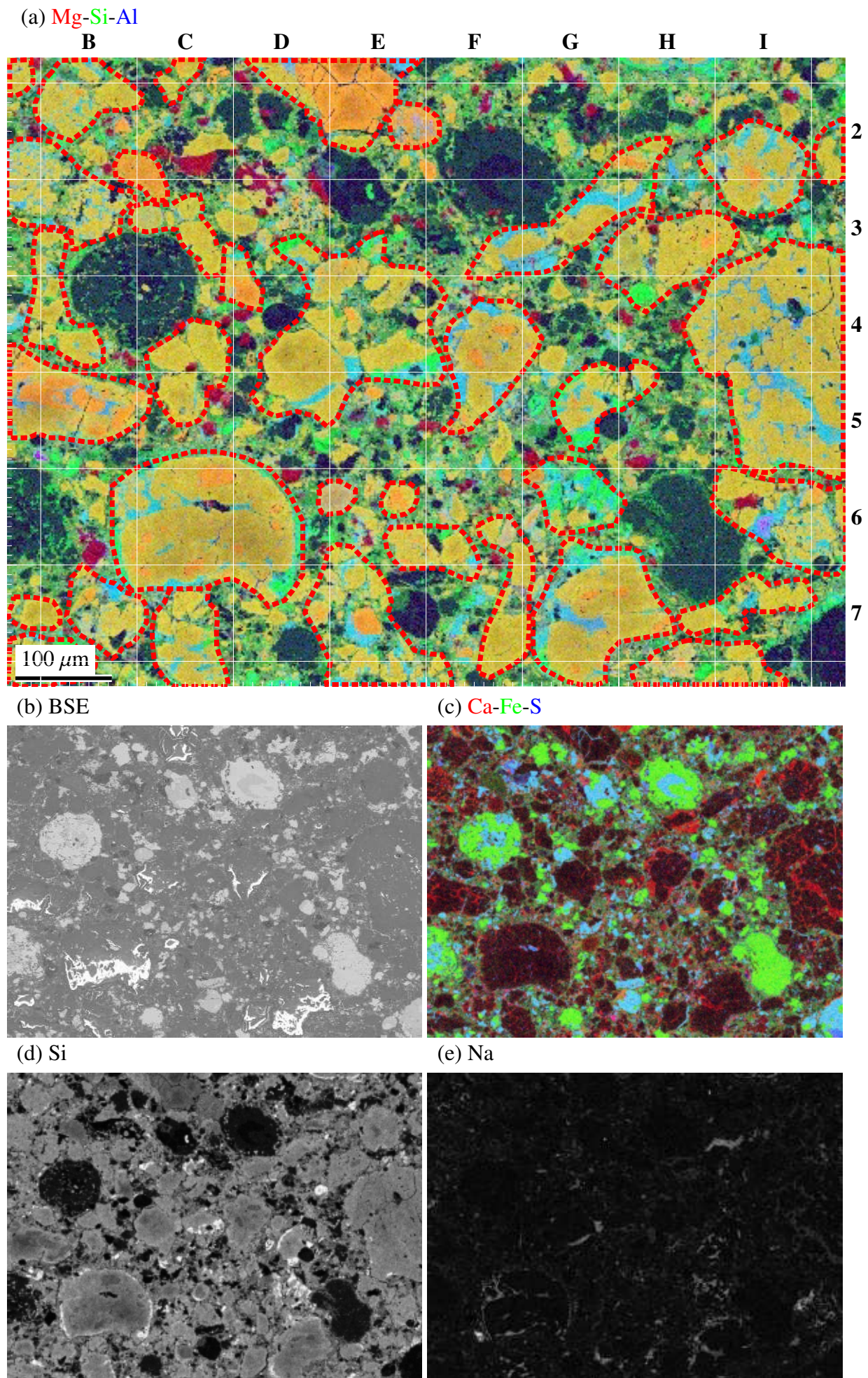


Figure 2.5: Site-5 of EET87746 (EH3). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.1.

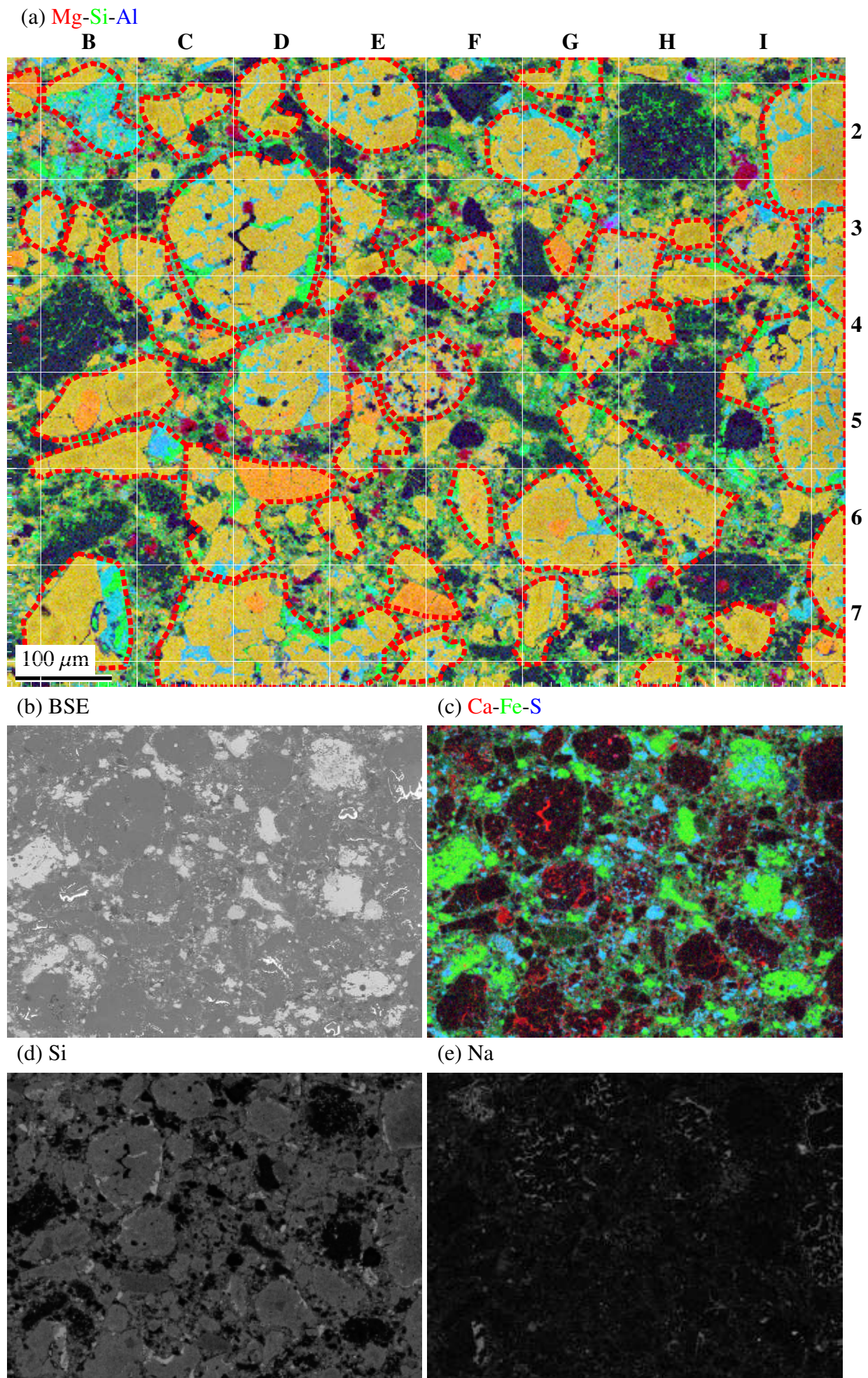


Figure 2.6: Site-6 of EET87746 (EH3). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.1.

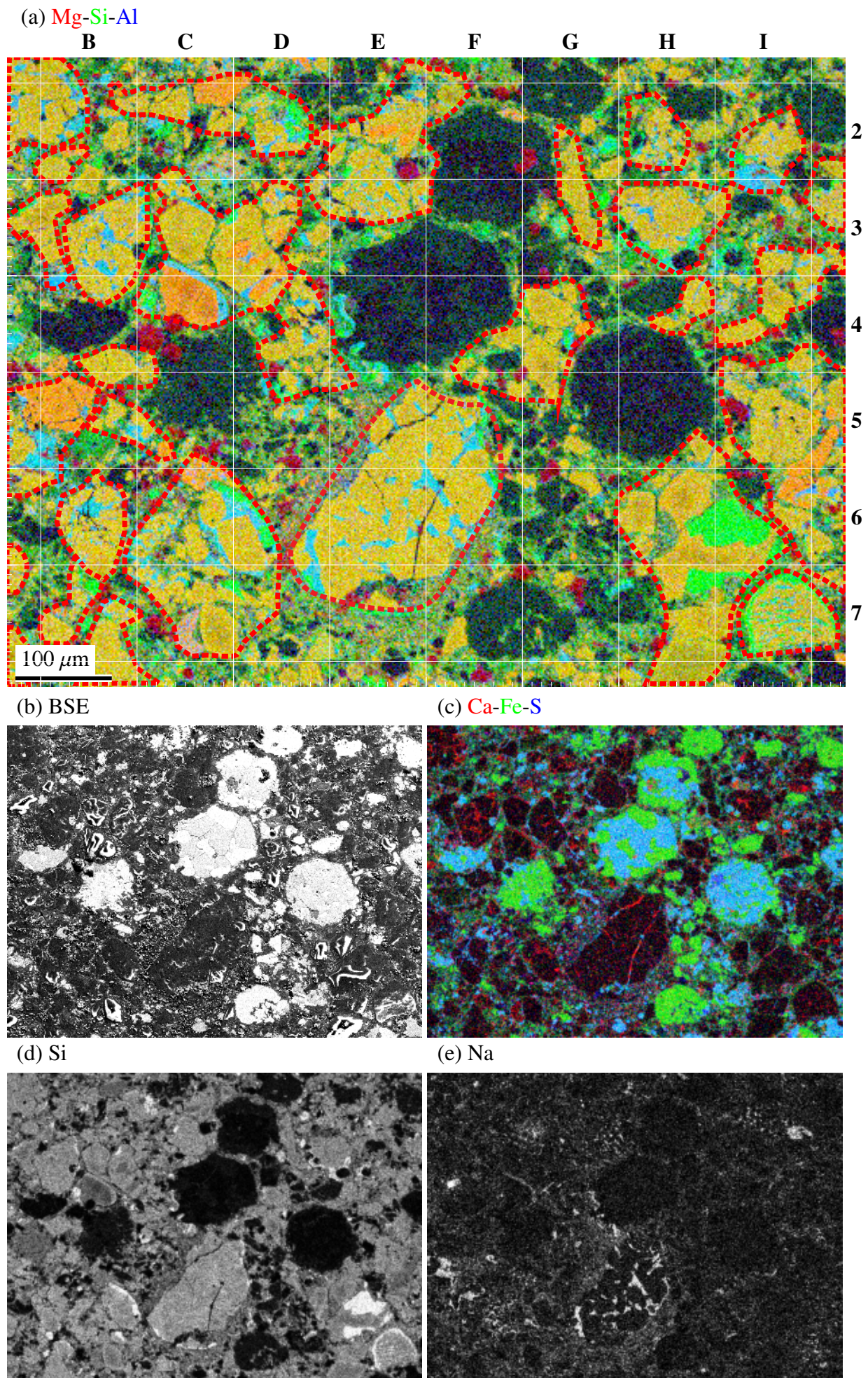


Figure 2.7: Site-7 of EET87746 (EH3). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.1.

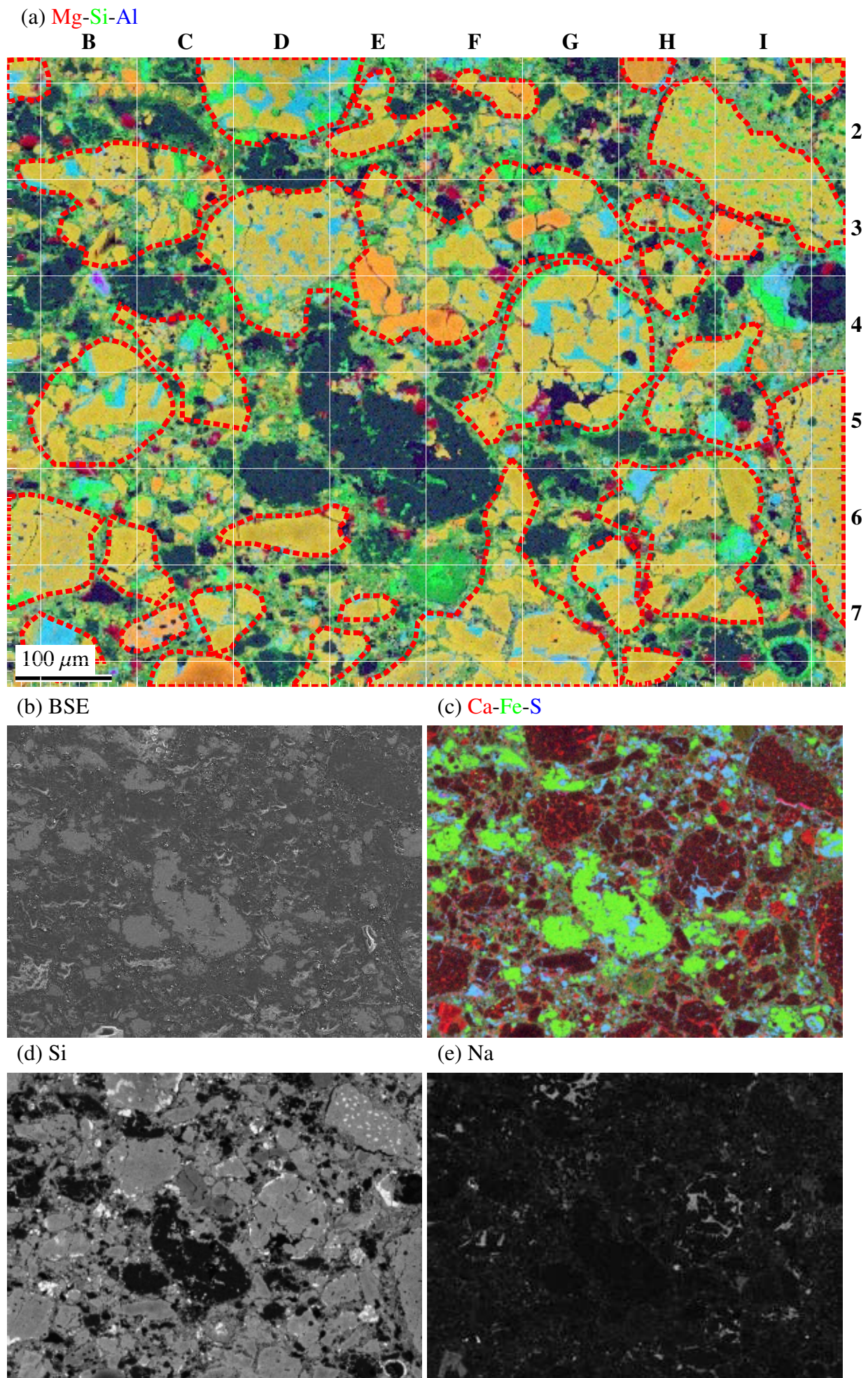


Figure 2.8: Site-8 of EET87746 (EH3). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.1.

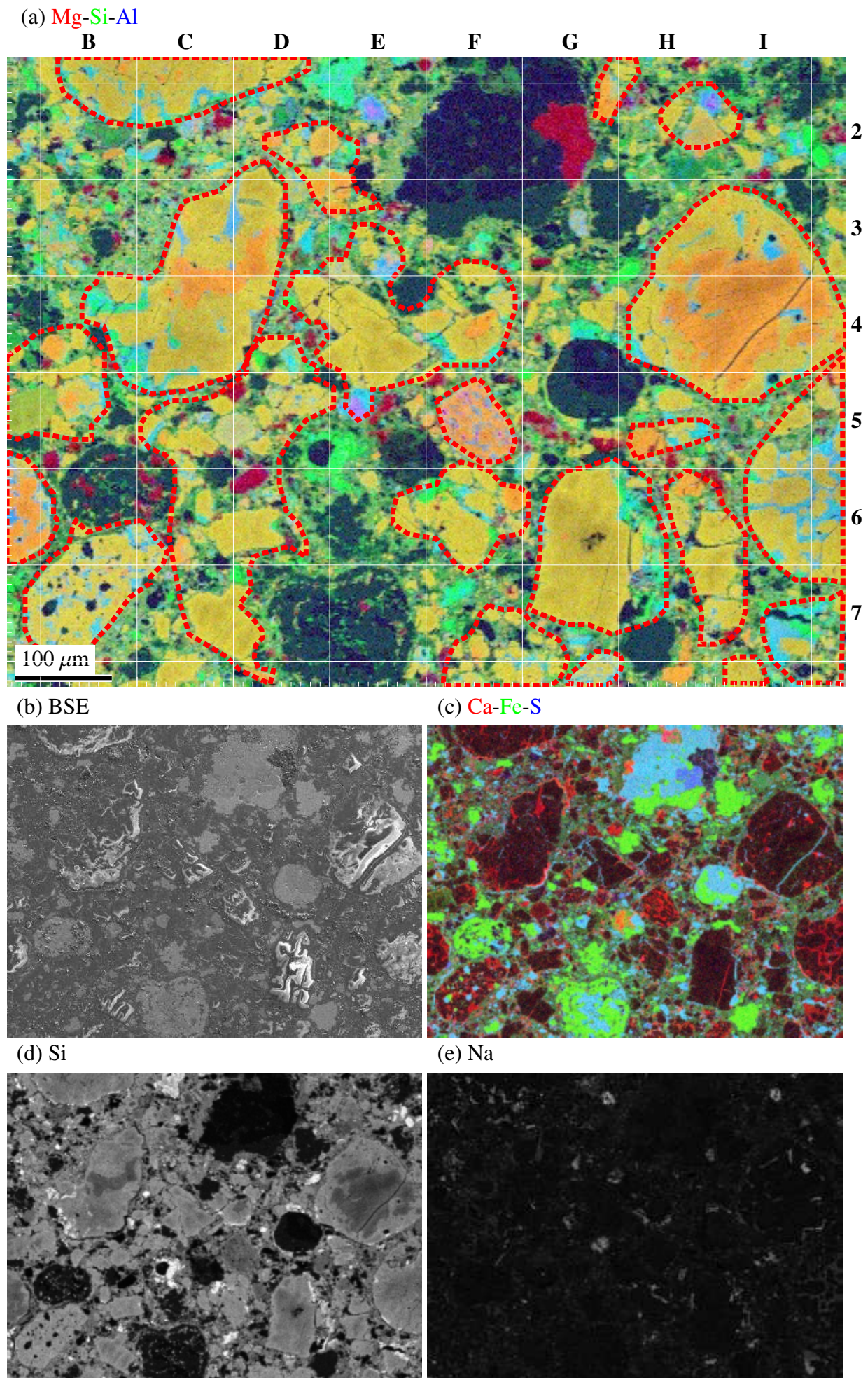


Figure 2.9: Site-9 of EET87746 (EH3). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.1.

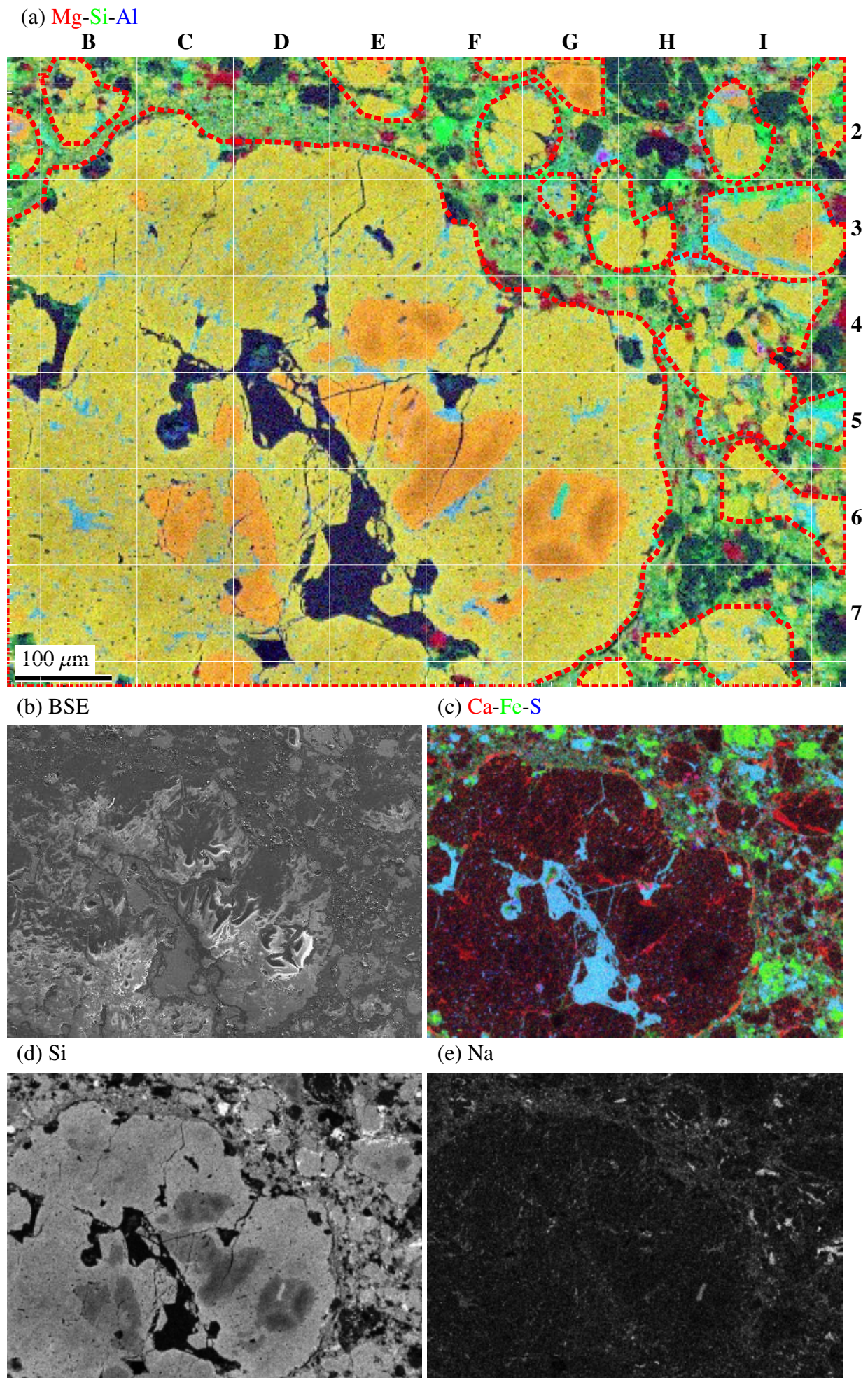


Figure 2.10: Site-10 of EET87746 (EH3). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.1.

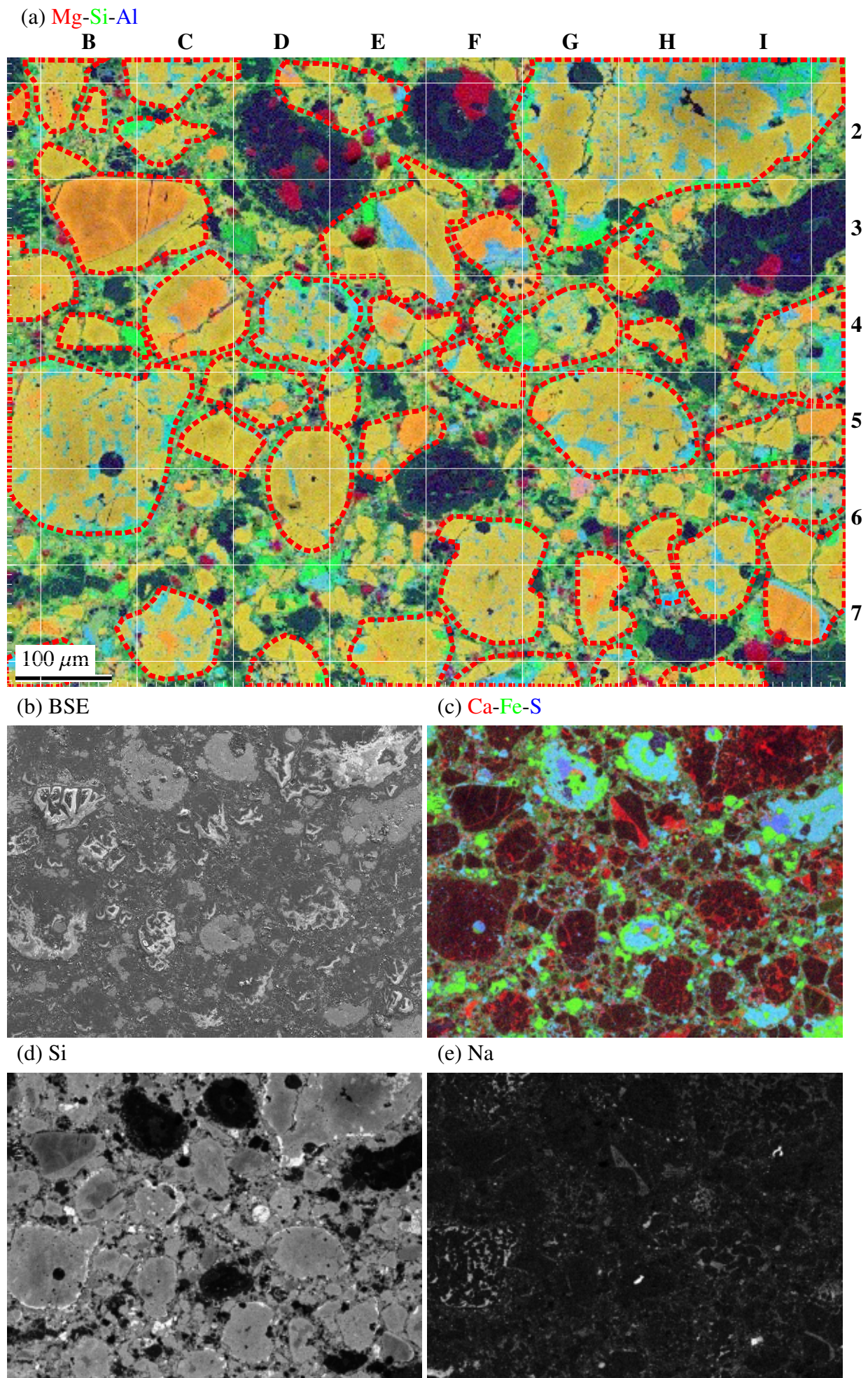


Figure 2.11: Site-11 of EET87746 (EH3). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.1.

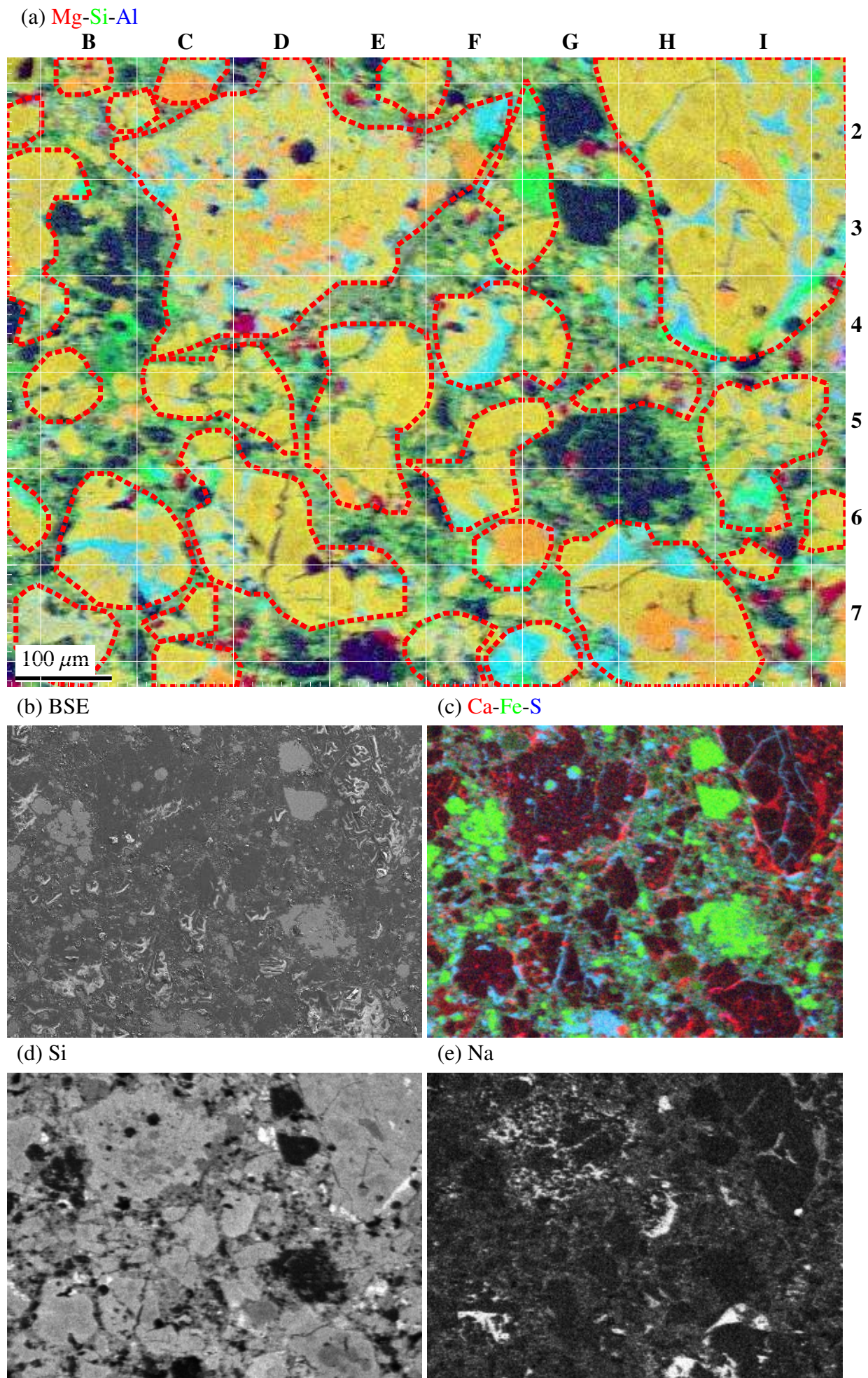


Figure 2.12: Site-12 of EET87746 (EH3). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.1.

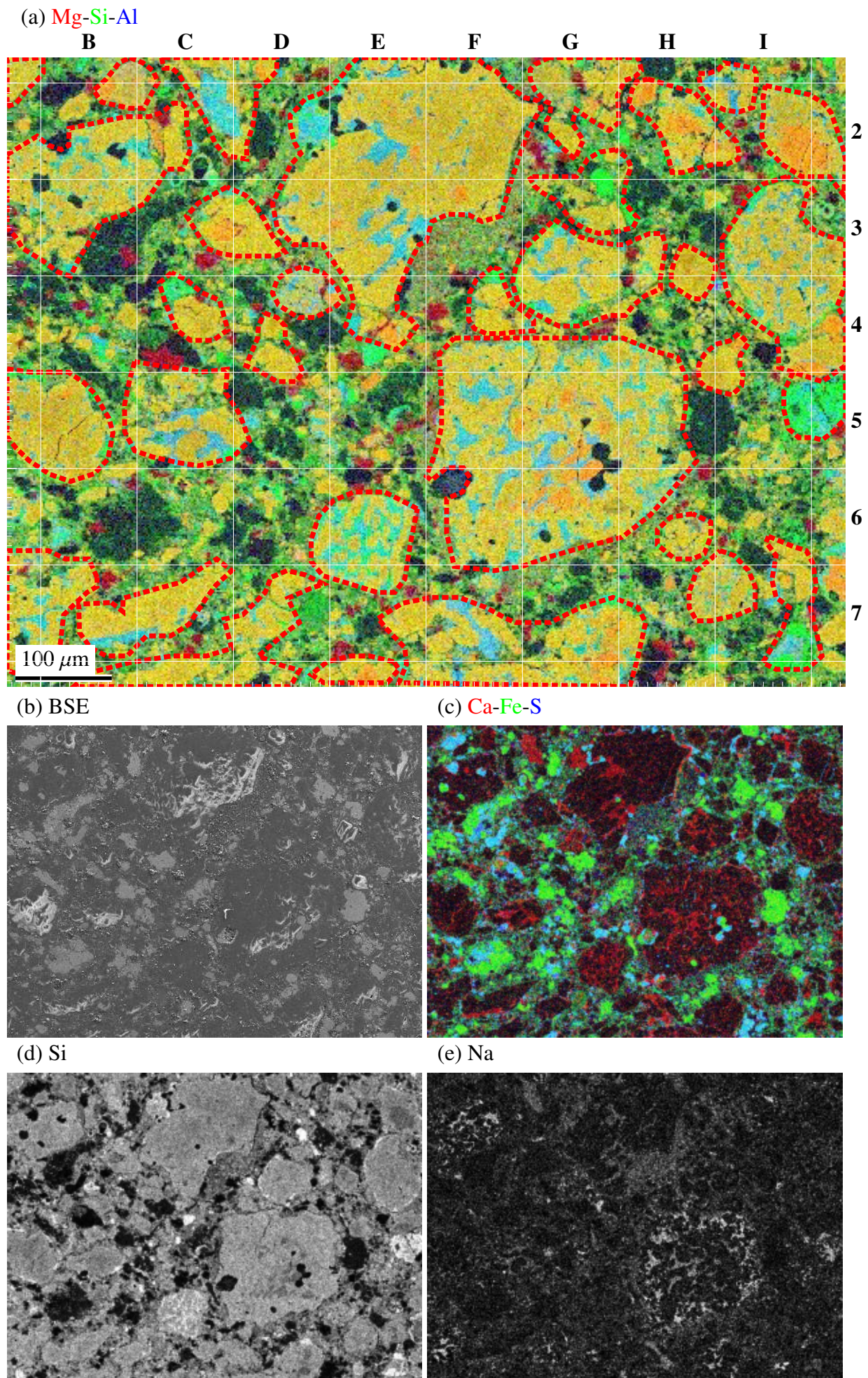


Figure 2.13: Site-13 of EET87746 (EH3). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.1.

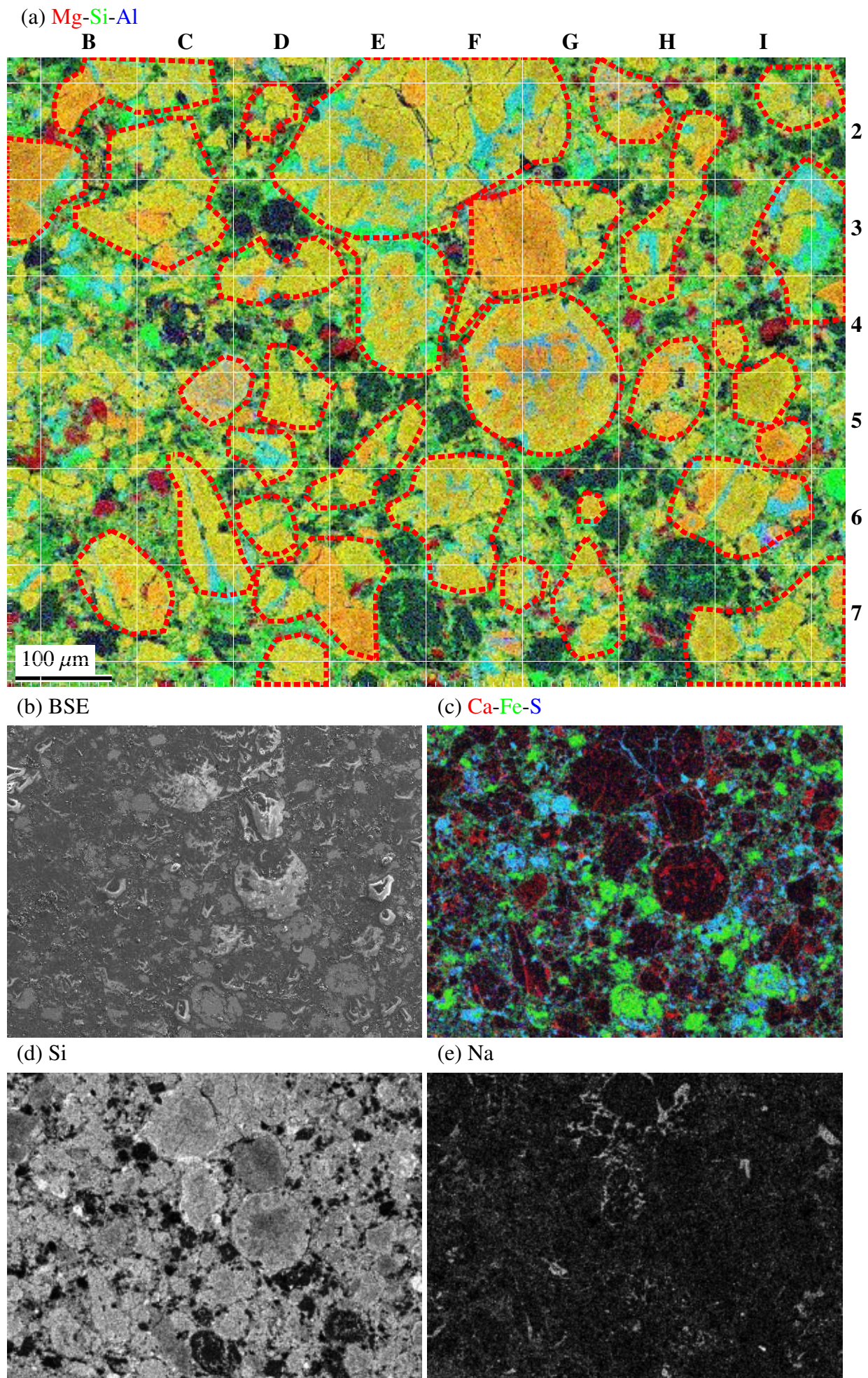


Figure 2.14: Site-14 of EET87746 (EH3). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.1.

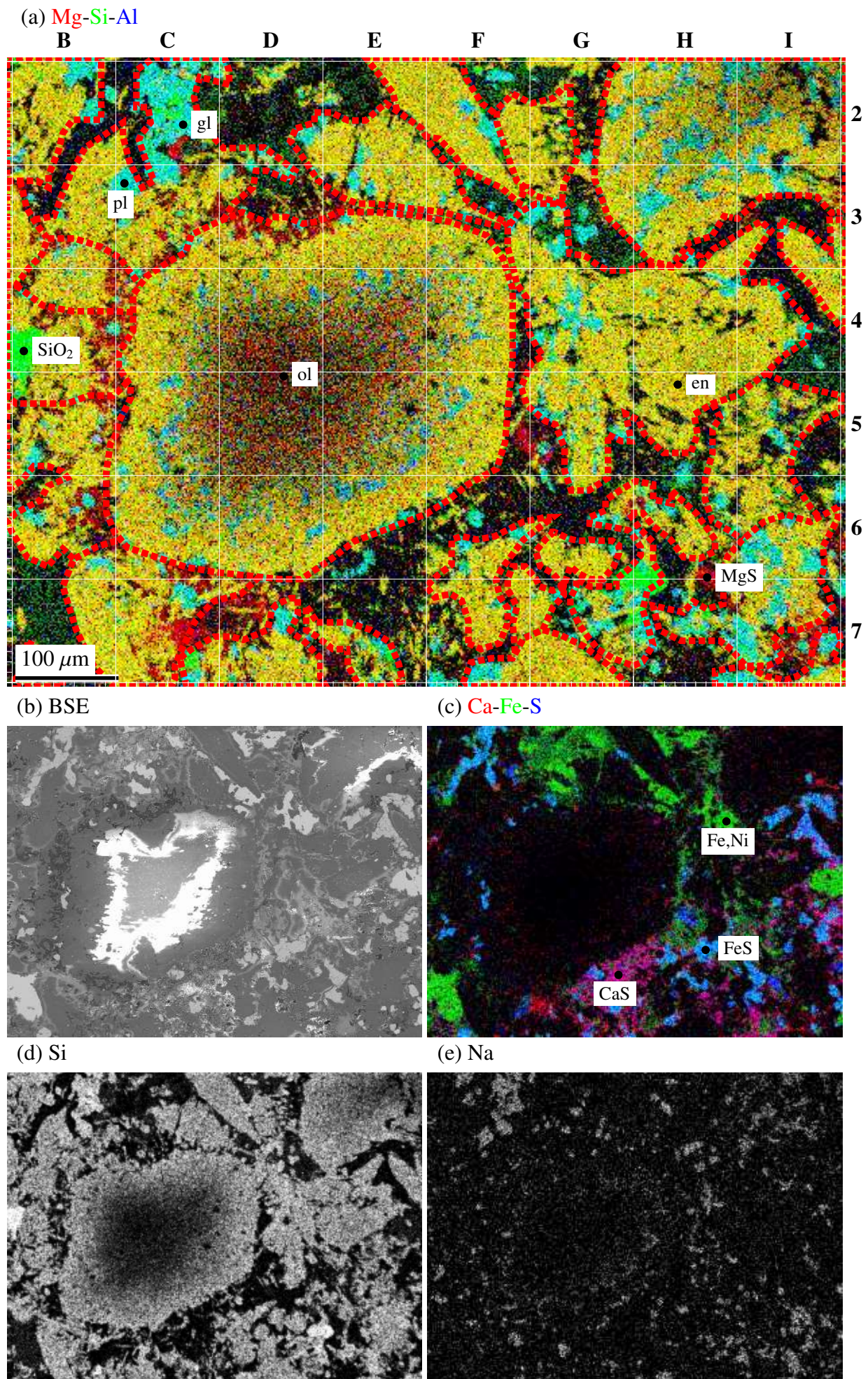


Figure 2.15: Site-1 of MET00783 (EH4). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown.

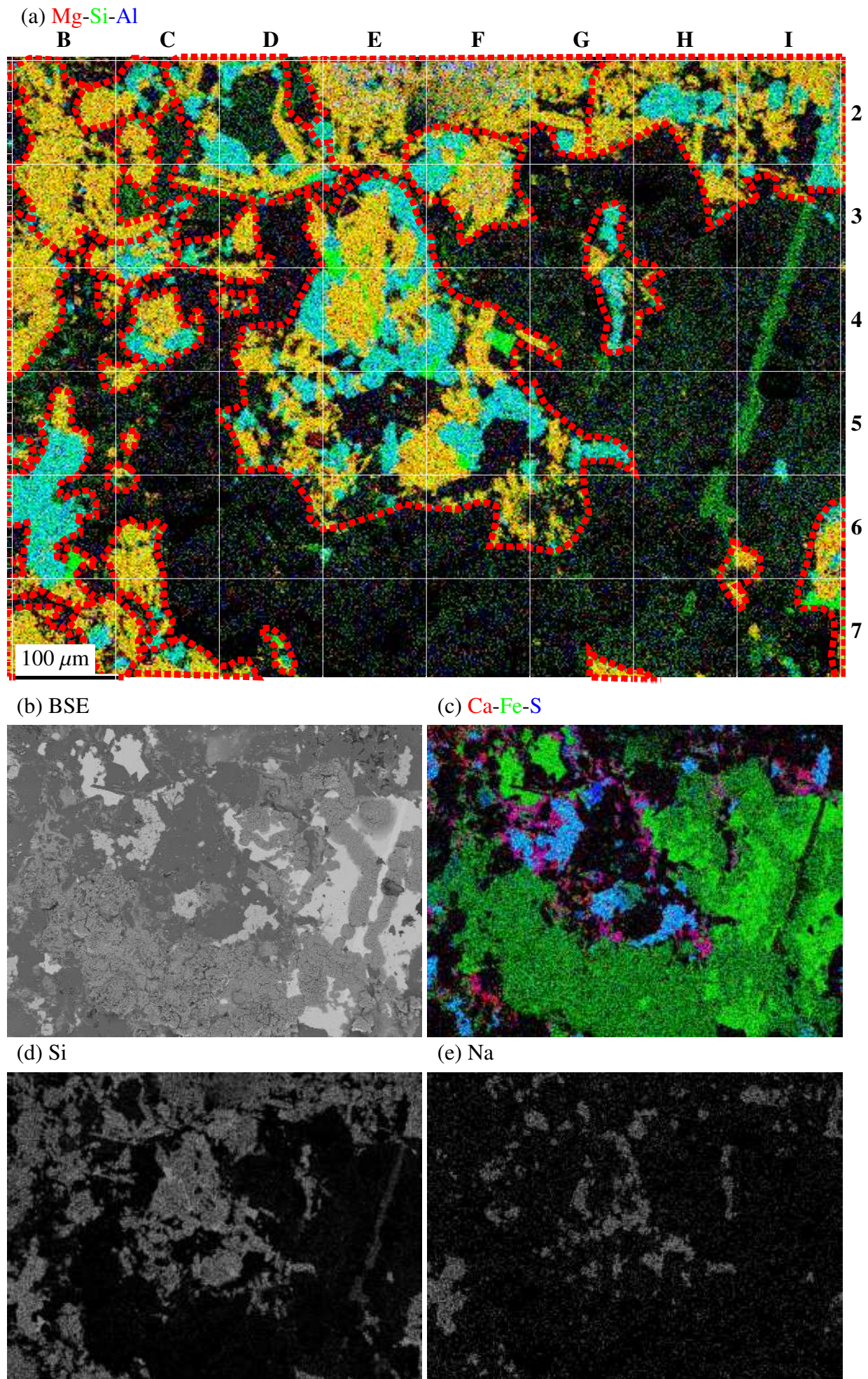


Figure 2.16: Site-2 of MET00783 (EH4). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.15.

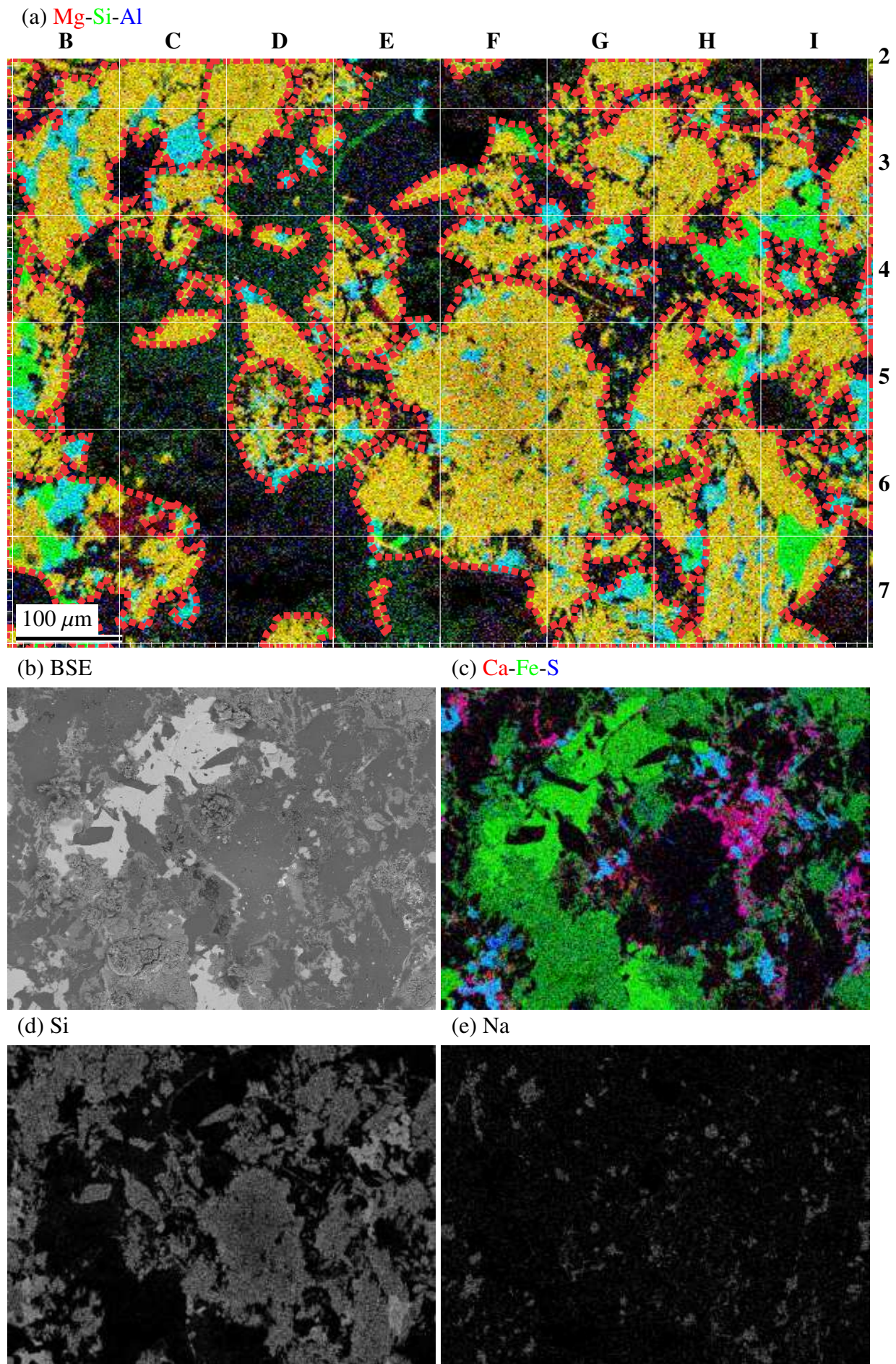


Figure 2.17: Site-3 of MET00783 (EH4). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.15.

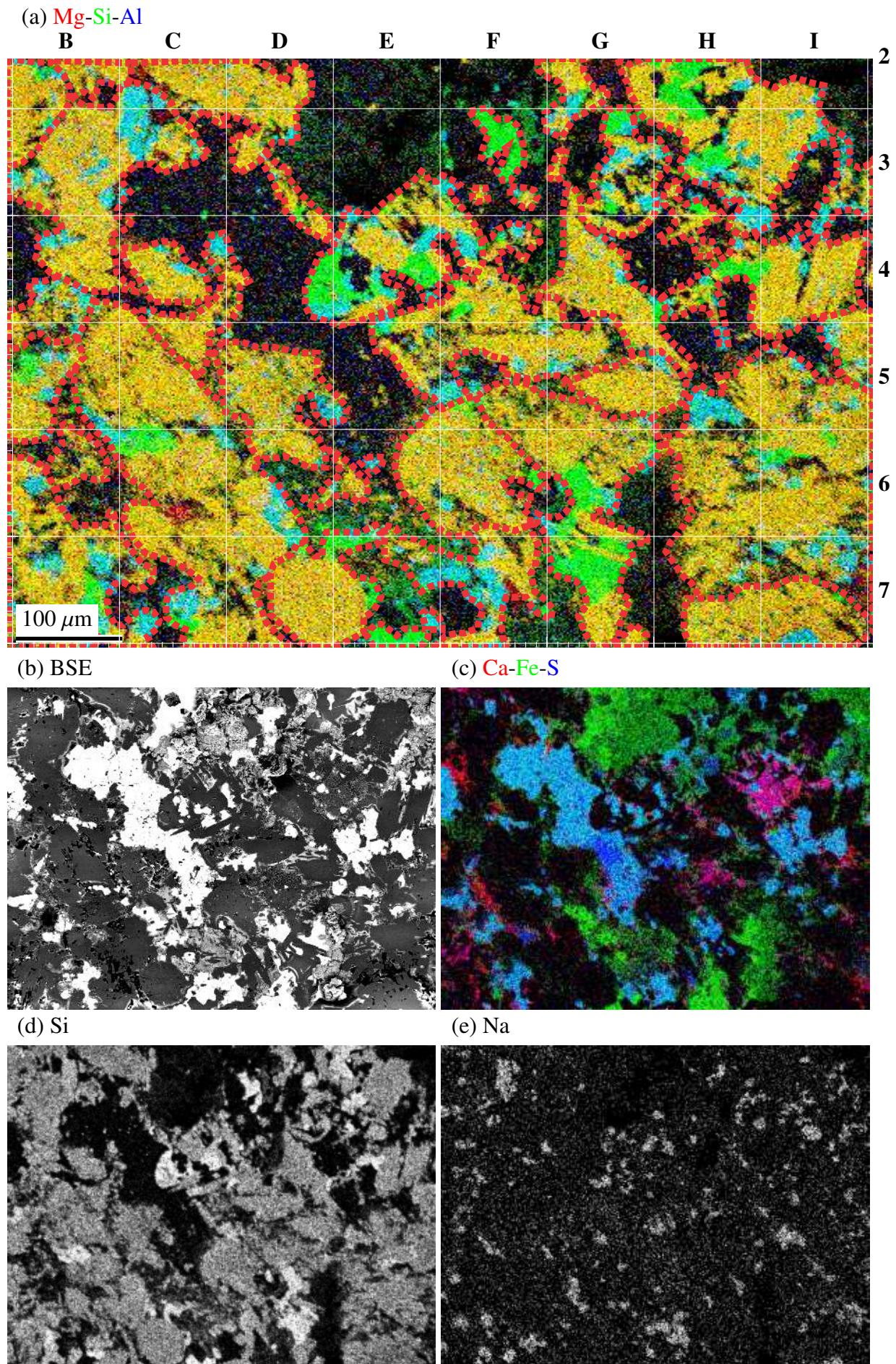


Figure 2.18: Site-4 of MET00783 (EH4). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.15.

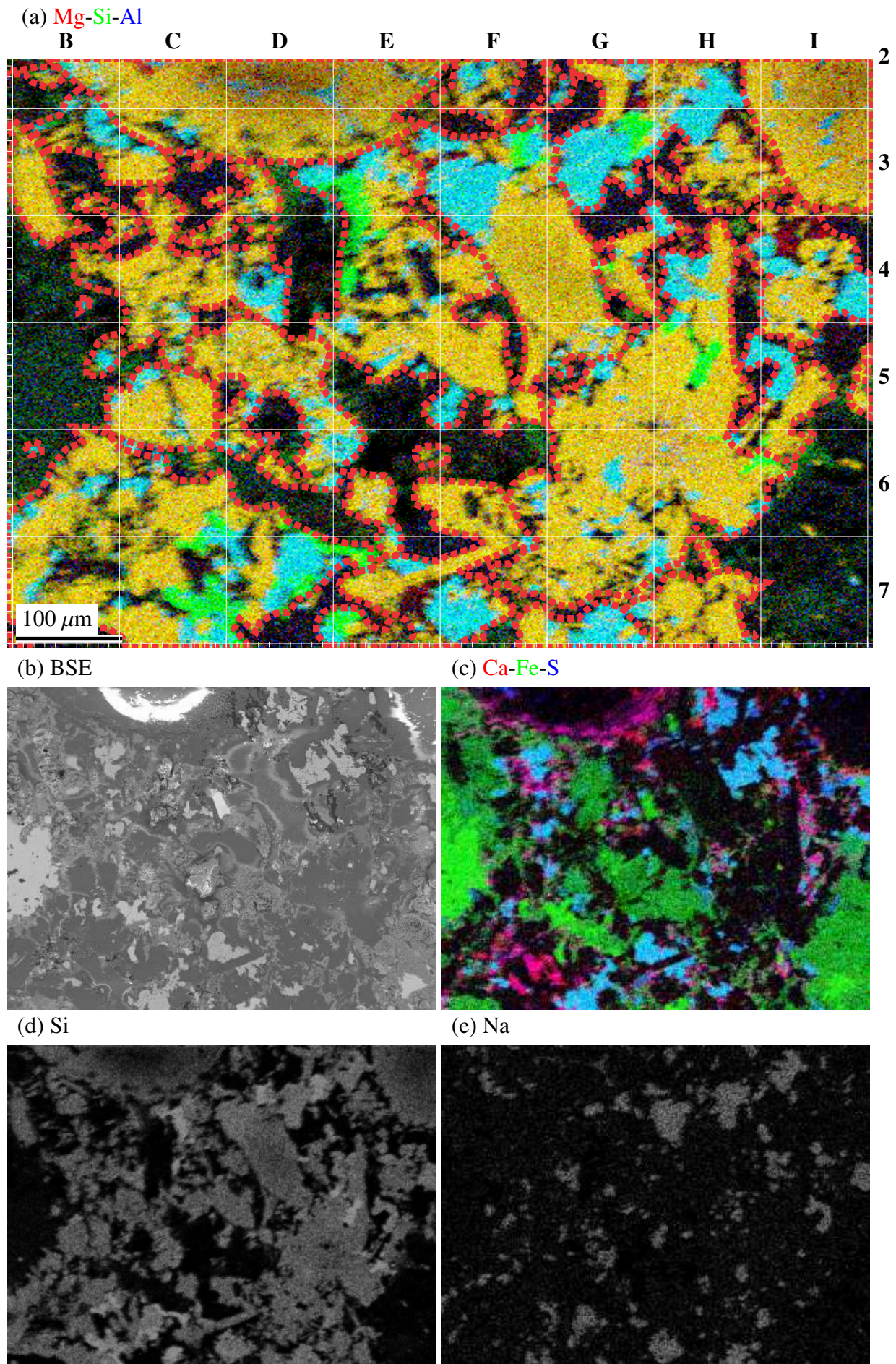


Figure 2.19: Site-5 of MET00783 (EH4). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.15.

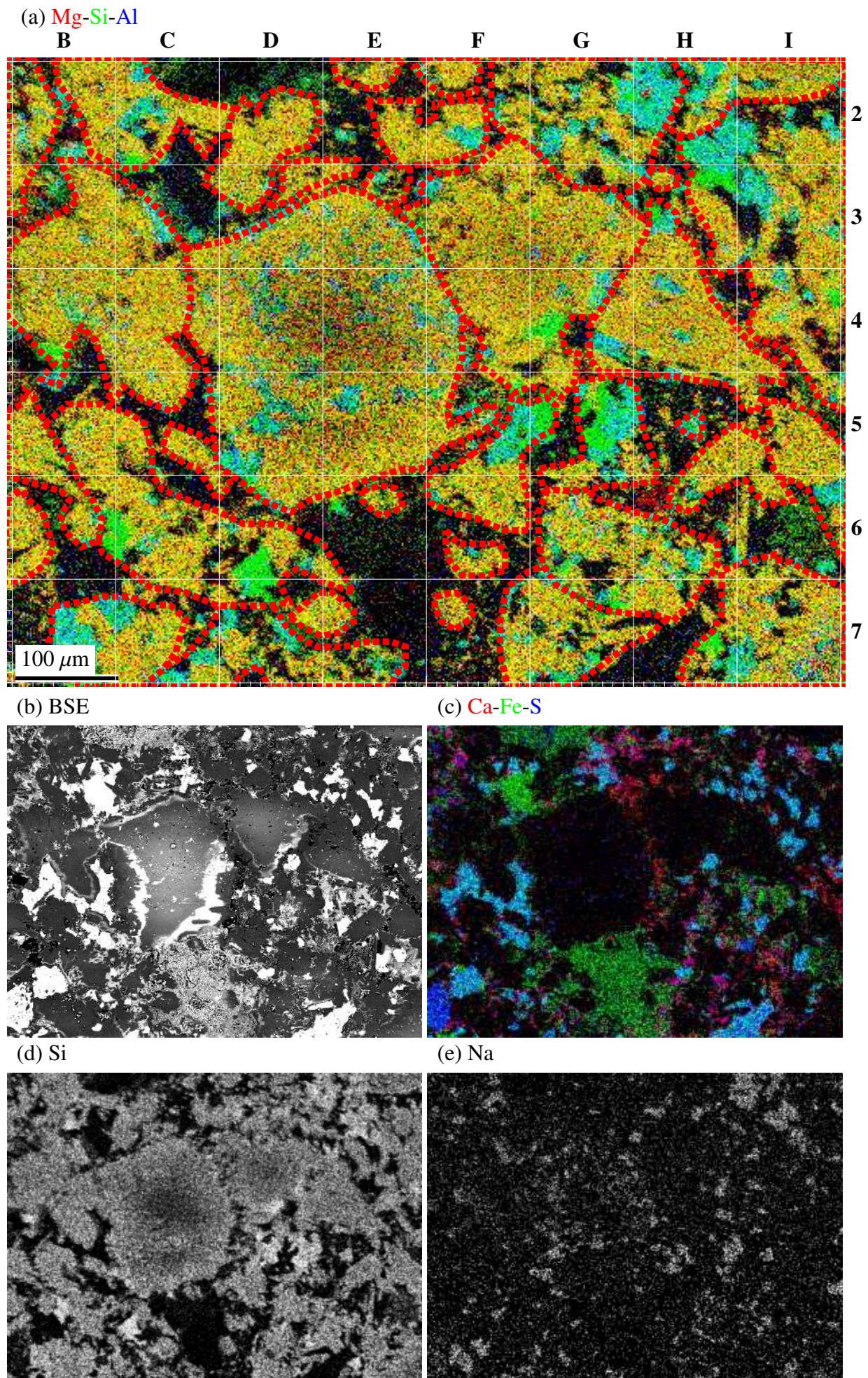


Figure 2.20: Site-6 of MET00783 (EH4). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.15.

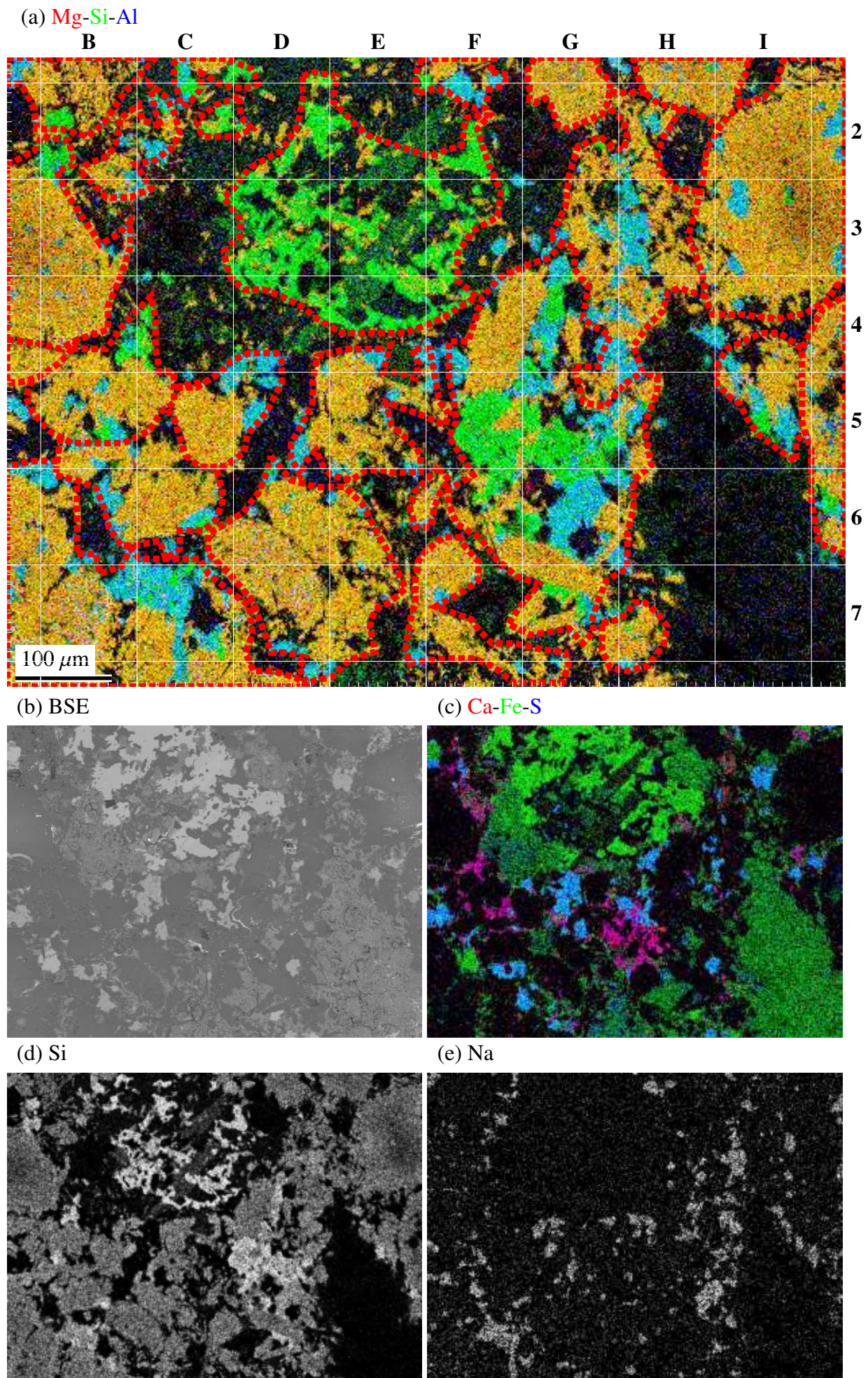


Figure 2.21: Site-7 of MET00783 (EH4). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.15.

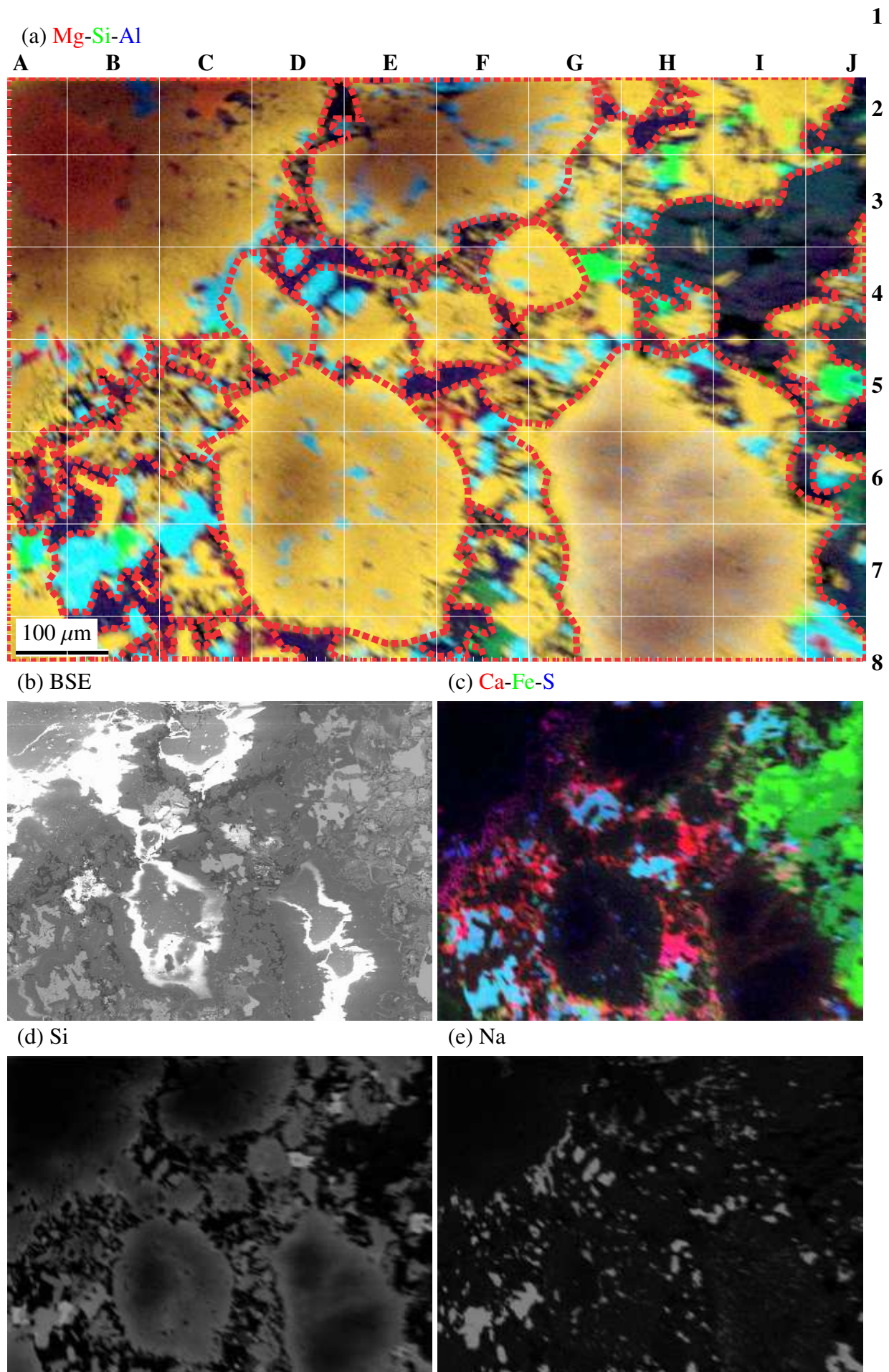


Figure 2.22: Site-8 of MET00783 (EH4). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.15.

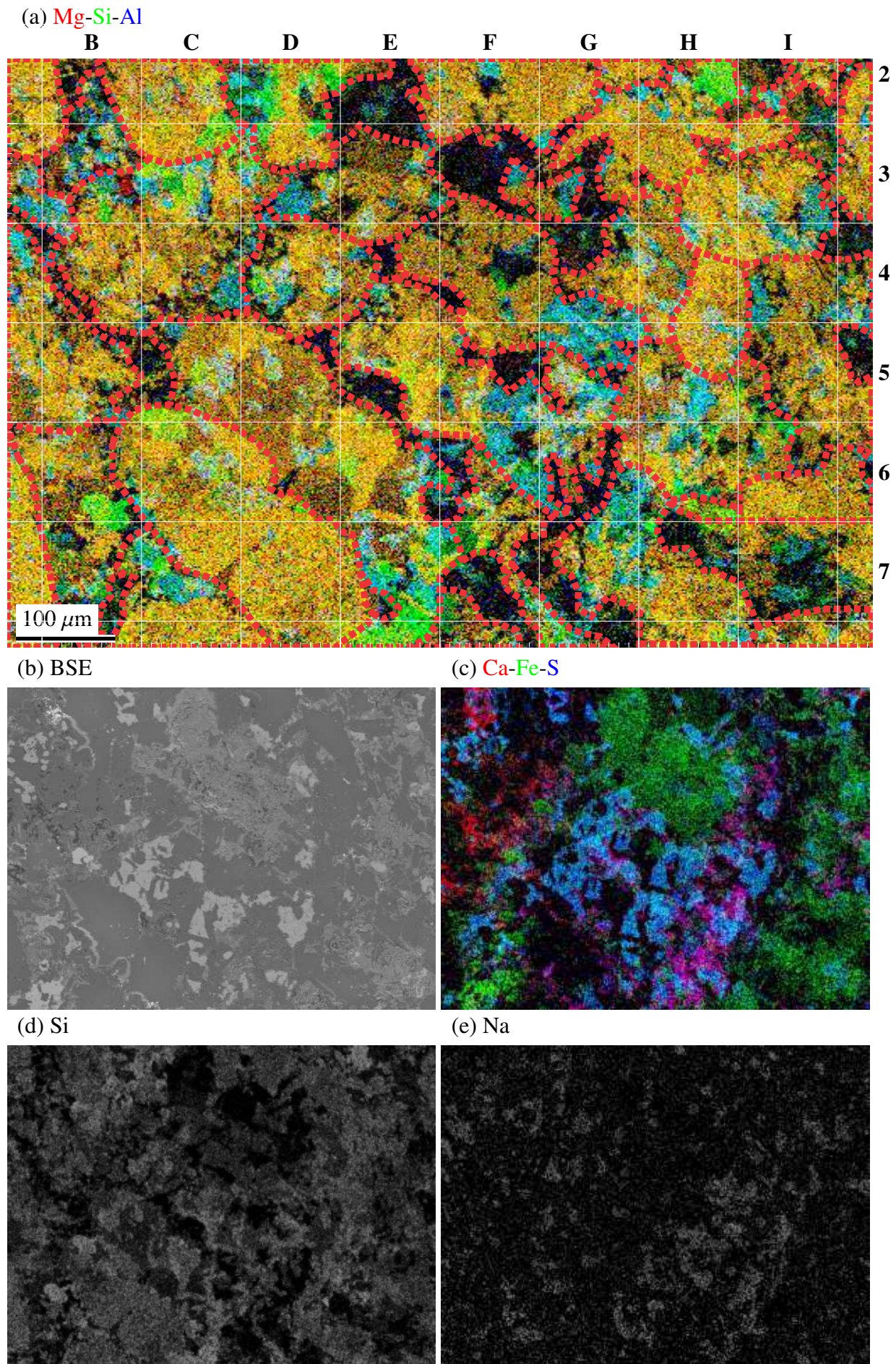


Figure 2.23: Site-9 of MET00783 (EH4). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.15.

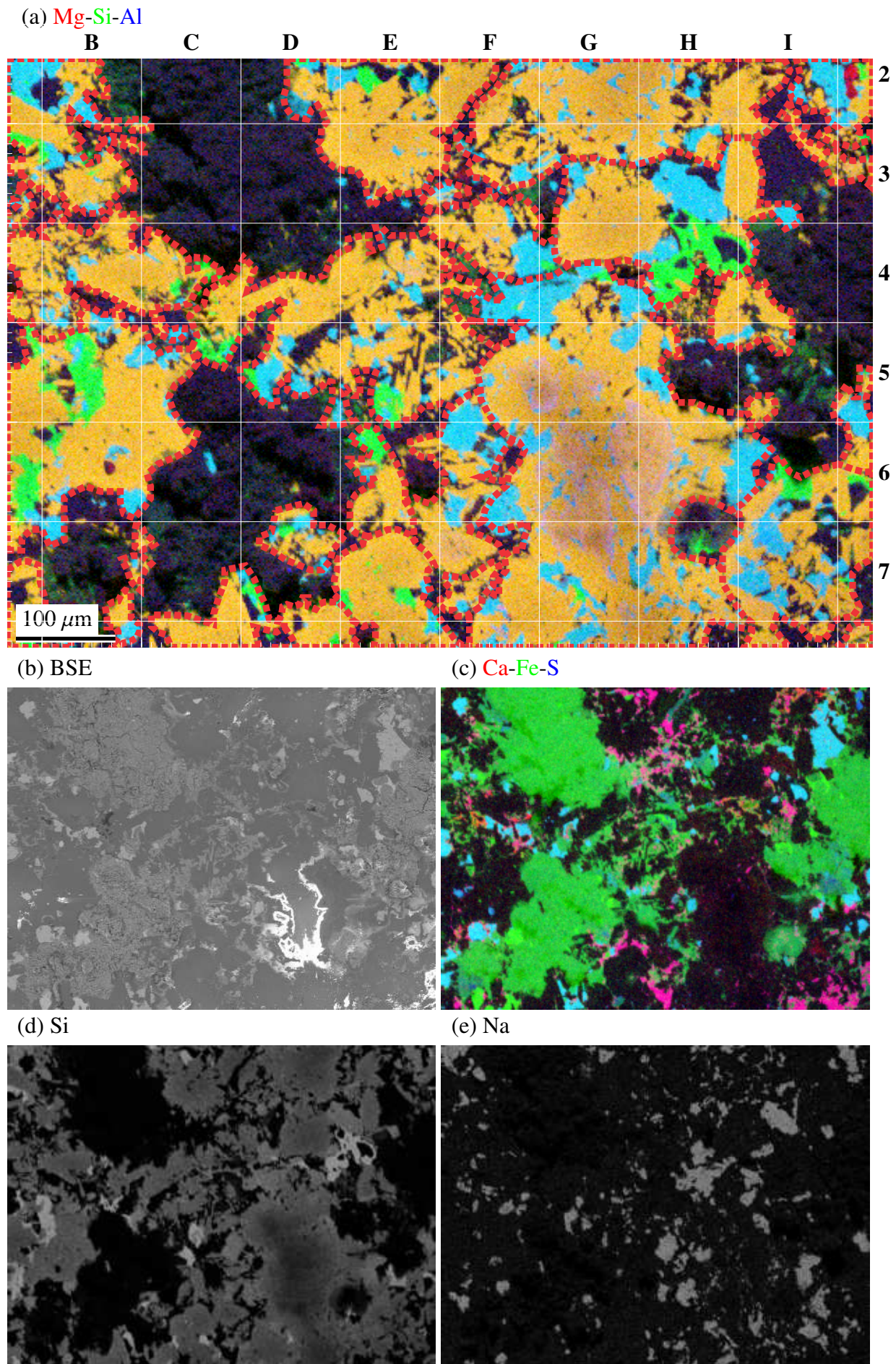


Figure 2.24: Site-10 of MET00783 (EH4). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.15.

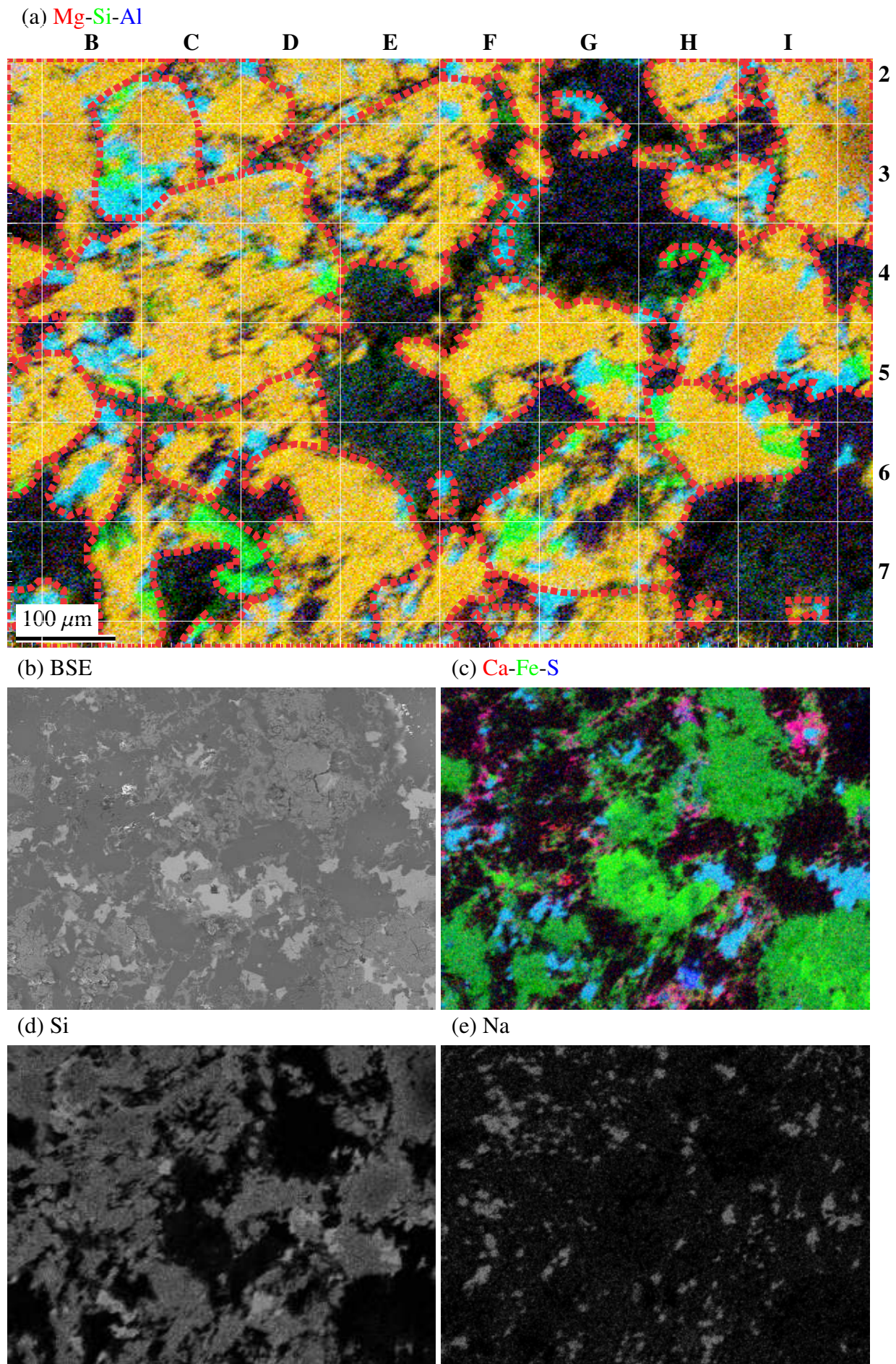


Figure 2.25: Site-11 of MET00783 (EH4). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.15.

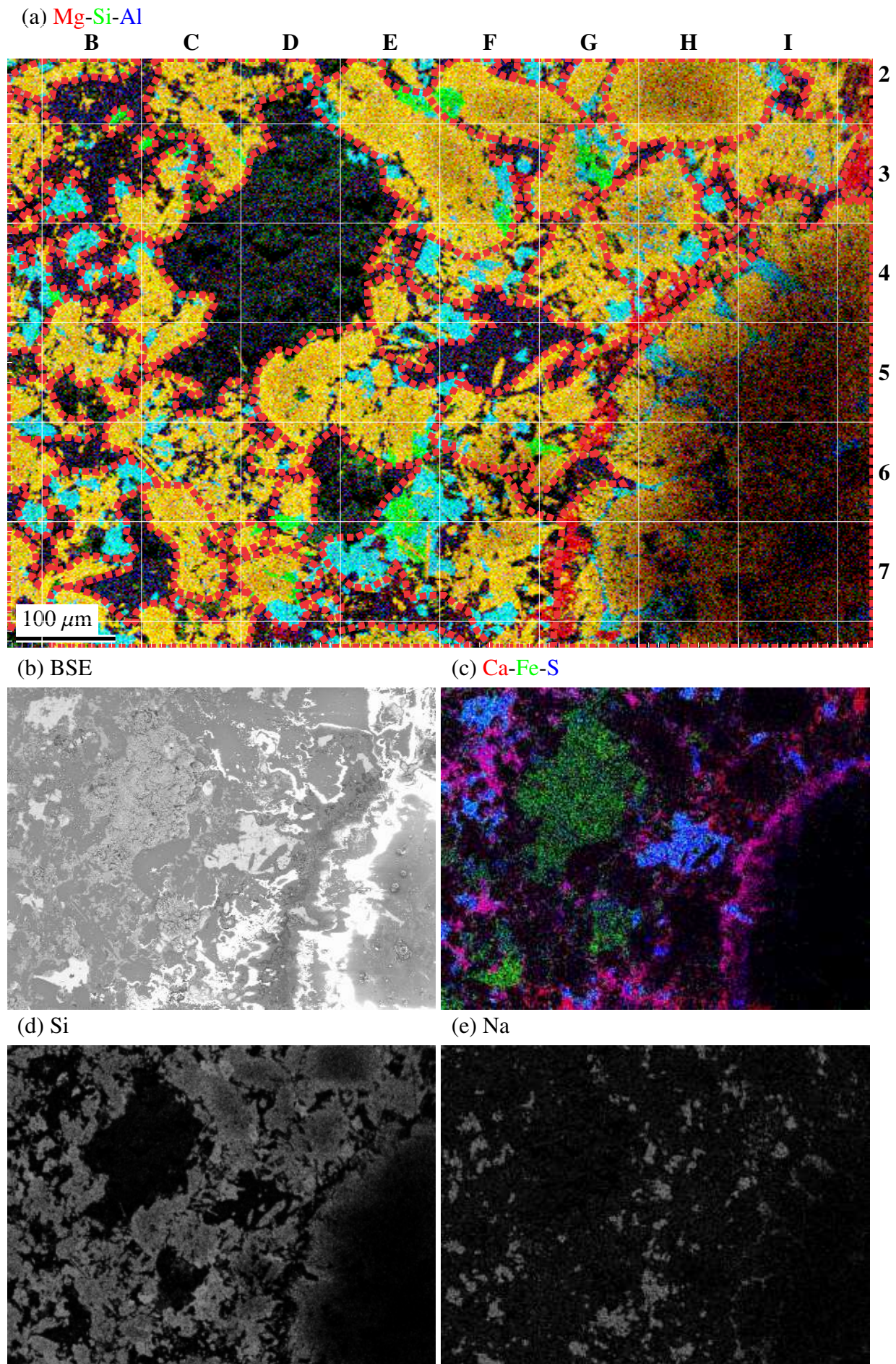


Figure 2.26: Site-12 of MET00783 (EH4). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.15.

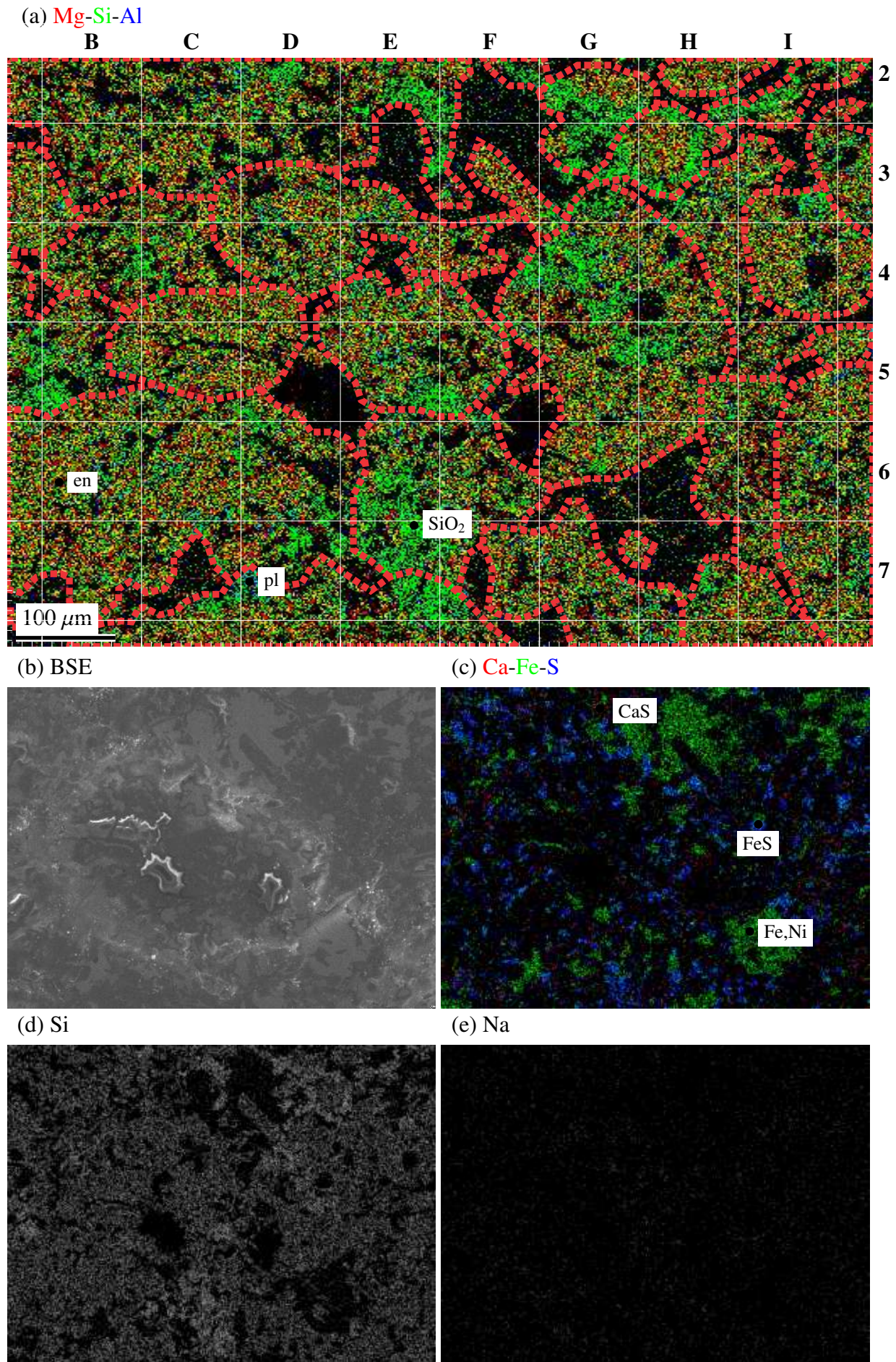


Figure 2.27: Site-1 of EET96135 (EH5). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown.

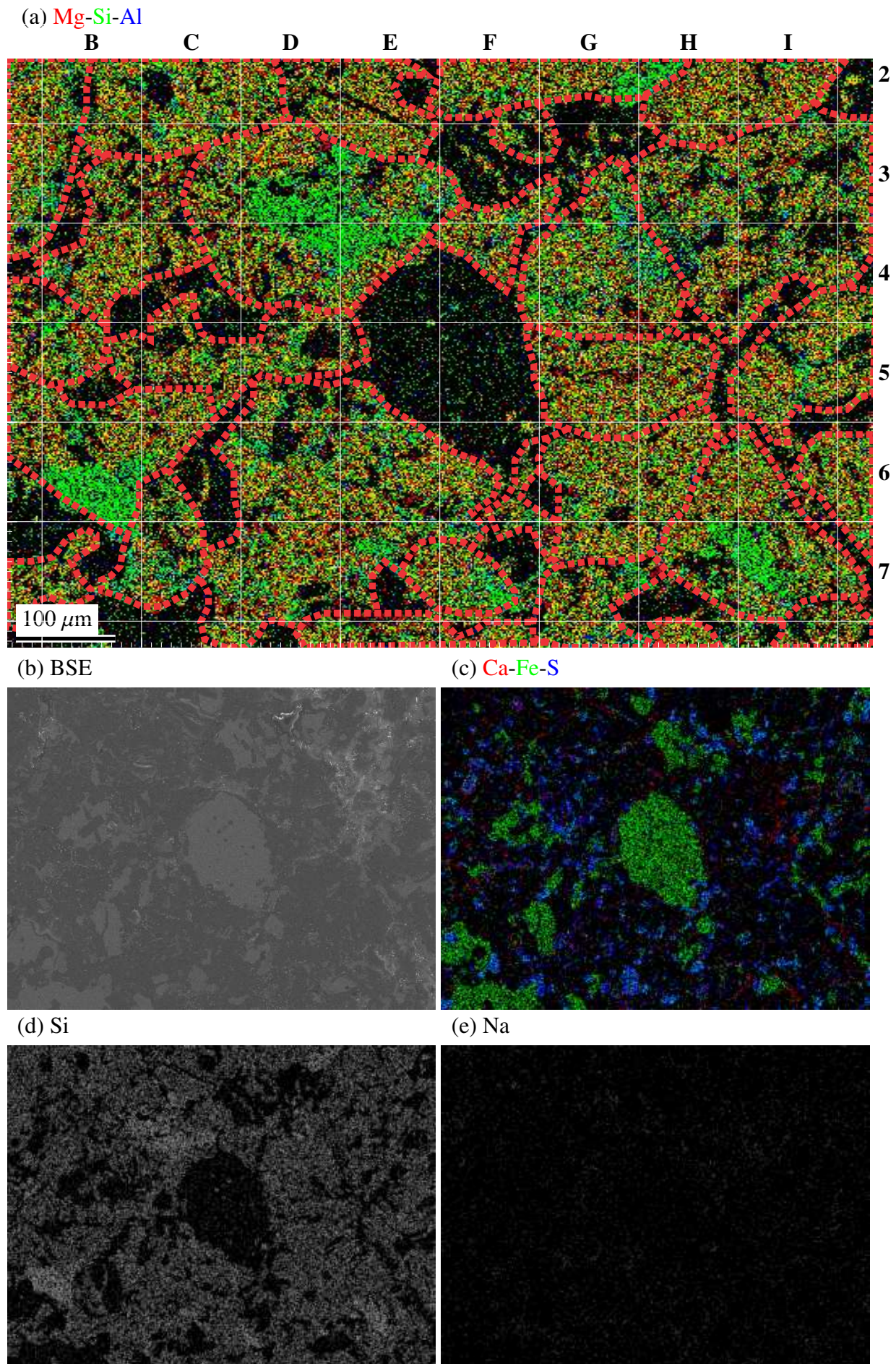


Figure 2.28: Site-2 of EET96135 (EH5). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.27.

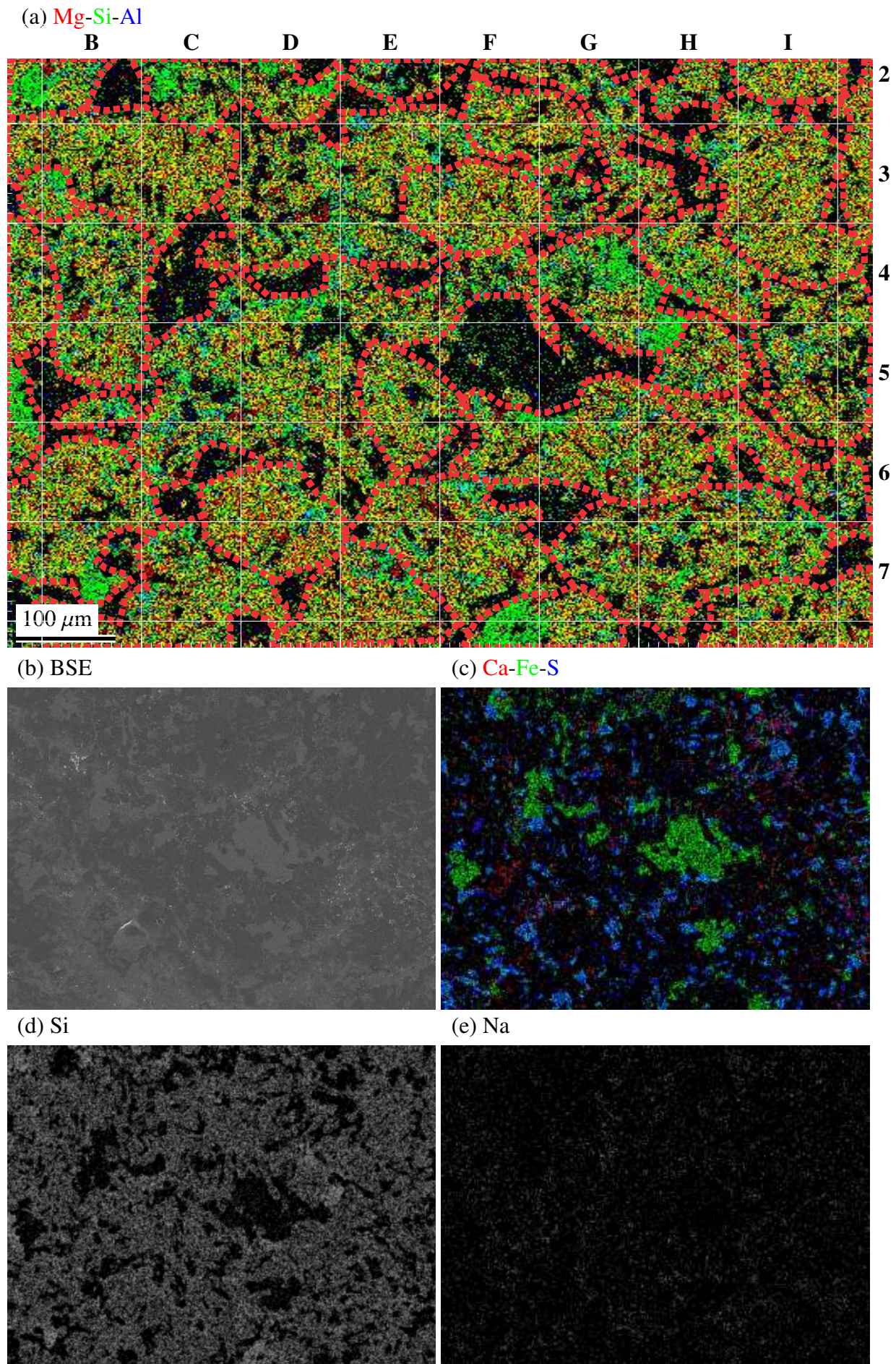


Figure 2.29: Site-3 of EET96135 (EH5). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.27.

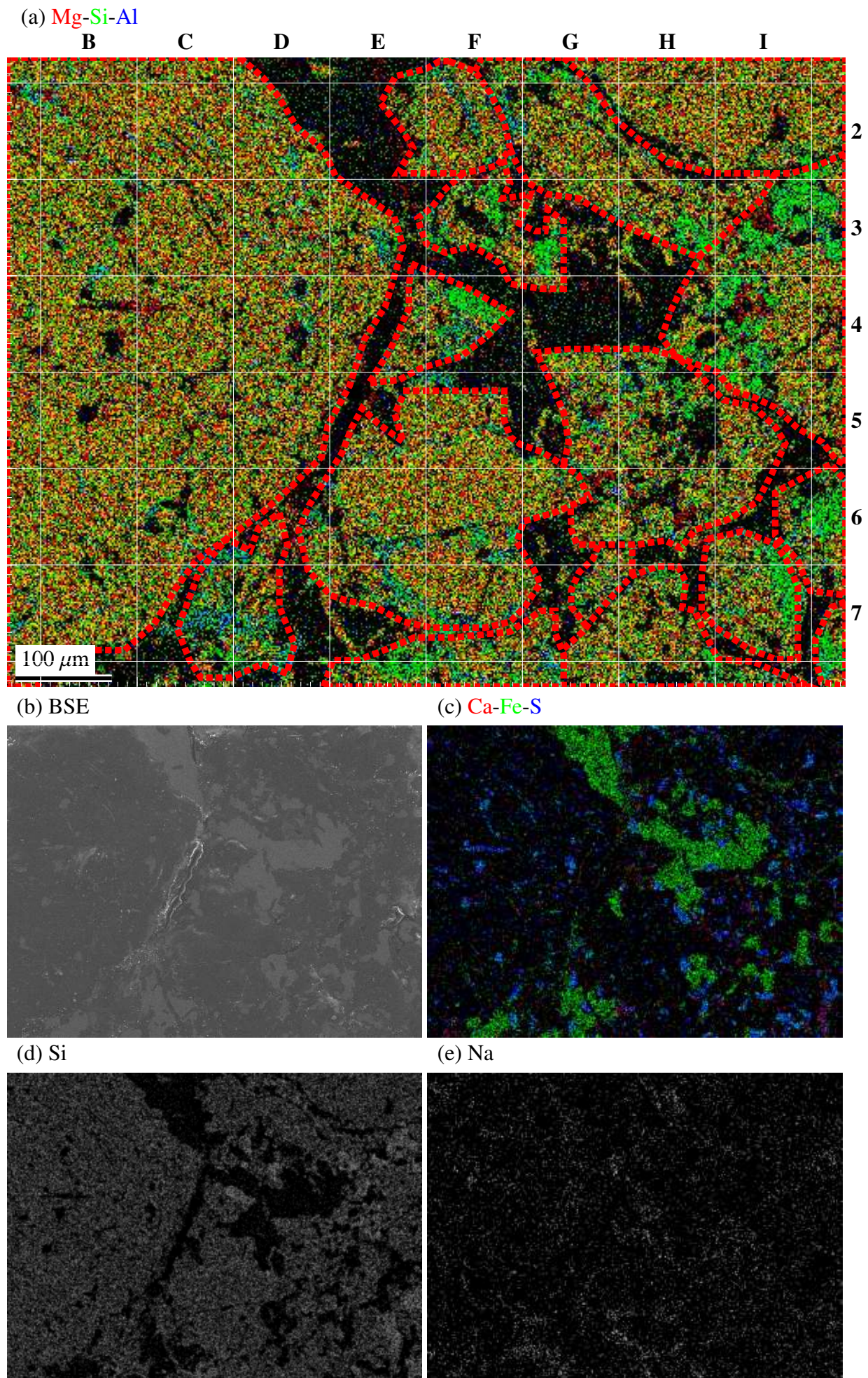


Figure 2.30: Site-4 of EET96135 (EH5). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.27.

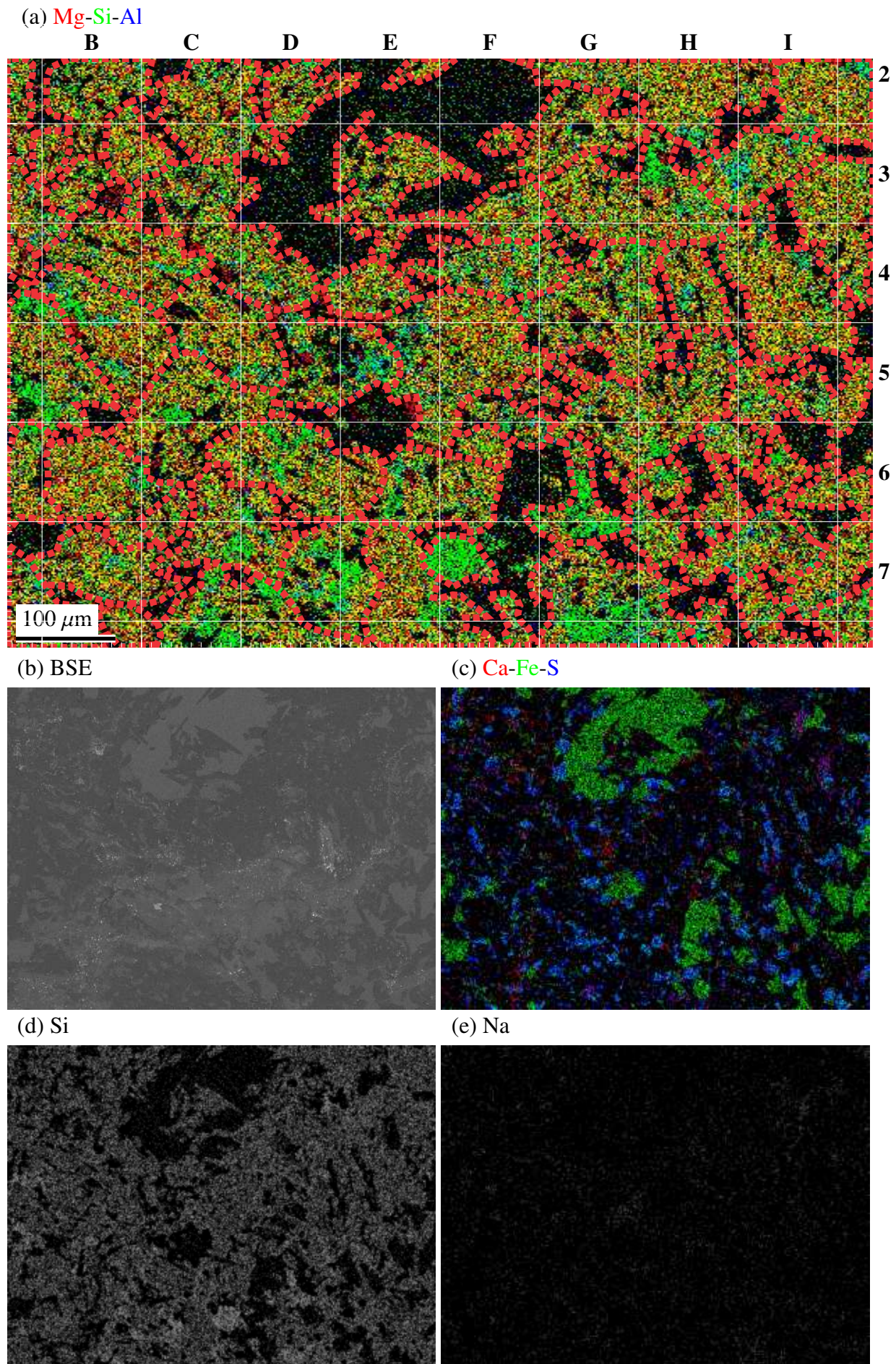


Figure 2.31: Site-5 of EET96135 (EH5). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.27.

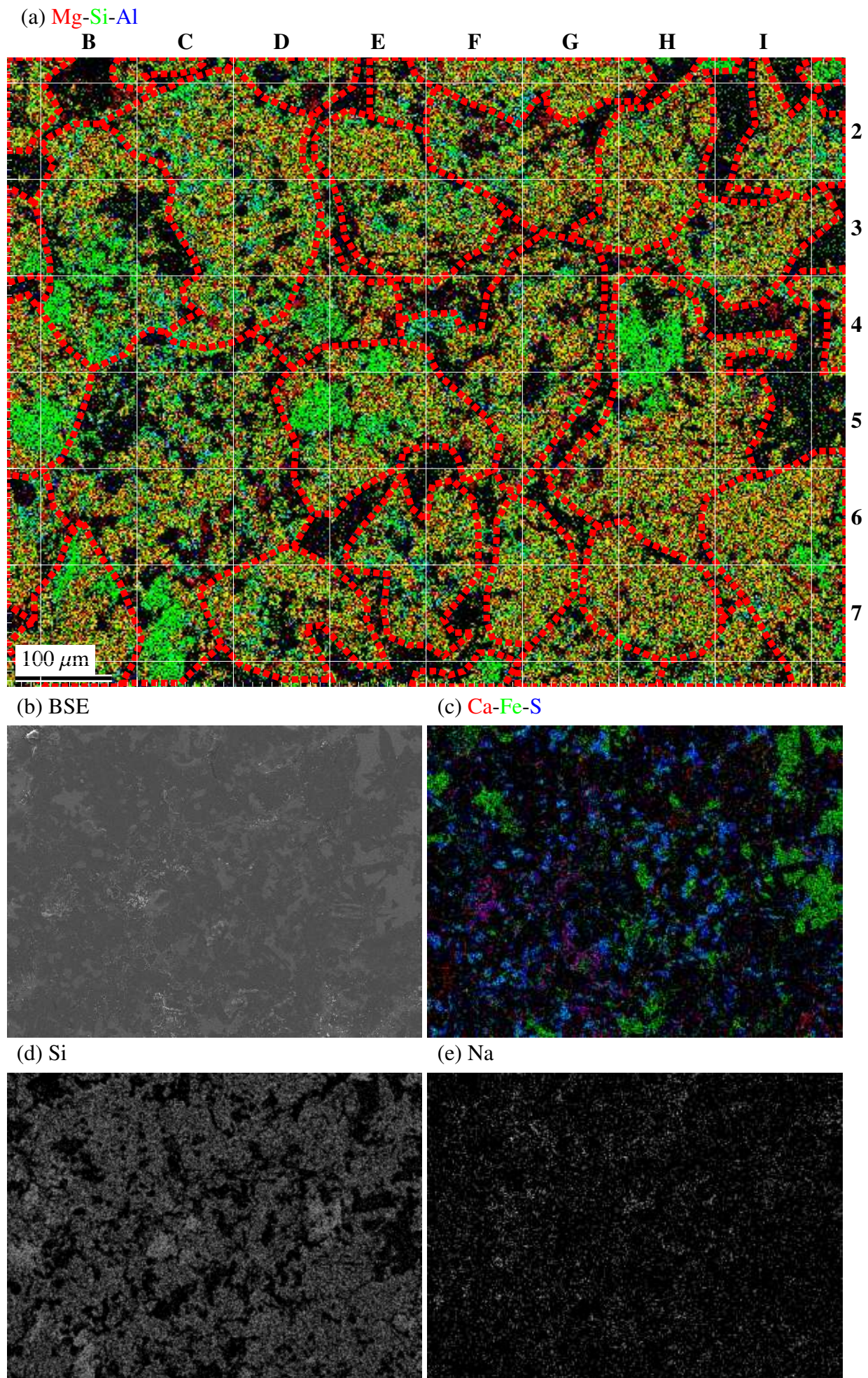


Figure 2.32: Site-6 of EET96135 (EH5). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.27.

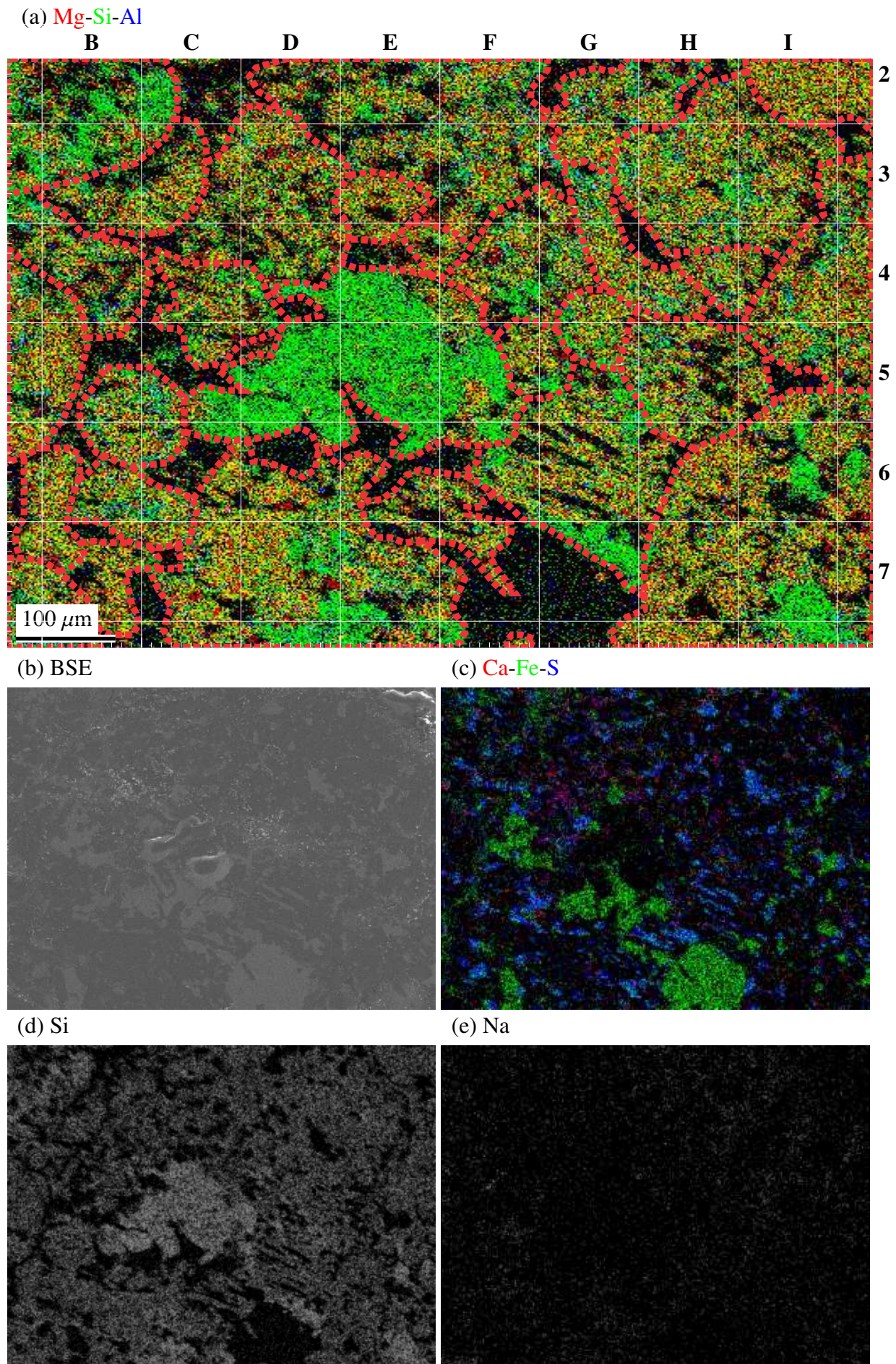


Figure 2.33: Site-7 of EET96135 (EH5). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.27.

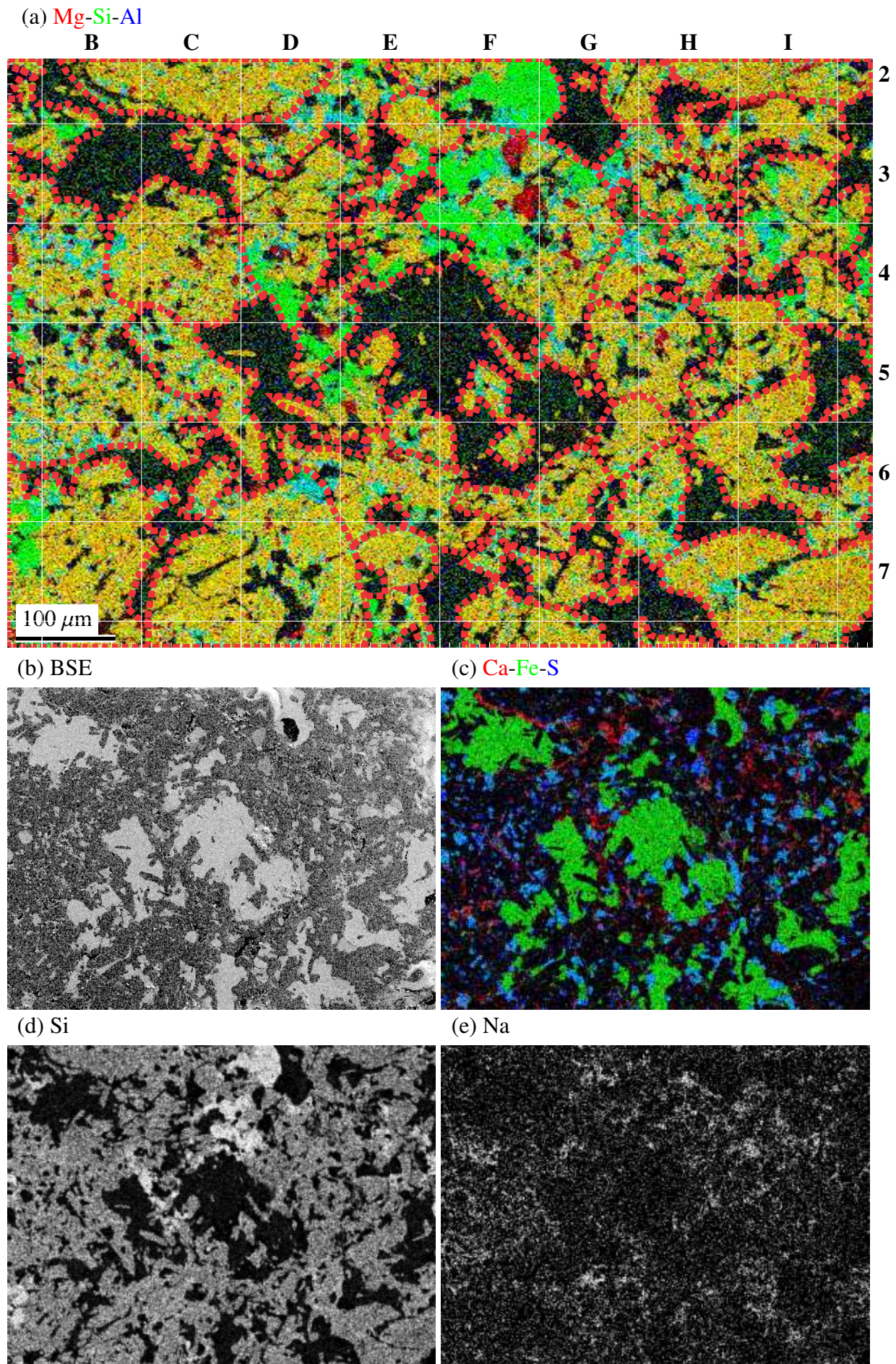


Figure 2.34: Site-8 of EET96135 (EH5). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.27.

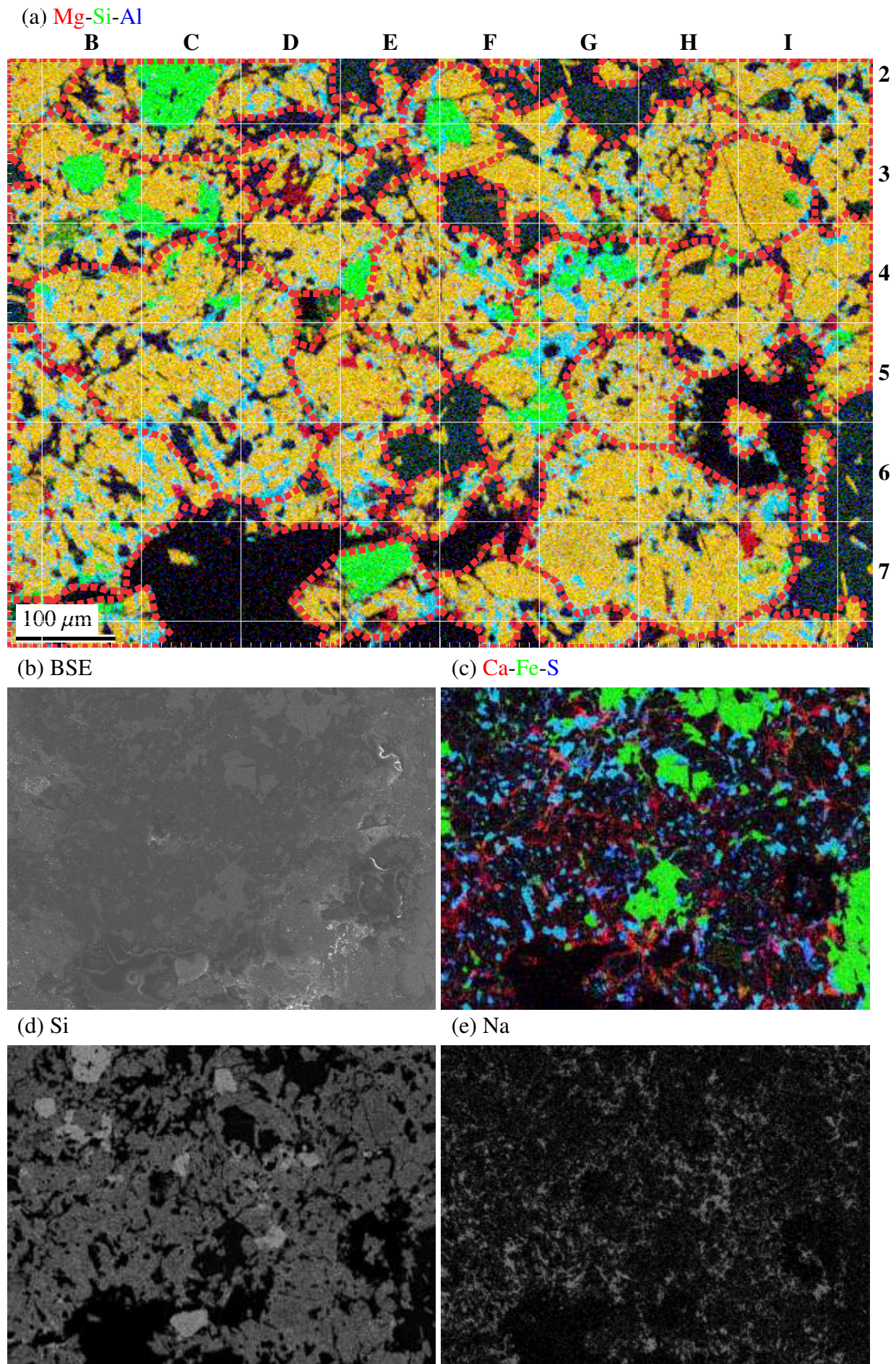


Figure 2.35: Site-9 of EET96135 (EH5). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.27.

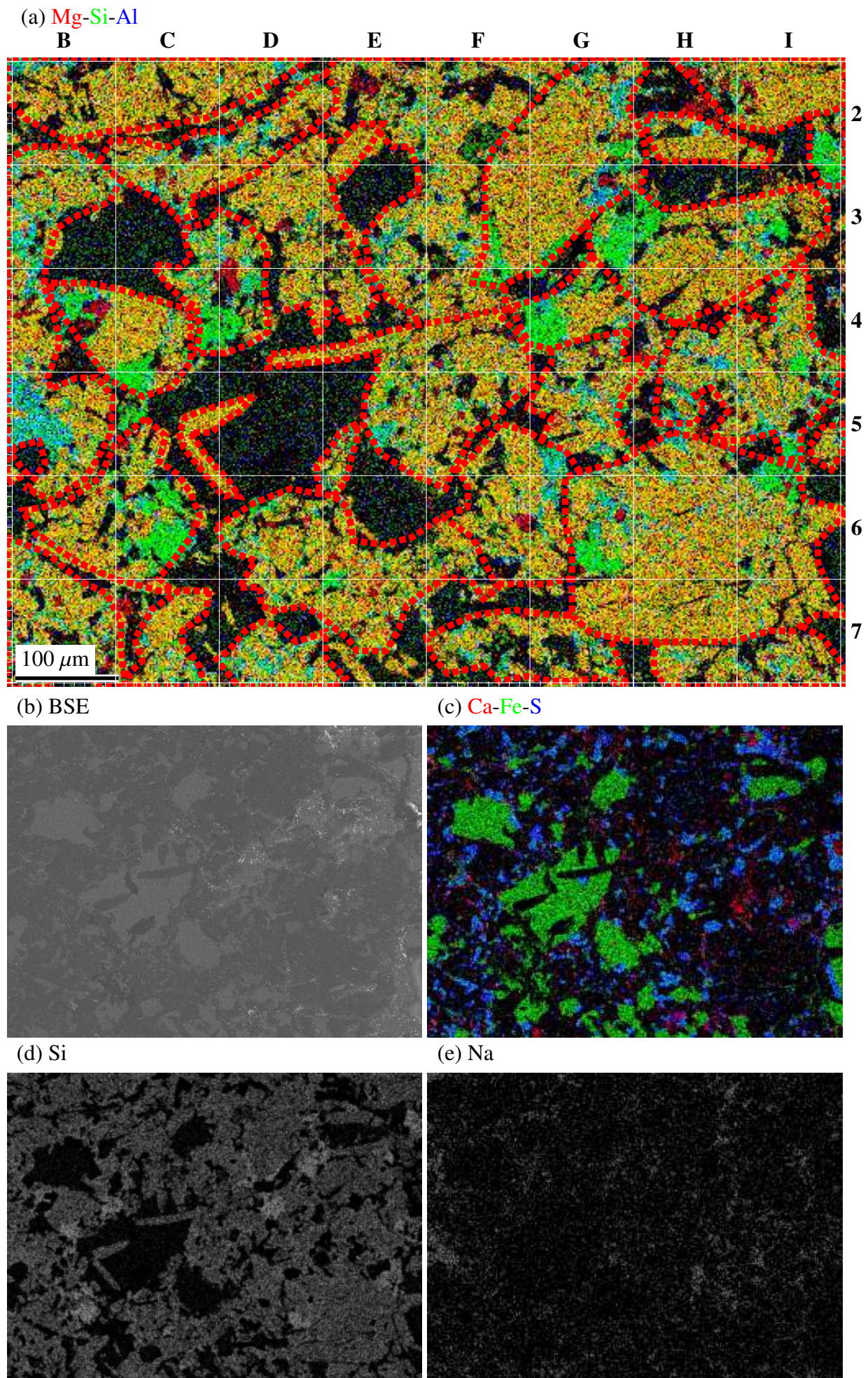


Figure 2.36: Site-10 of EET96135 (EH5). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.27.

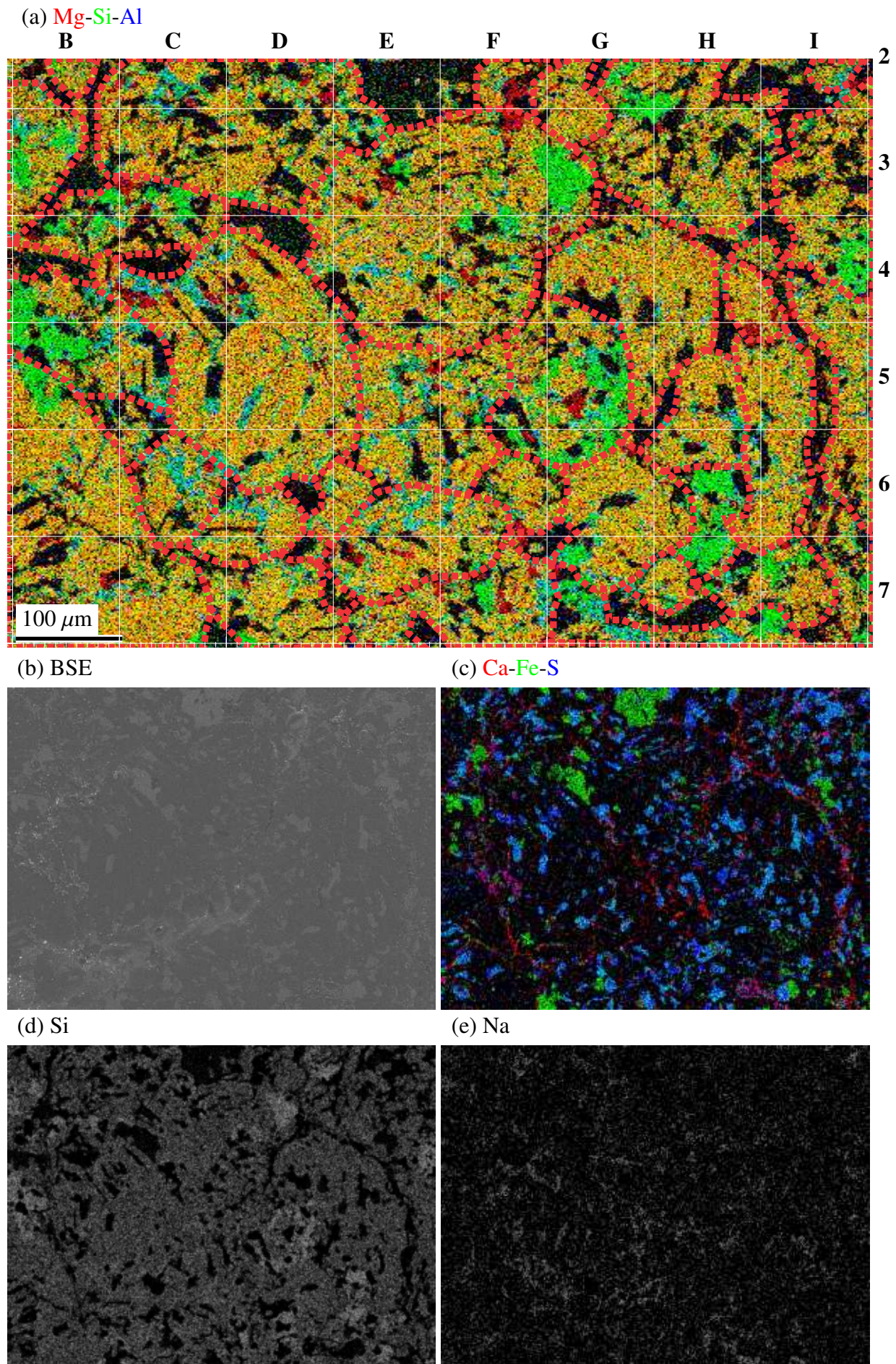


Figure 2.37: Site-11 of EET96135 (EH5). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.27.

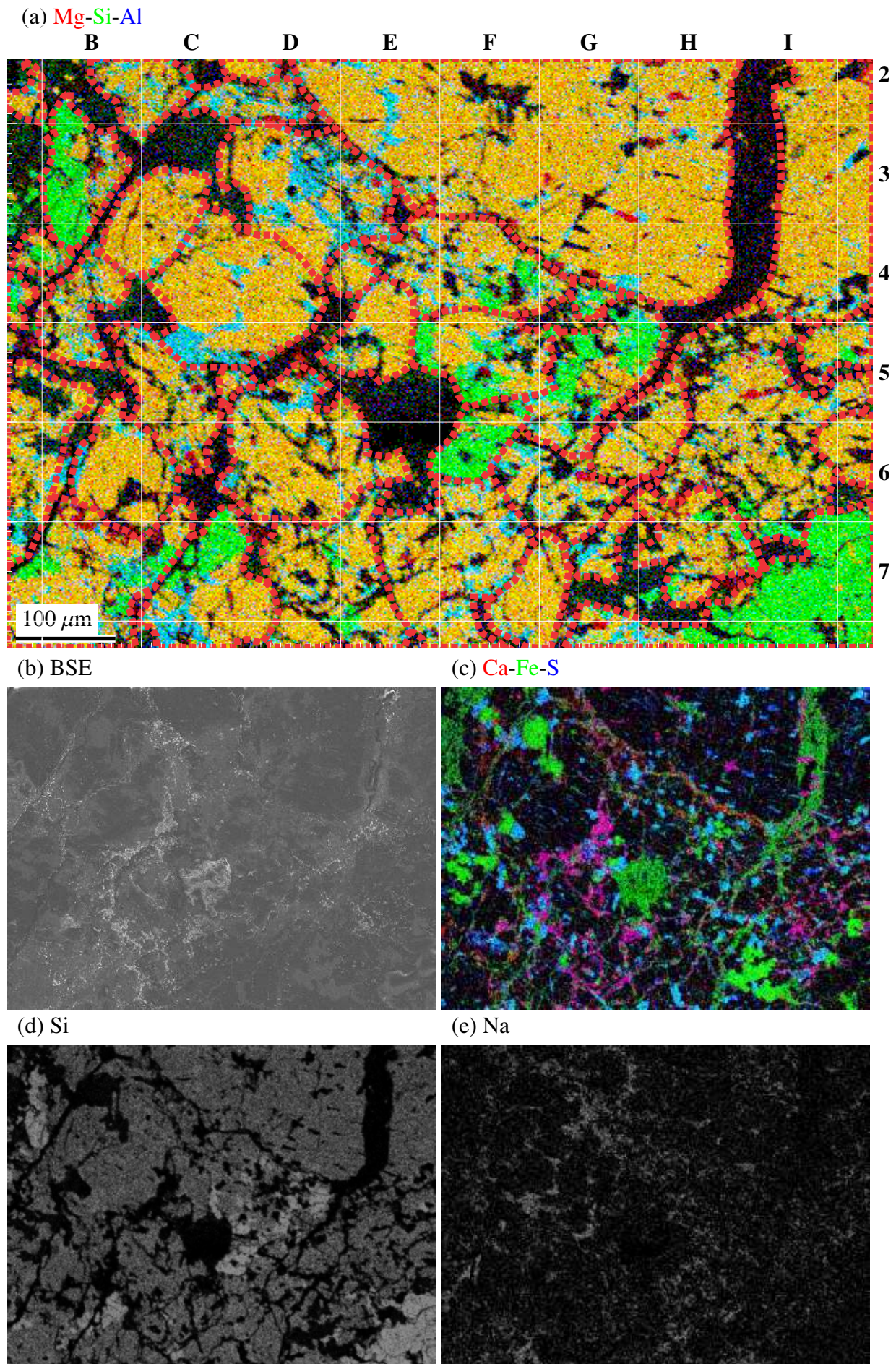


Figure 2.38: Site-12 of EET96135 (EH5). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.27.

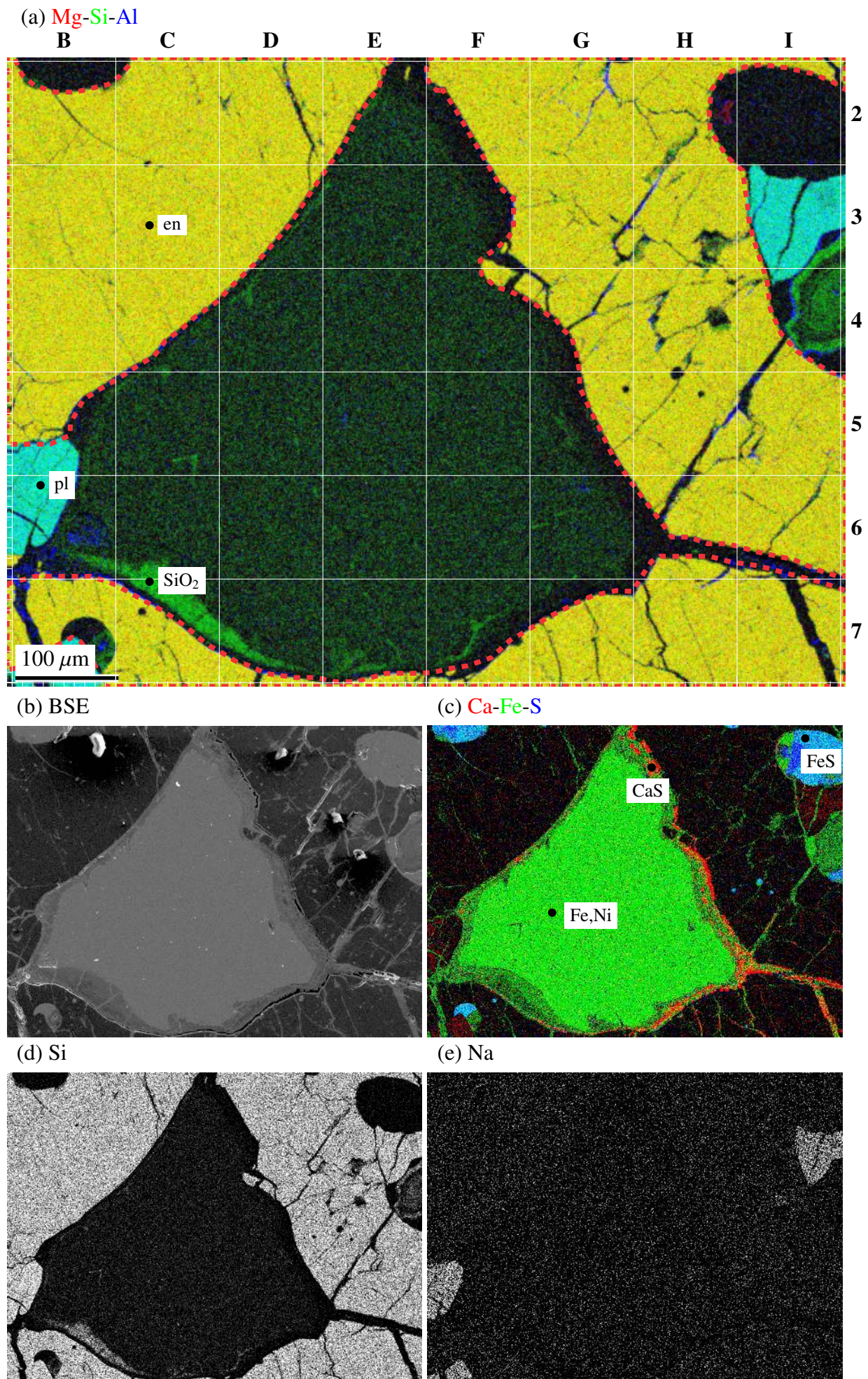


Figure 2.39: Site-1 of QUE94204 (EH7). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown.

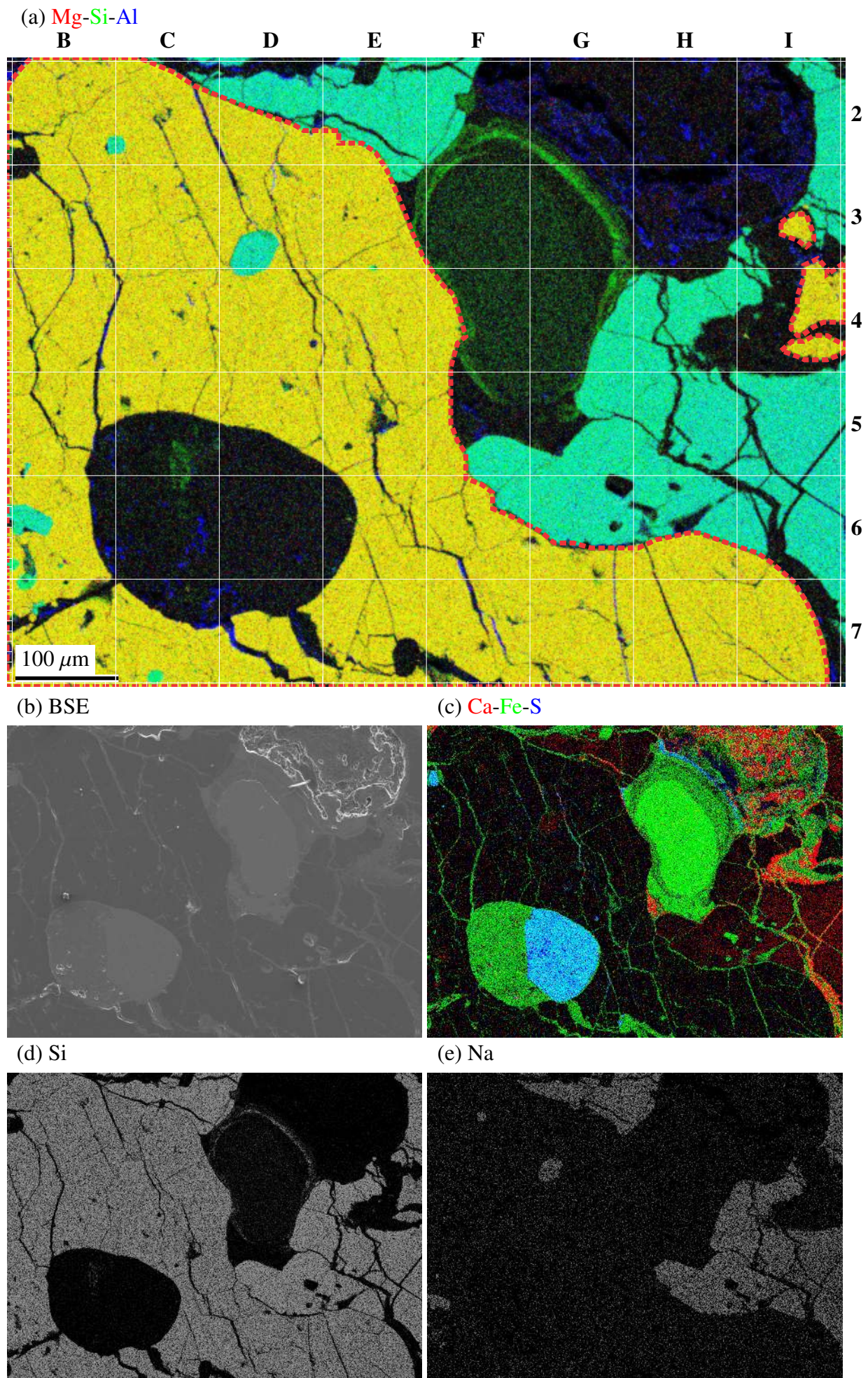


Figure 2.40: Site-2 of QUE94204 (EH7). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.39.

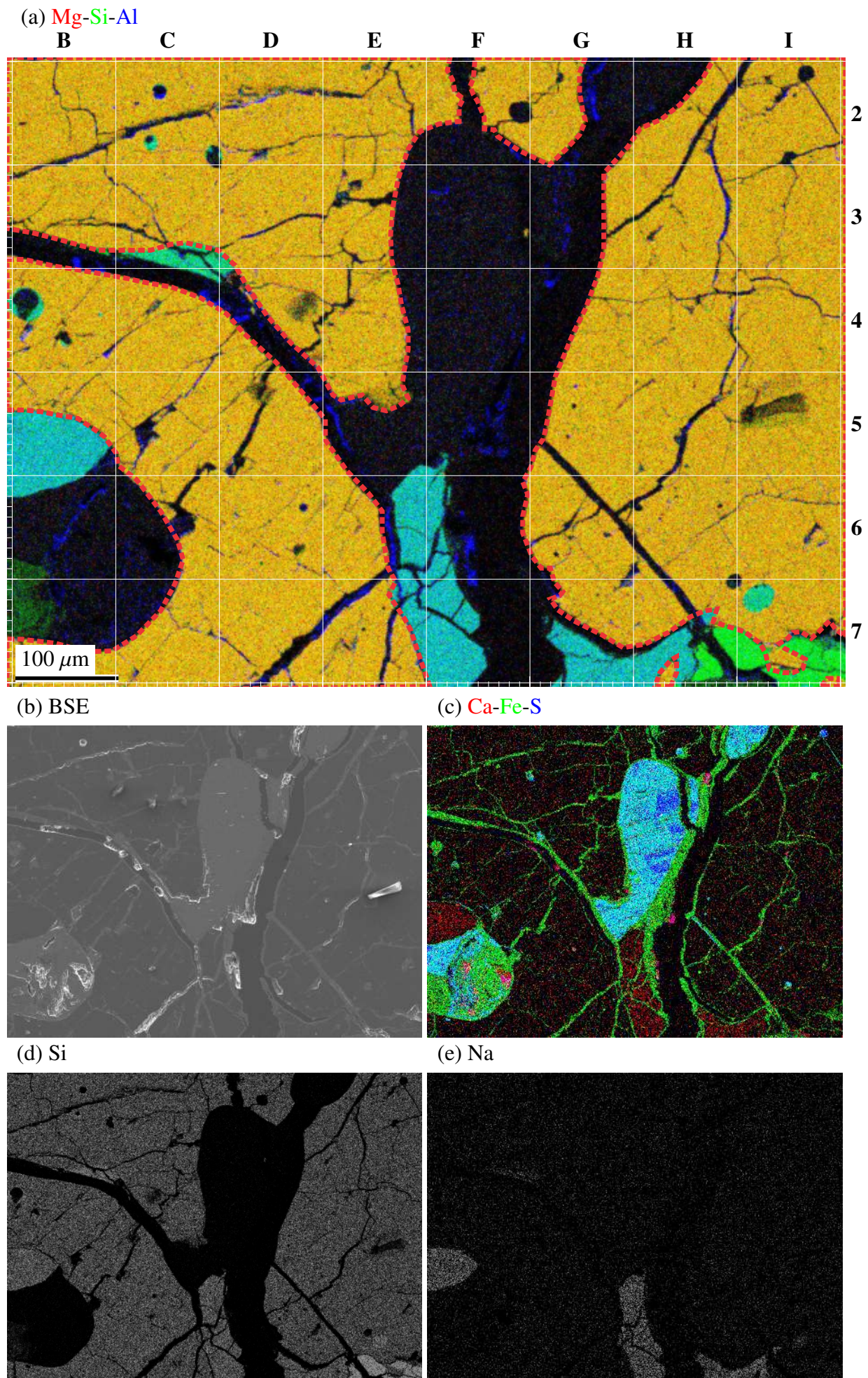


Figure 2.41: Site-3 of QUE94204 (EH7). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.39.

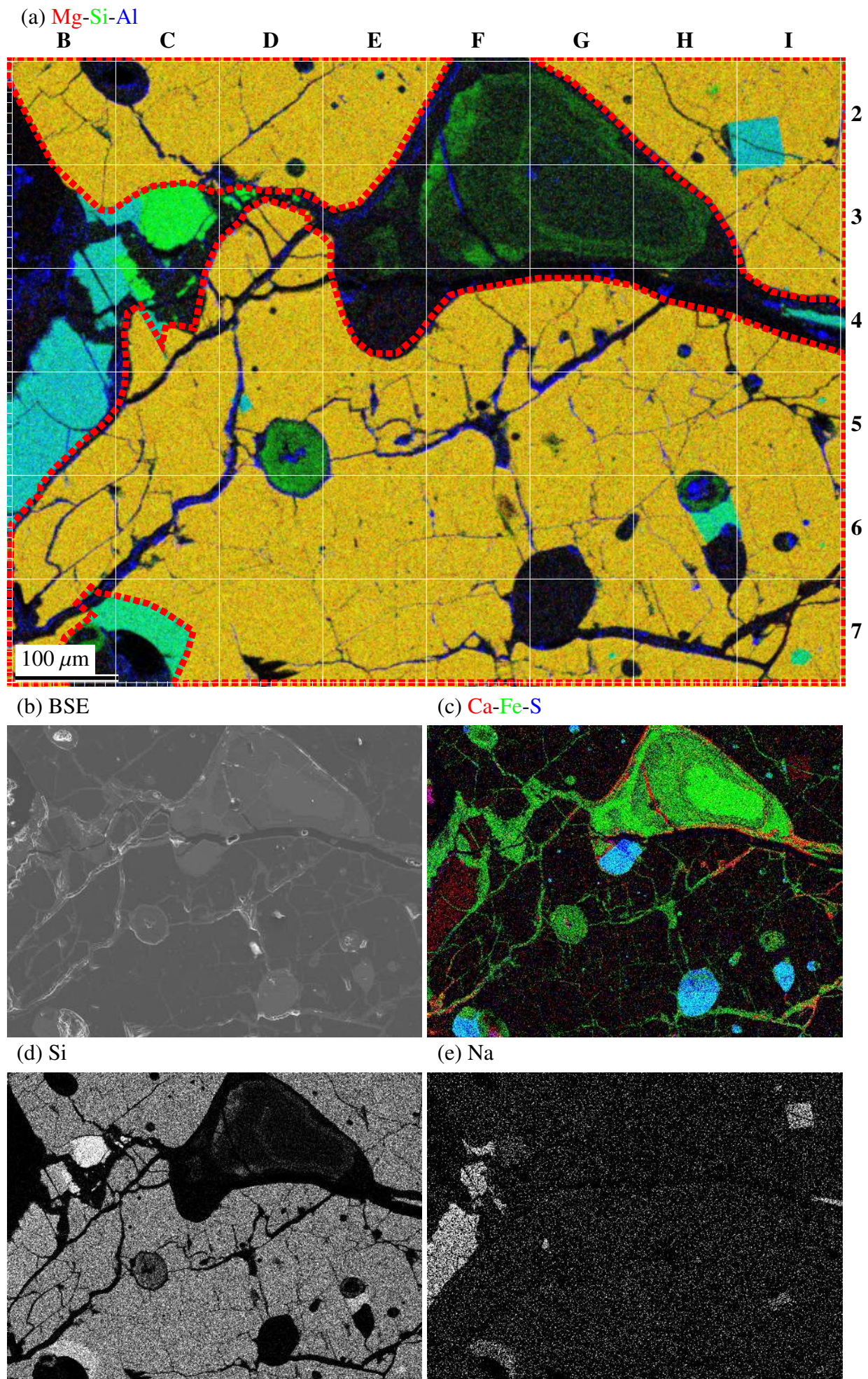


Figure 2.42: Site-4 of QUE94204 (EH7). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.39.

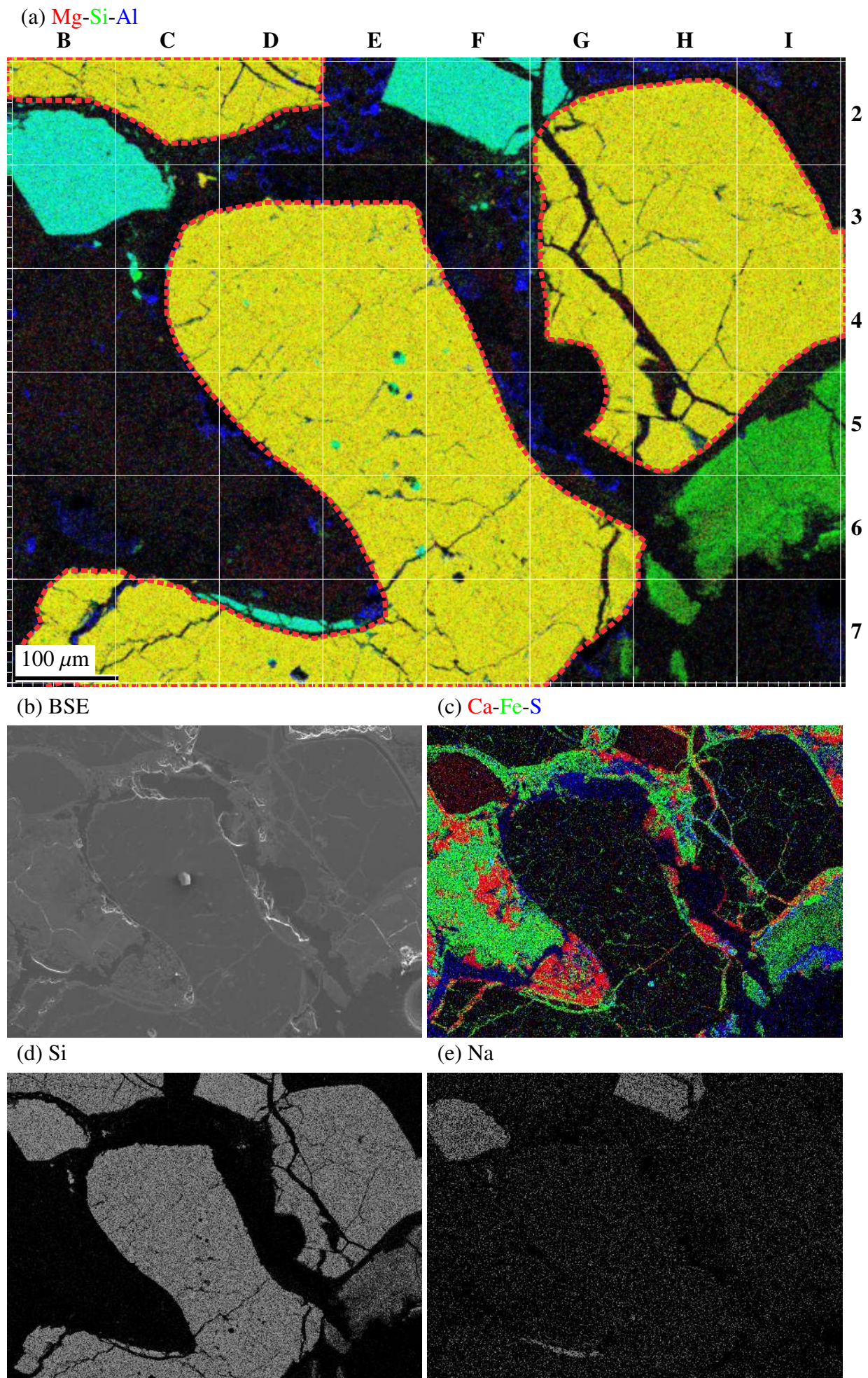


Figure 2.43: Site-5 of QUE94204 (EH7). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.39.

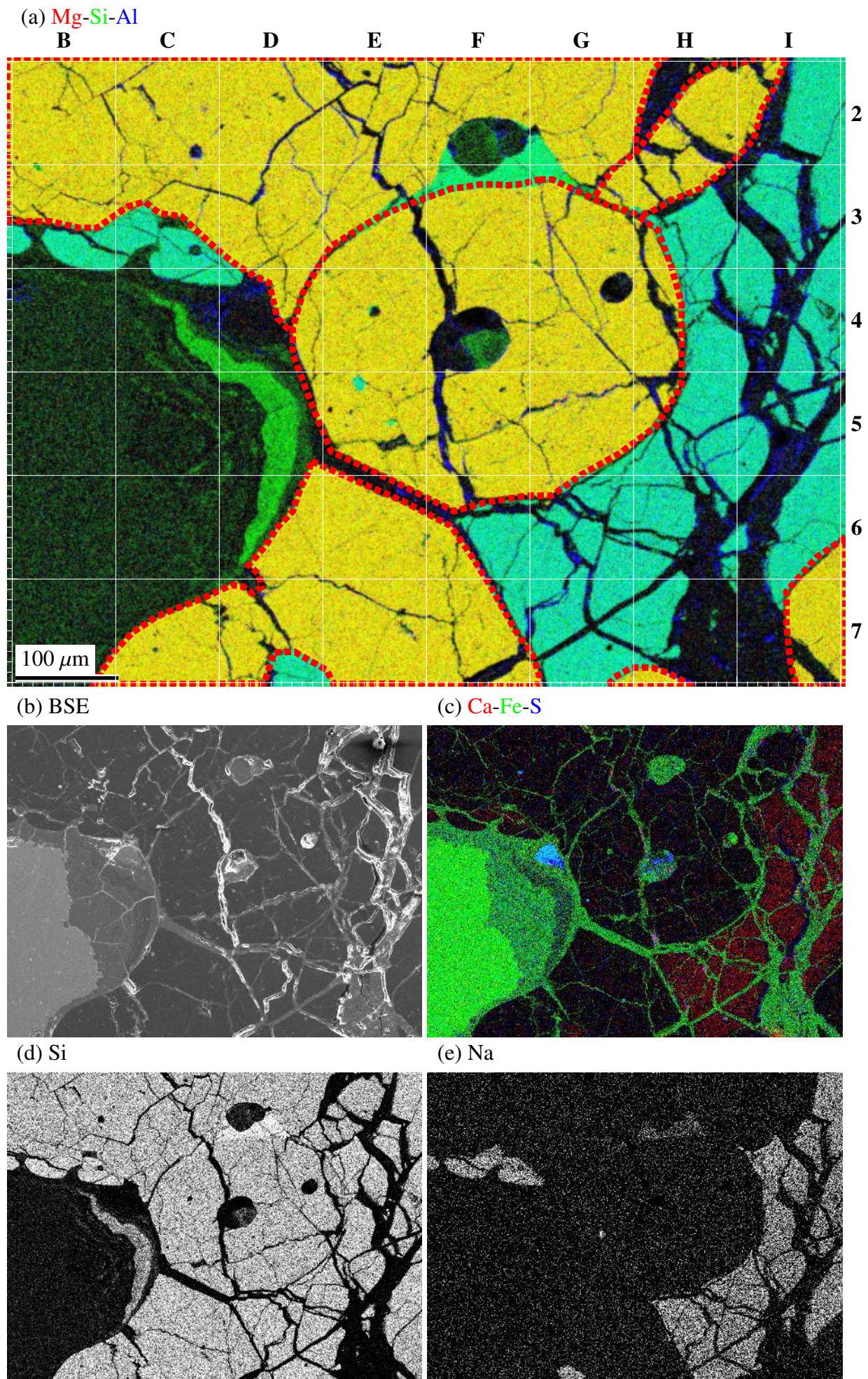


Figure 2.44: Site-6 of QUE94204 (EH7). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.39.

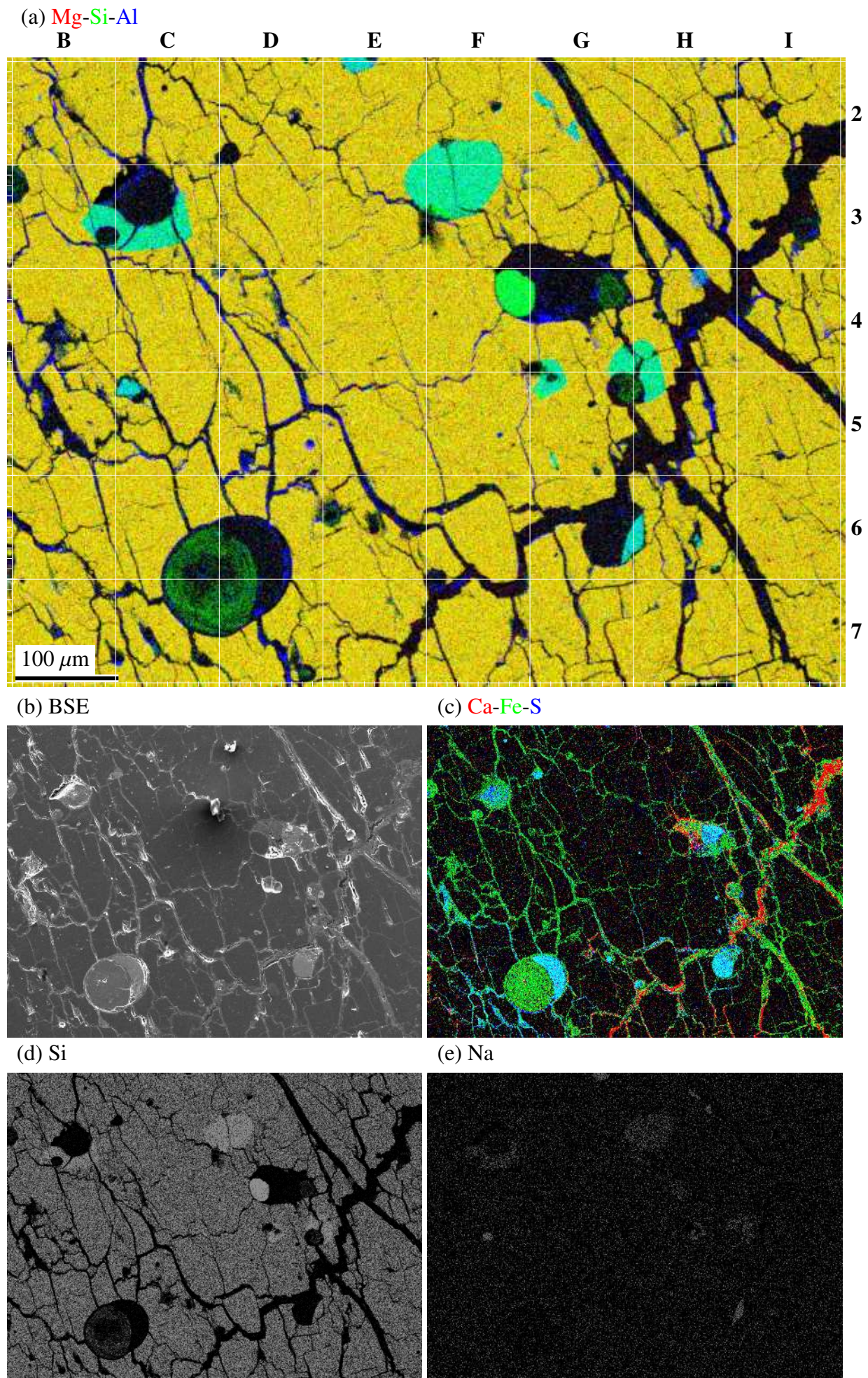


Figure 2.45: Site-7 of QUE94204 (EH7). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.39.

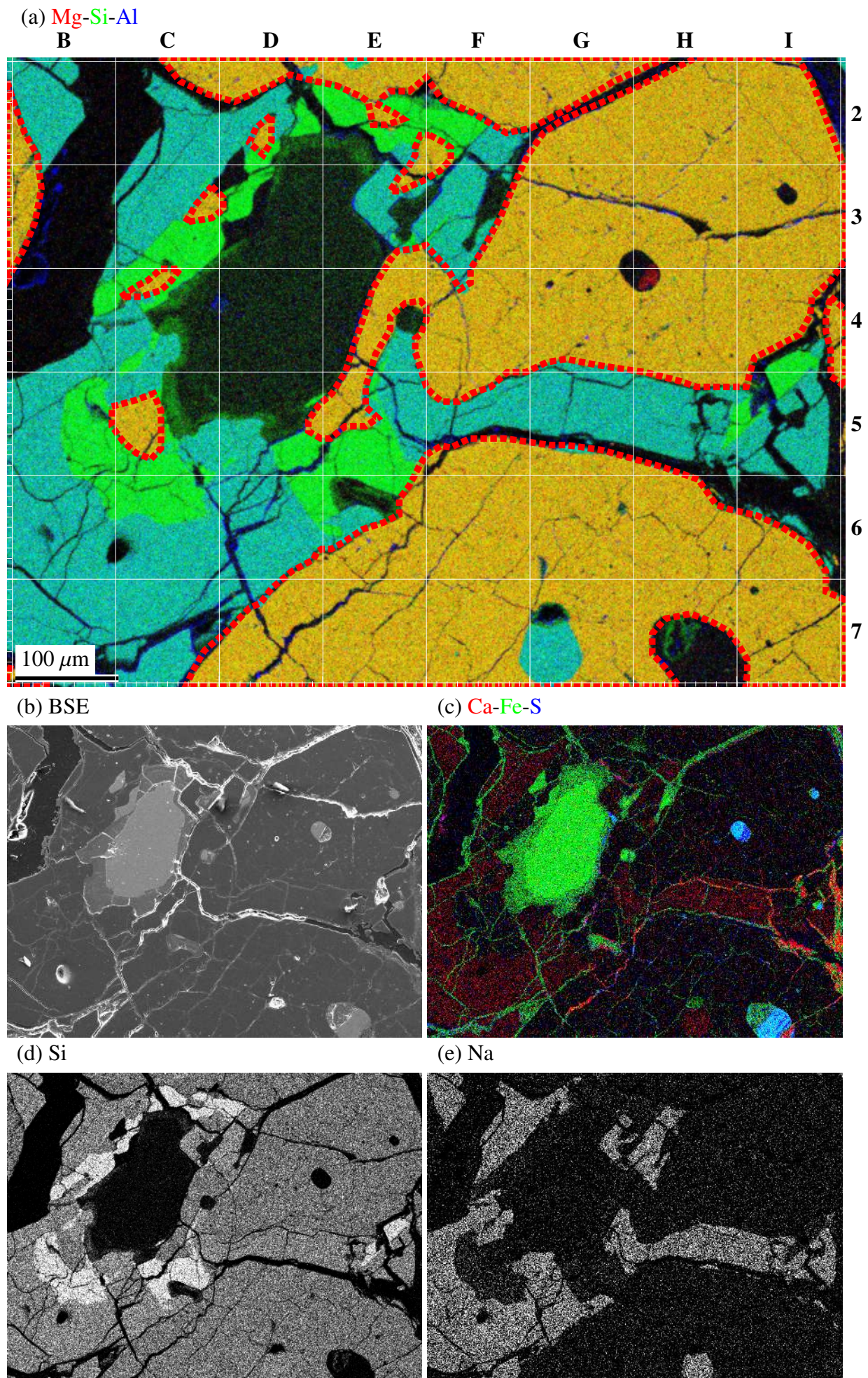


Figure 2.46: Site-8 of QUE94204 (EH7). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.39.

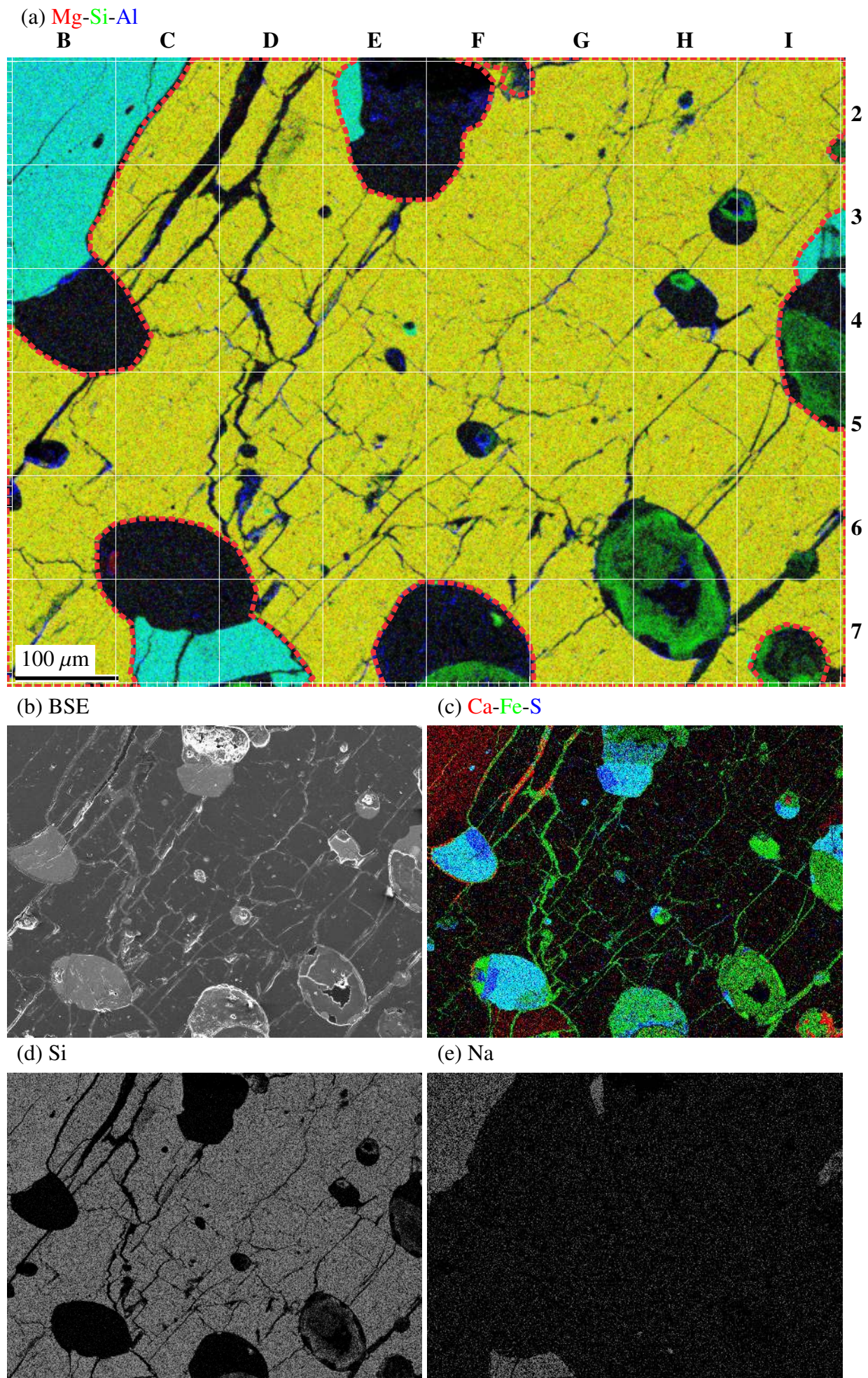


Figure 2.47: Site-9 of QUE94204 (EH7). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.39.

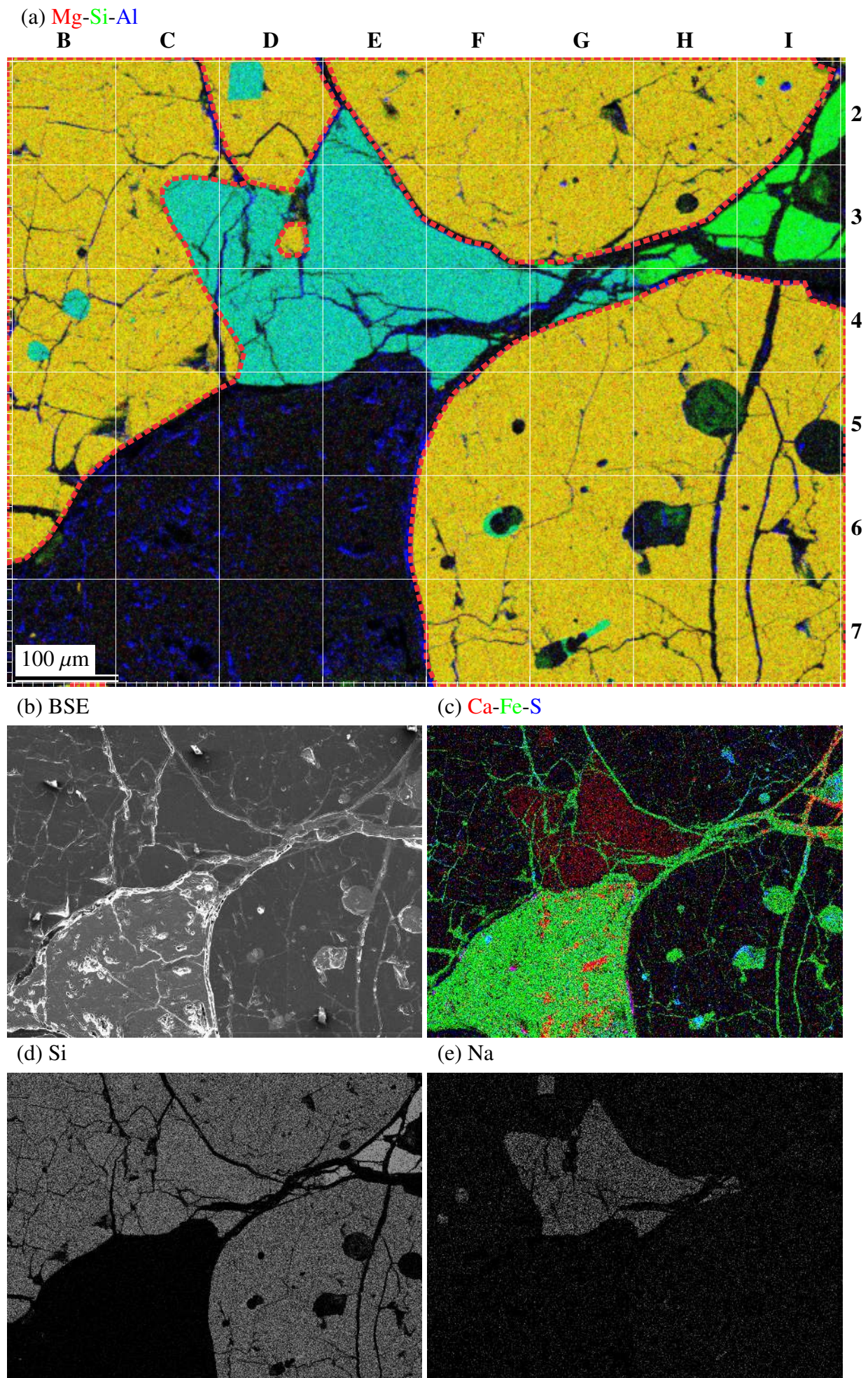


Figure 2.48: Site-10 of QUE94204 (EH7). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.39.

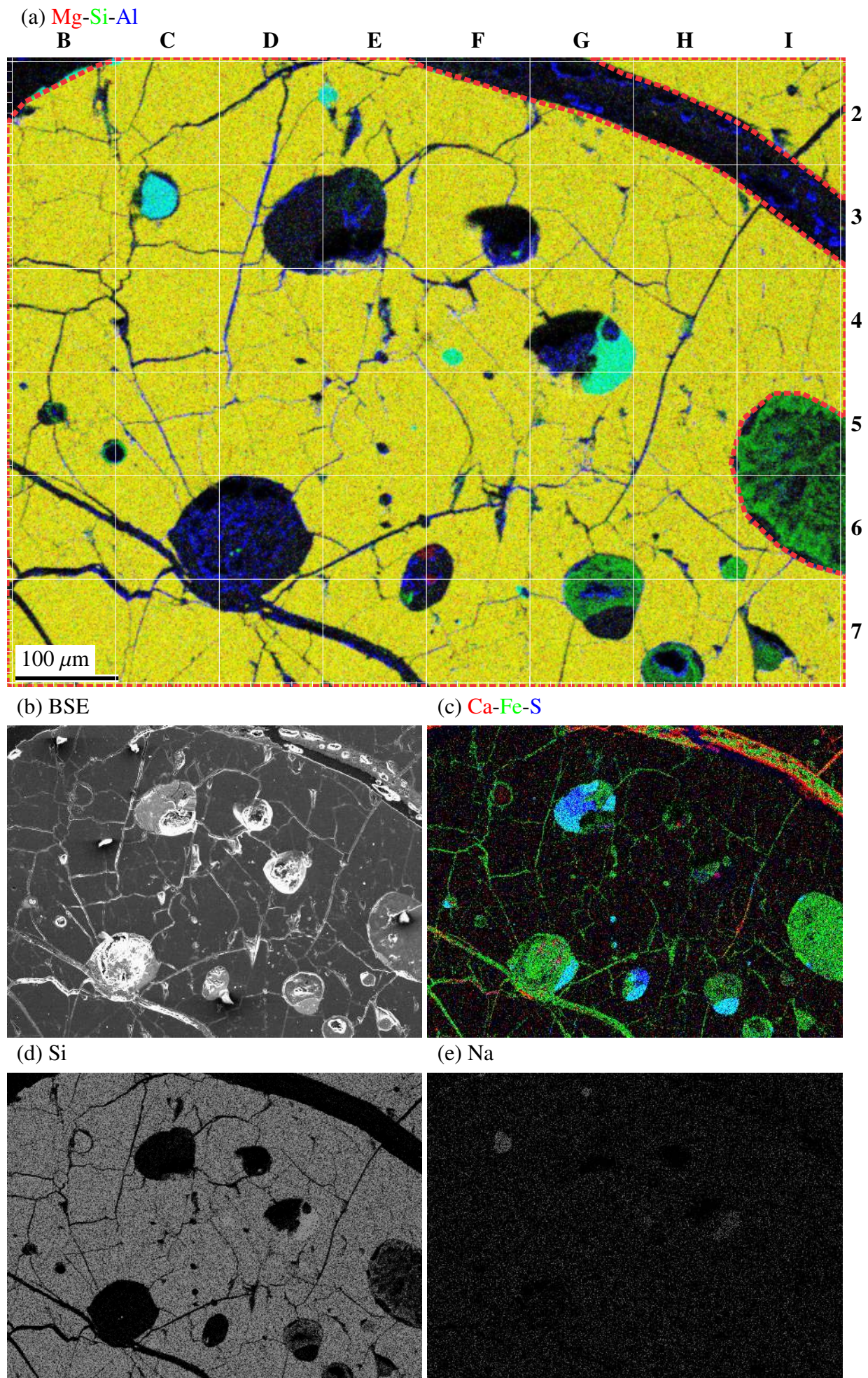


Figure 2.49: Site-11 of QUE94204 (EH7). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.39.

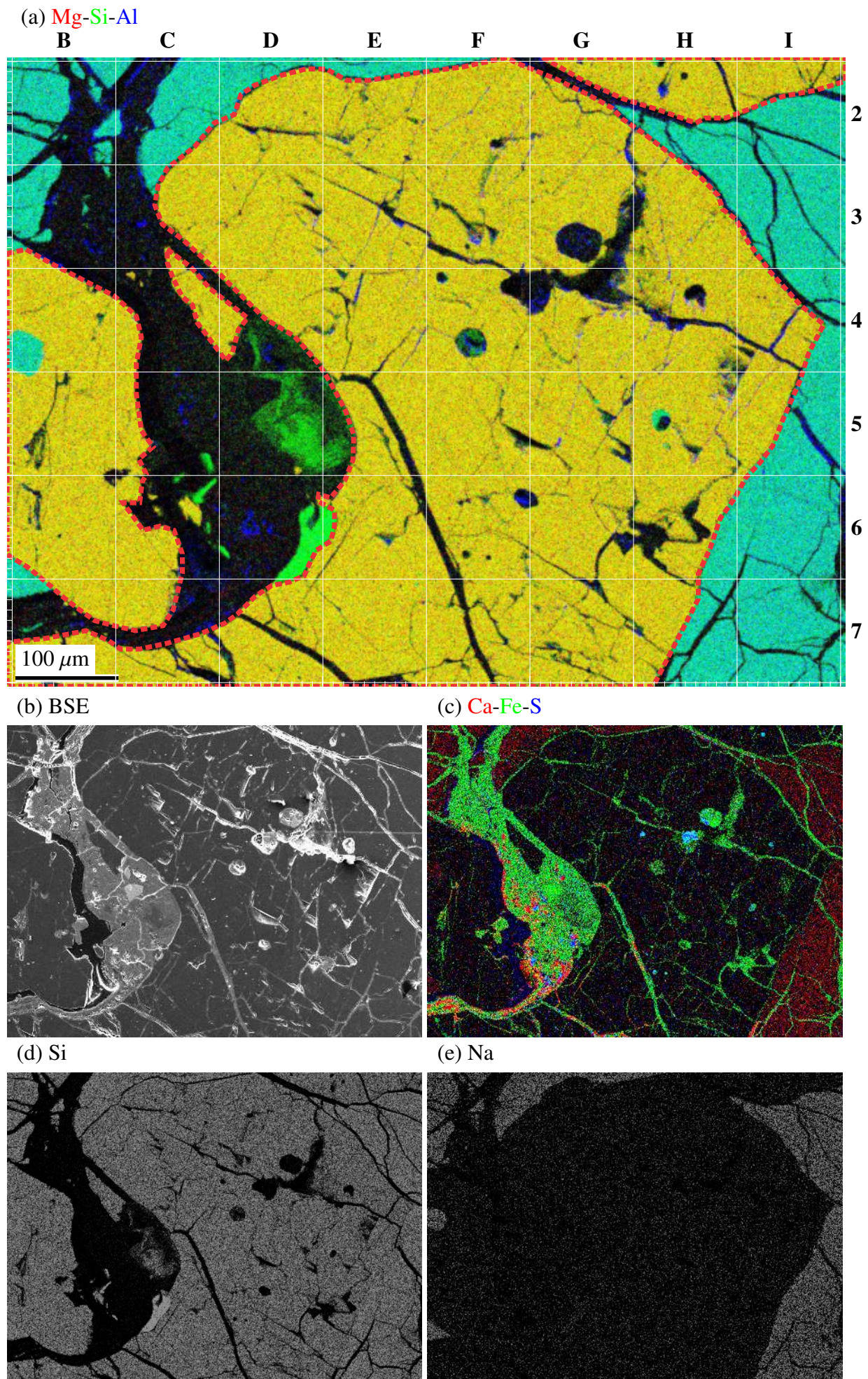


Figure 2.50: Site-12 of QUE94204 (EH7). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.39.

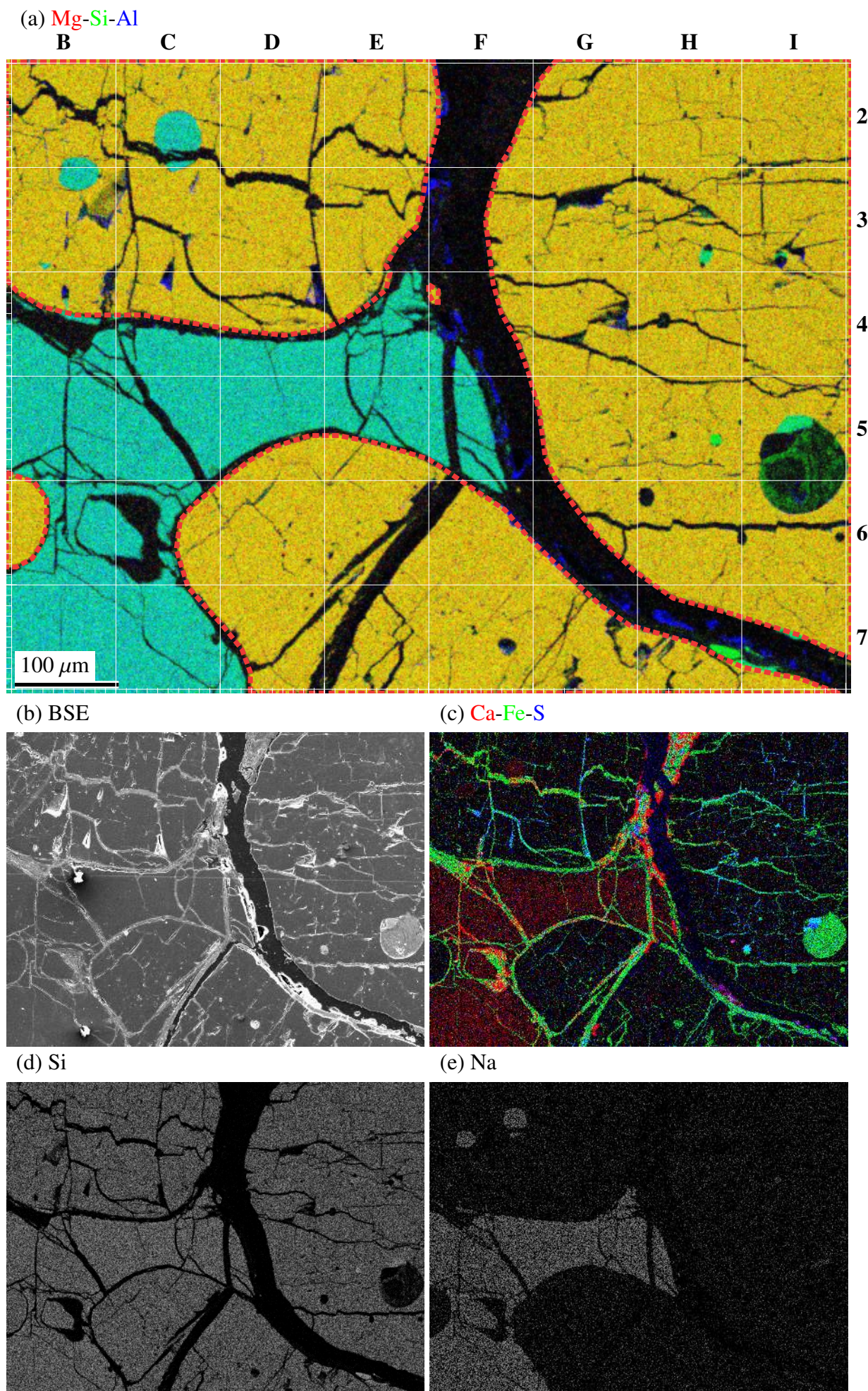


Figure 2.51: Site-13 of QUE94204 (EH7). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.39.

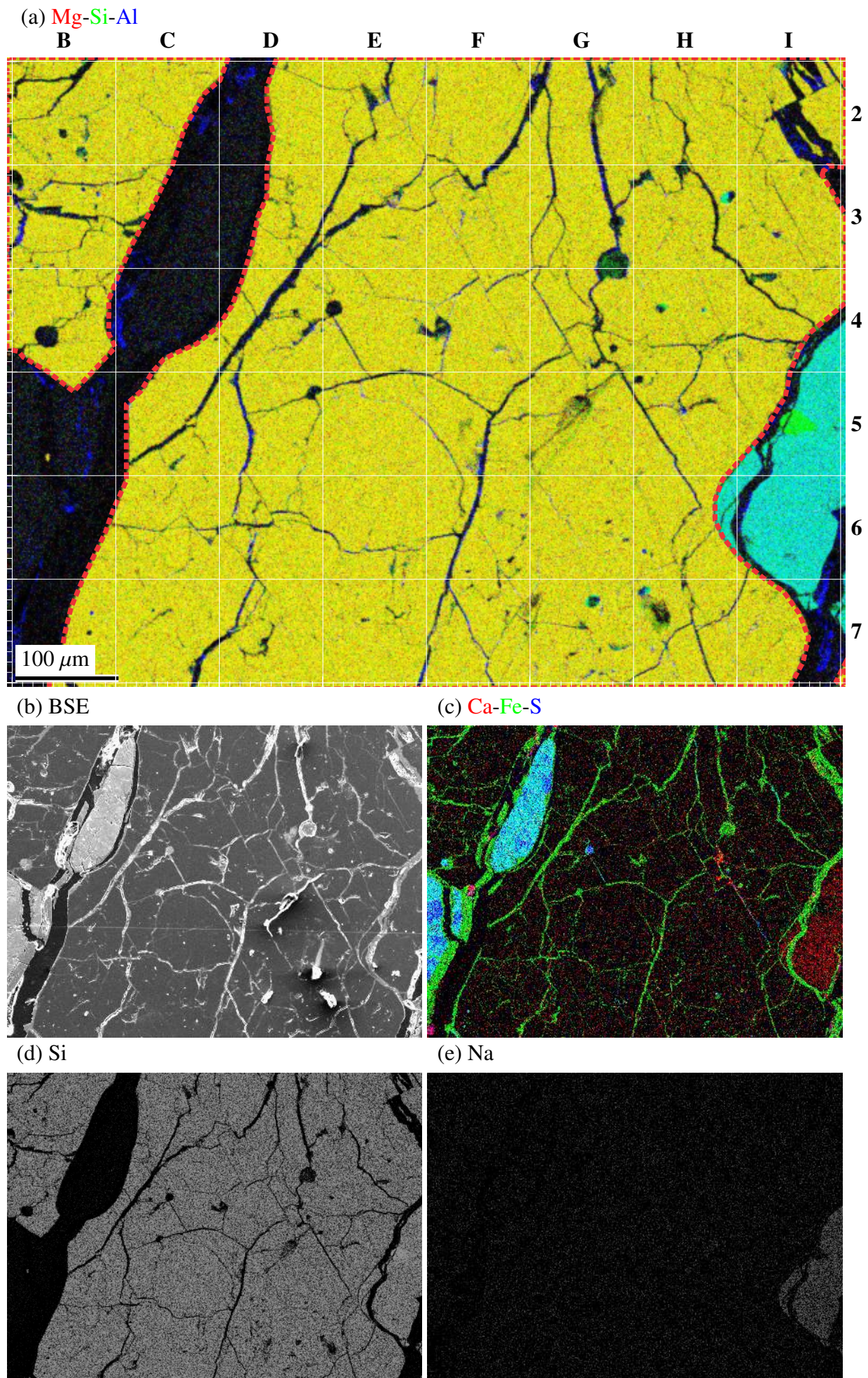


Figure 2.52: Site-14 of QUE94204 (EH7). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.39.

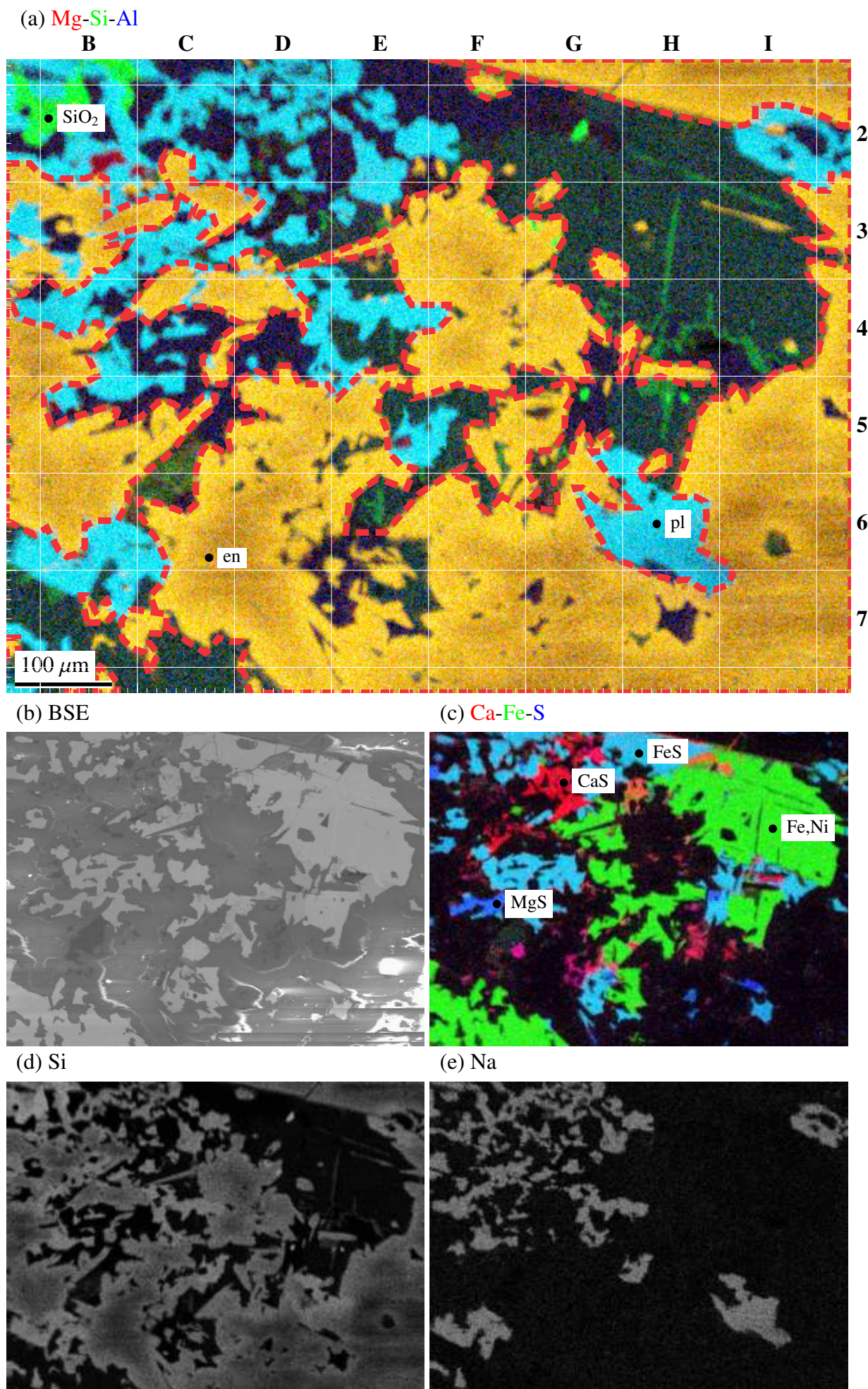


Figure 2.53: Site-1 of LAP02225 (EH imp melt). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown.

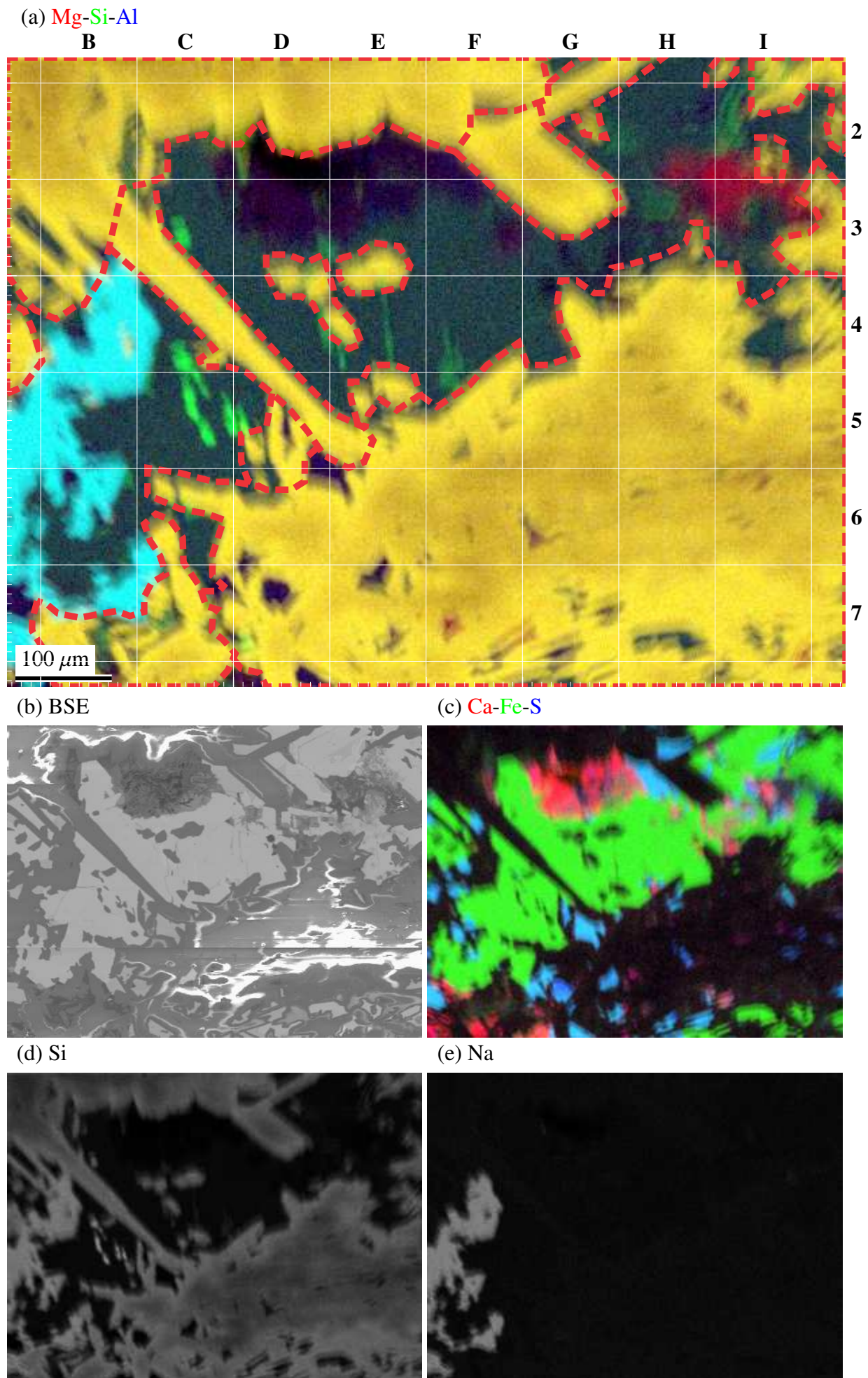


Figure 2.54: Site-2 of LAP02225 (EH imp melt). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.53.

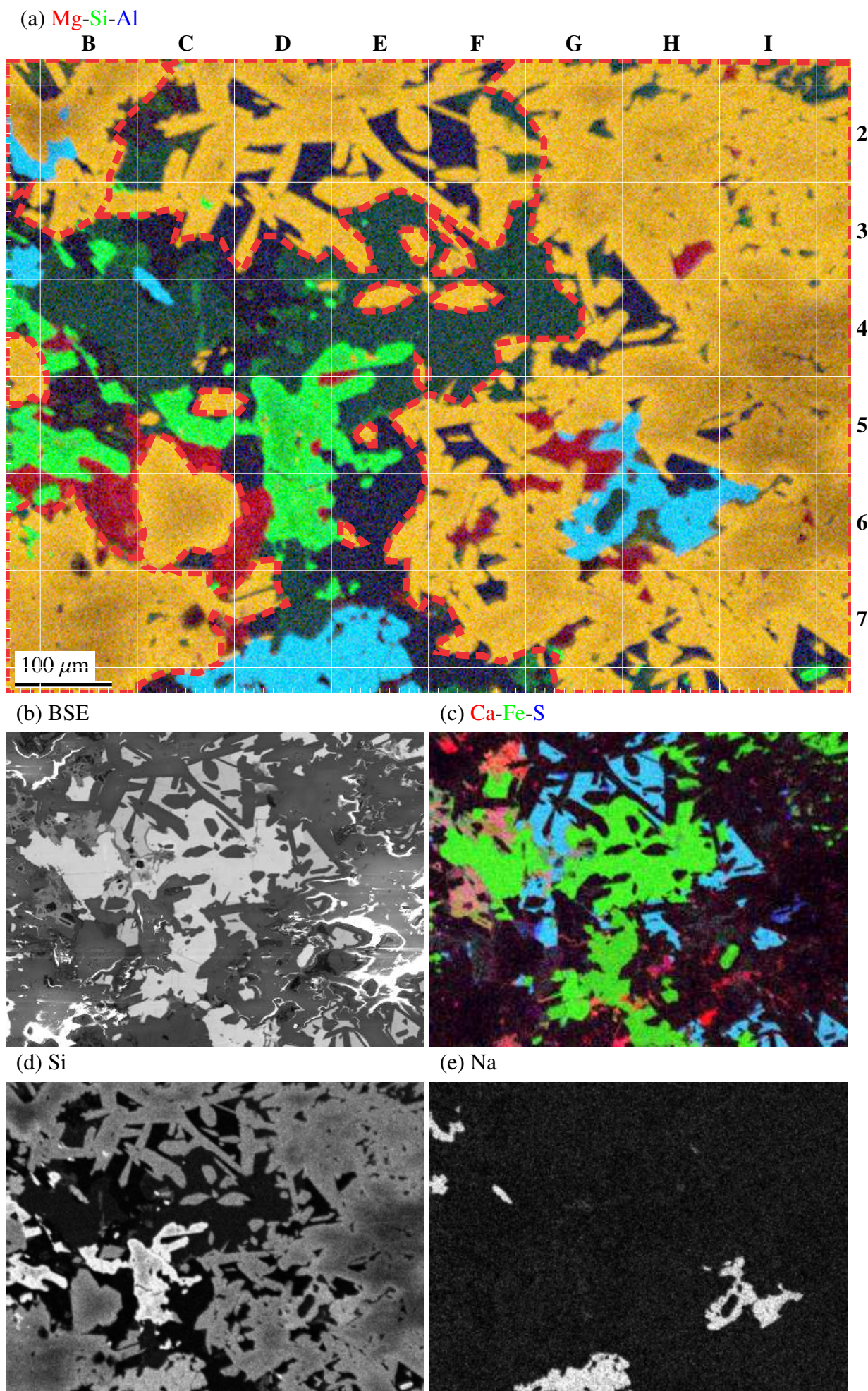


Figure 2.55: Site-3 of LAP02225 (EH imp melt). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.53.

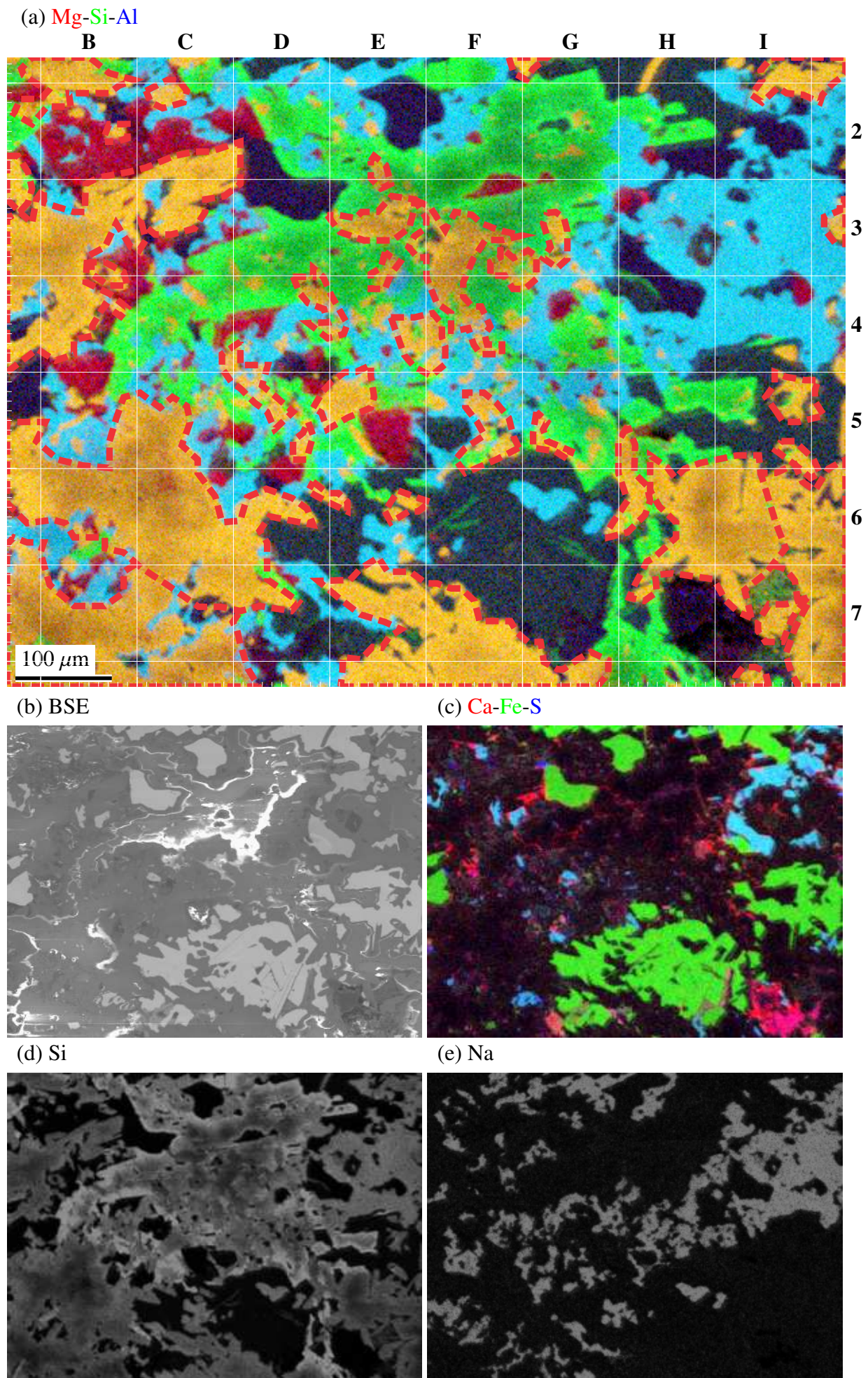


Figure 2.56: Site-4 of LAP02225 (EH imp melt). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.53.

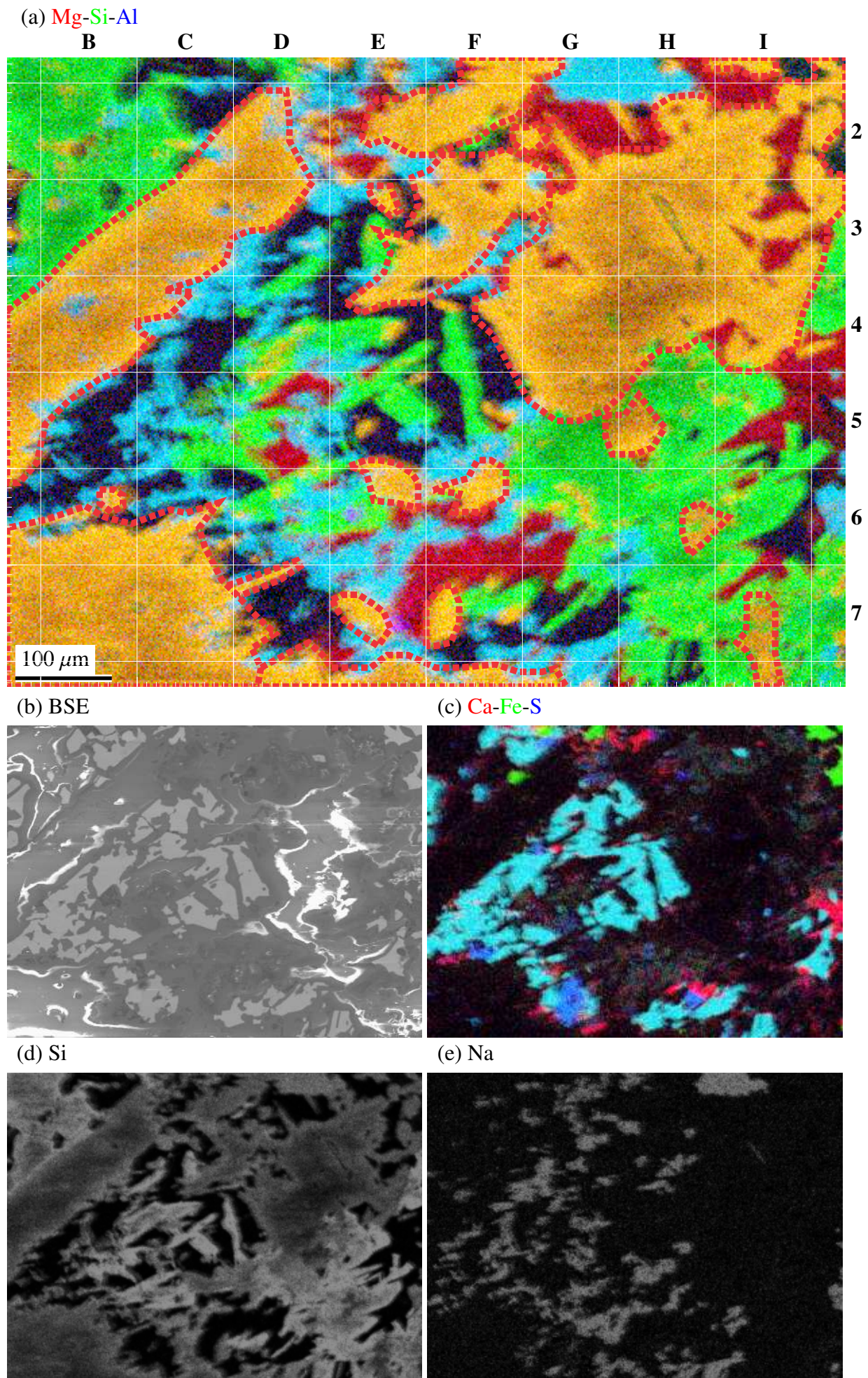


Figure 2.57: Site-5 of LAP02225 (EH imp melt). (a) Mg:Si:Al image with enstatite grains outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.53.

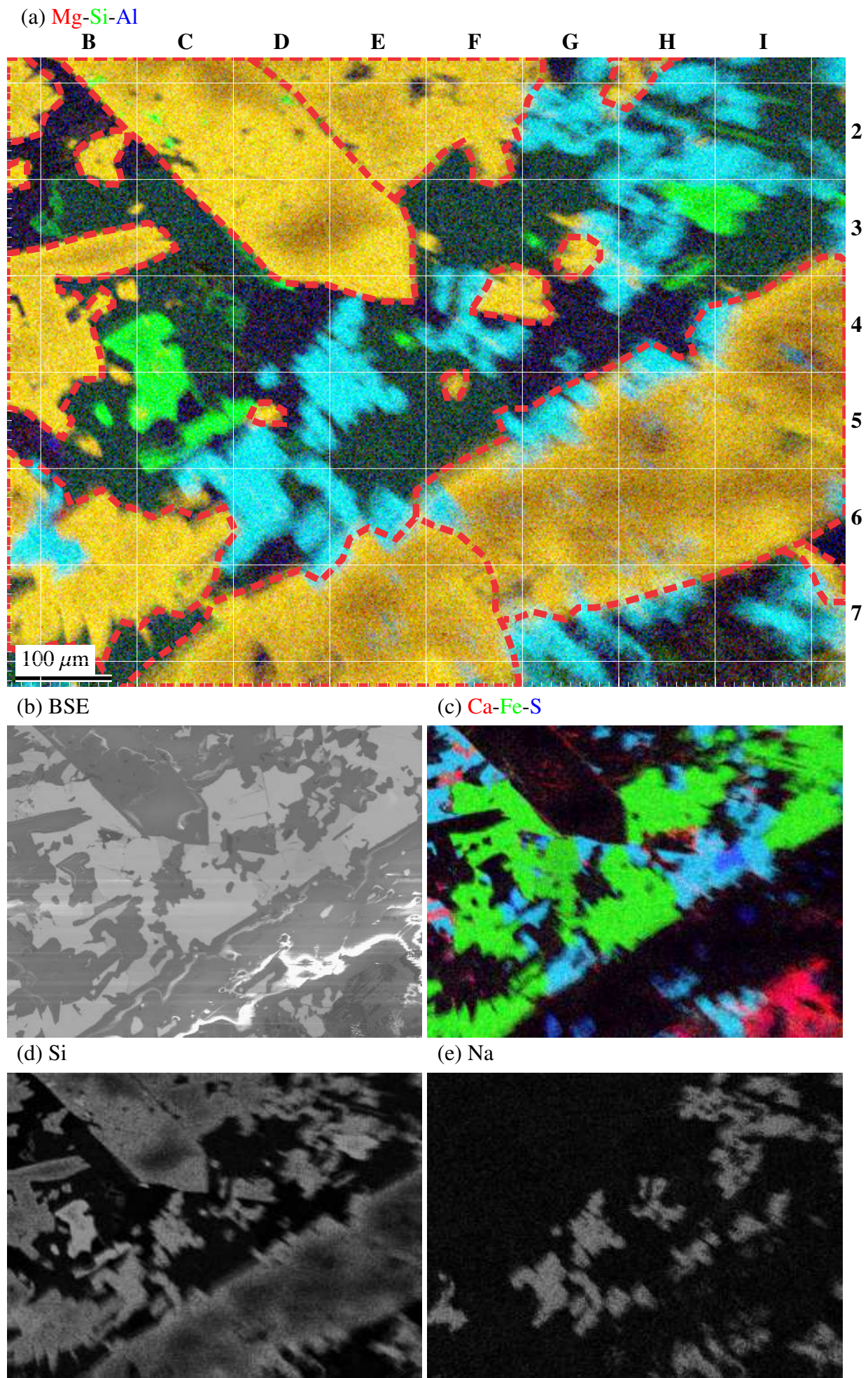


Figure 2.58: Site-6 of LAP02225 (EH imp melt). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.53.

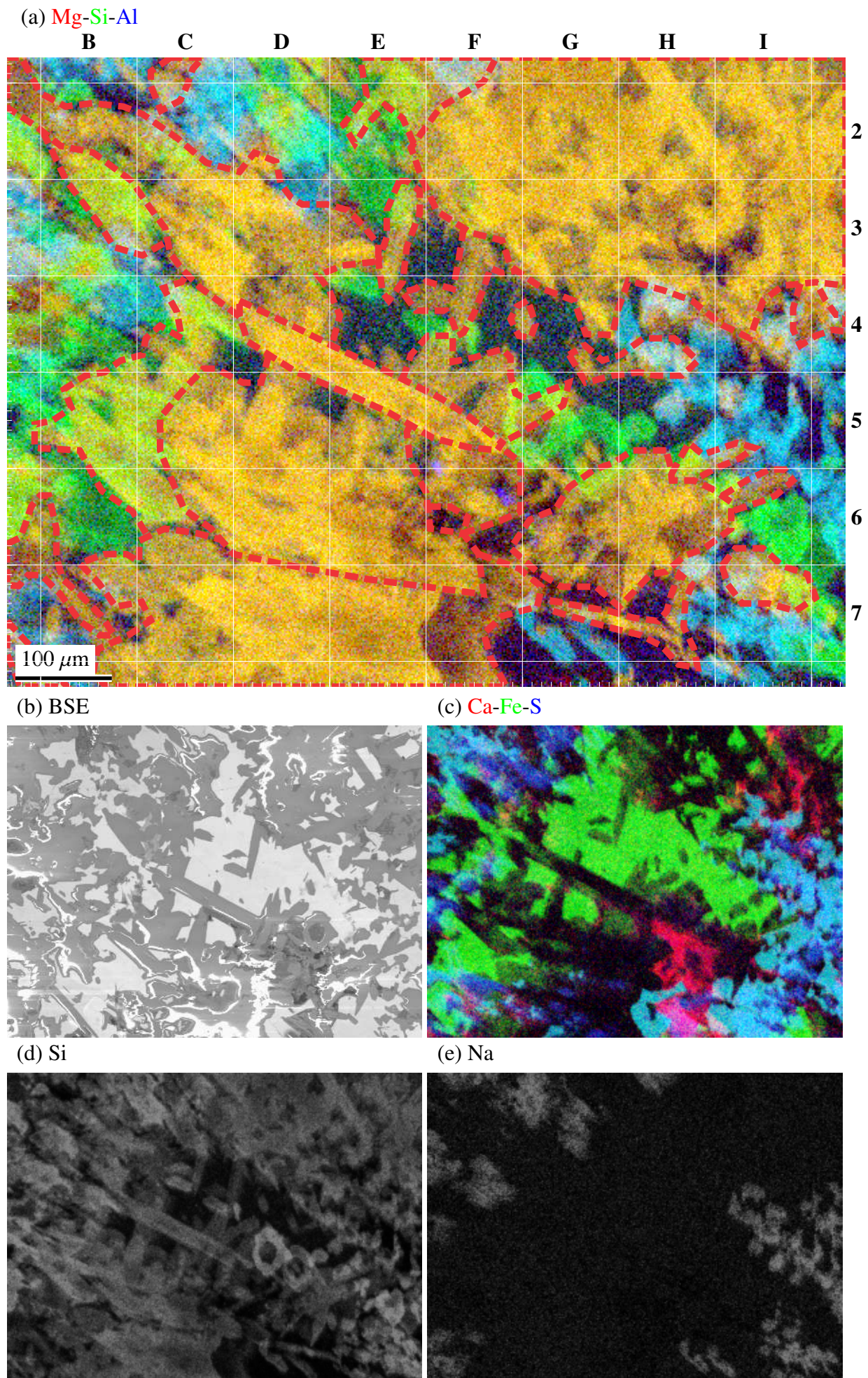


Figure 2.59: Site-7 of LAP02225 (EH imp melt). (a) Mg:Si:Al image with large enstatite grains outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.53.

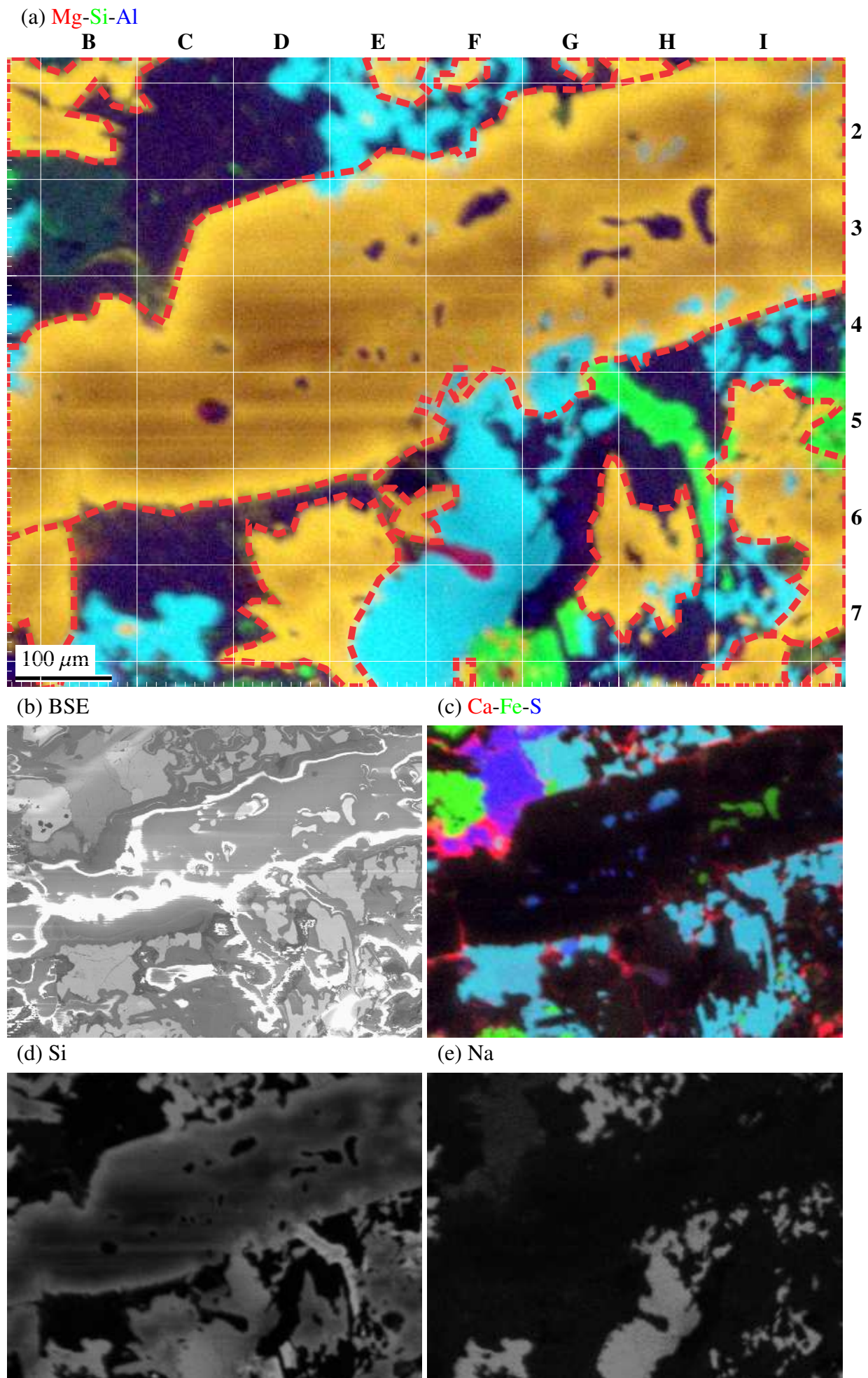


Figure 2.60: Site-8 of LAP02225 (EH imp melt). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.53.

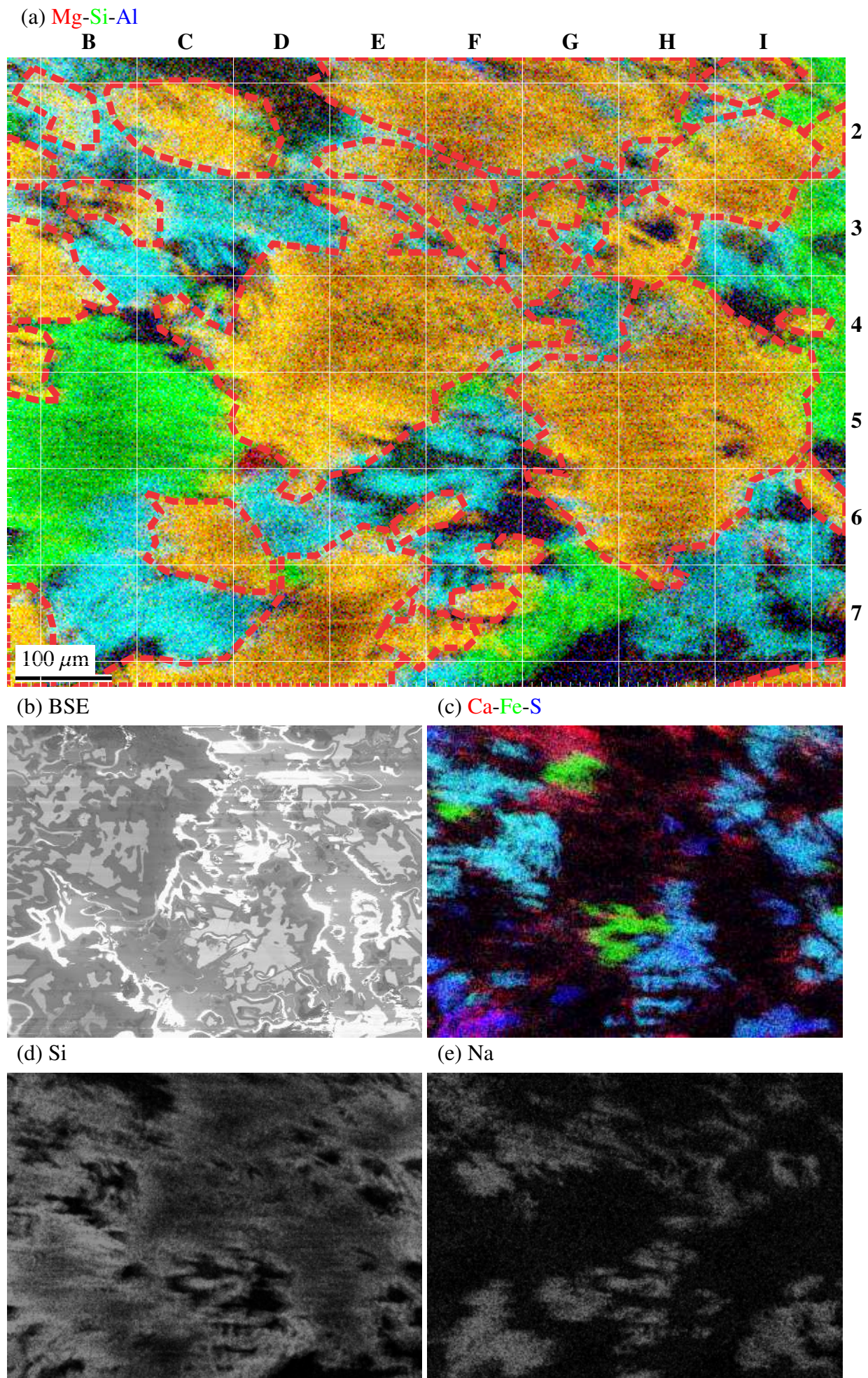


Figure 2.61: Site-9 of LAP02225 (EH imp melt). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.53.

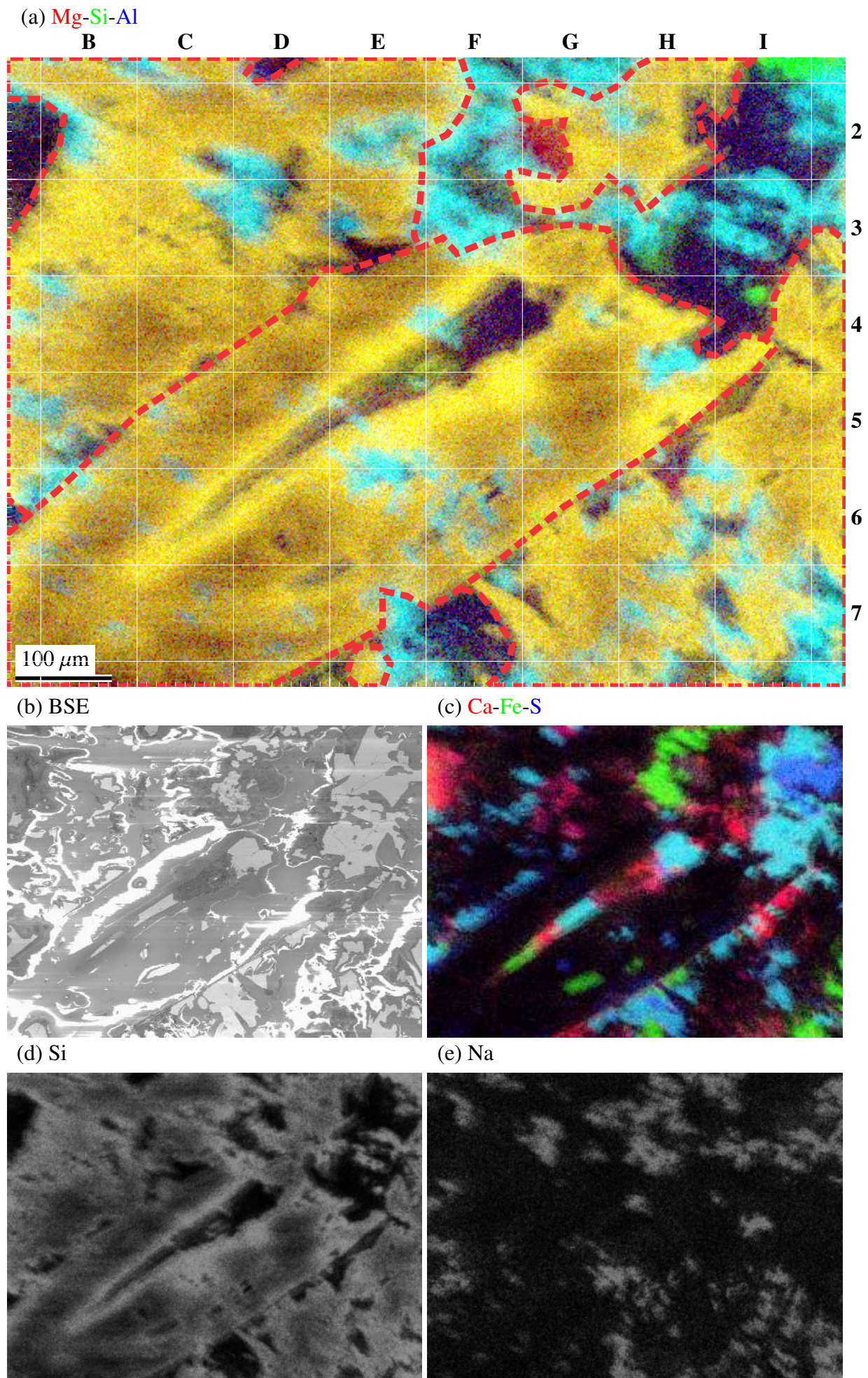


Figure 2.62: Site-10 of LAP02225 (EH imp melt). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.53.

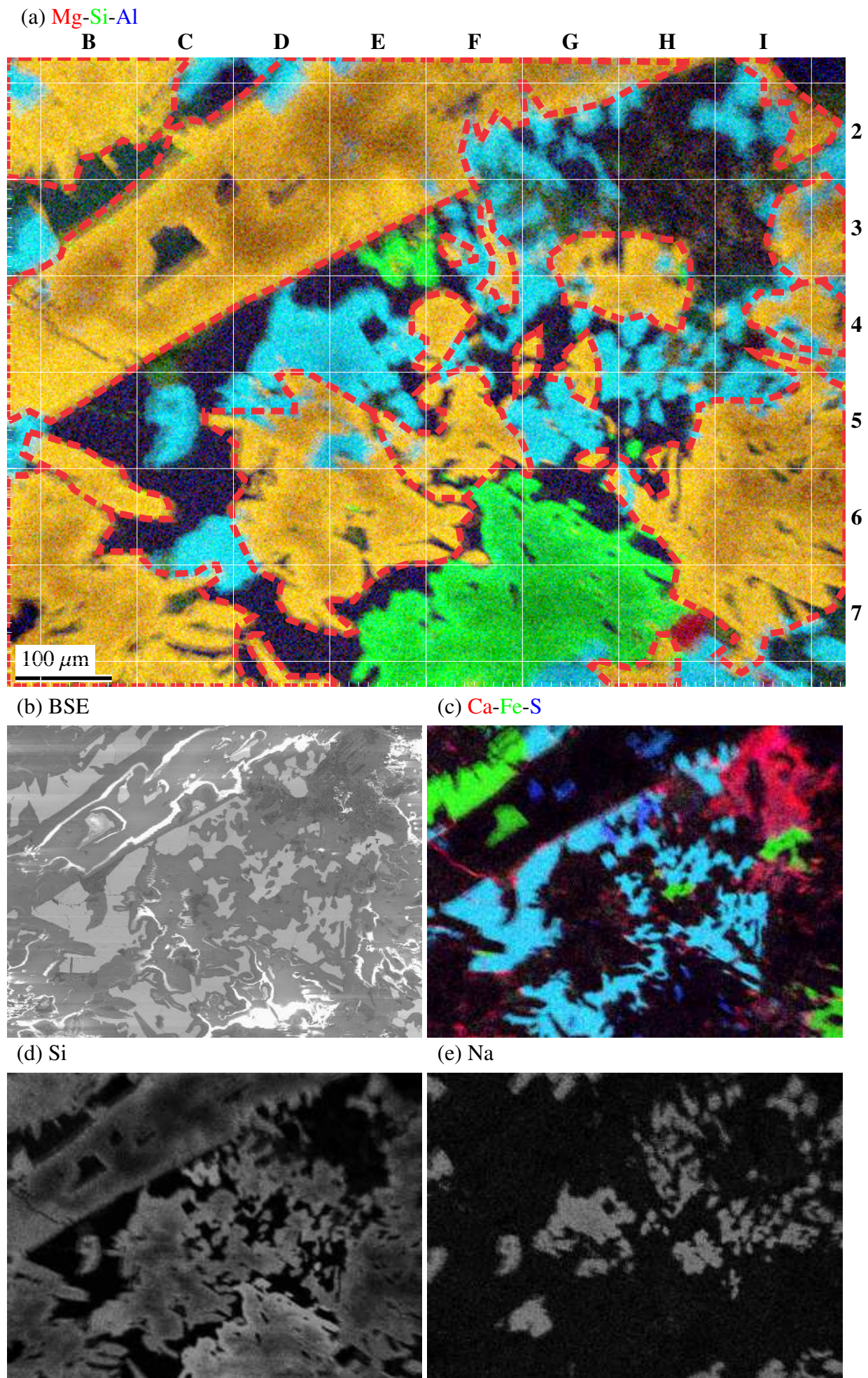


Figure 2.63: Site-11 of LAP02225 (EH imp melt). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.53.

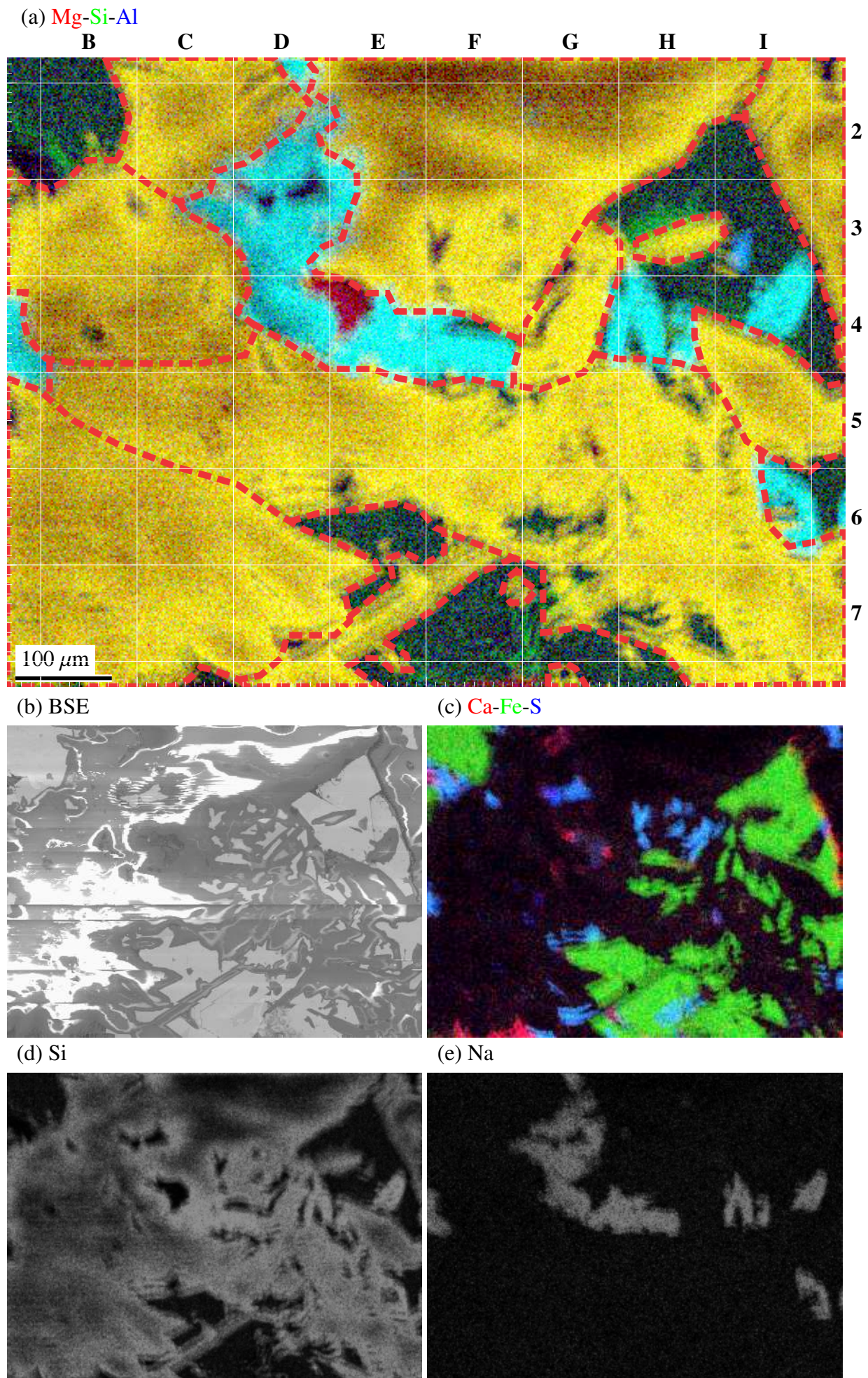


Figure 2.64: Site-12 of LAP02225 (EH imp melt). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.53.

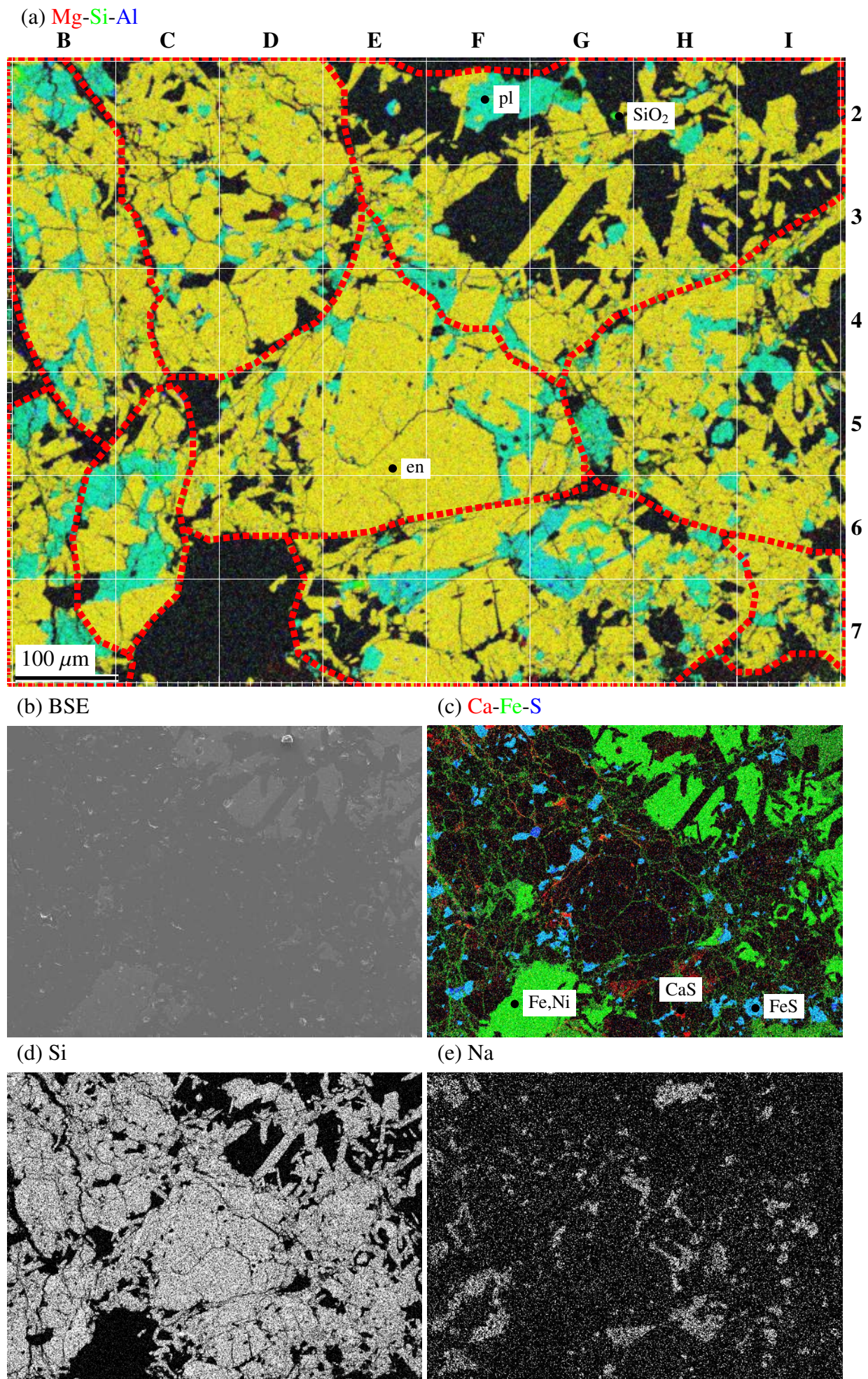


Figure 2.65: Site-1 of MAC02837 (EL3). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown.

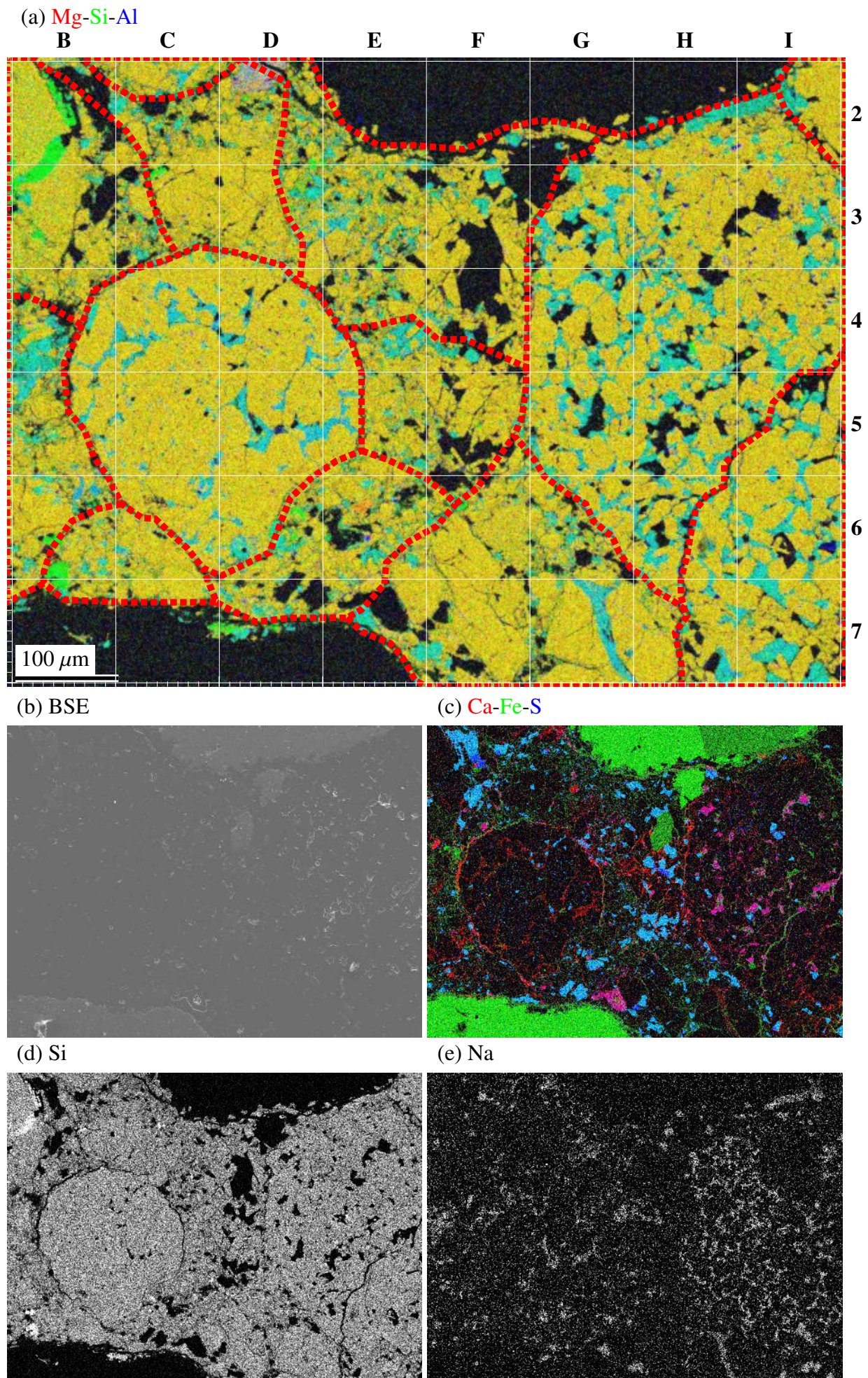


Figure 2.66: Site-2 of MAC02837 (EL3). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.65.

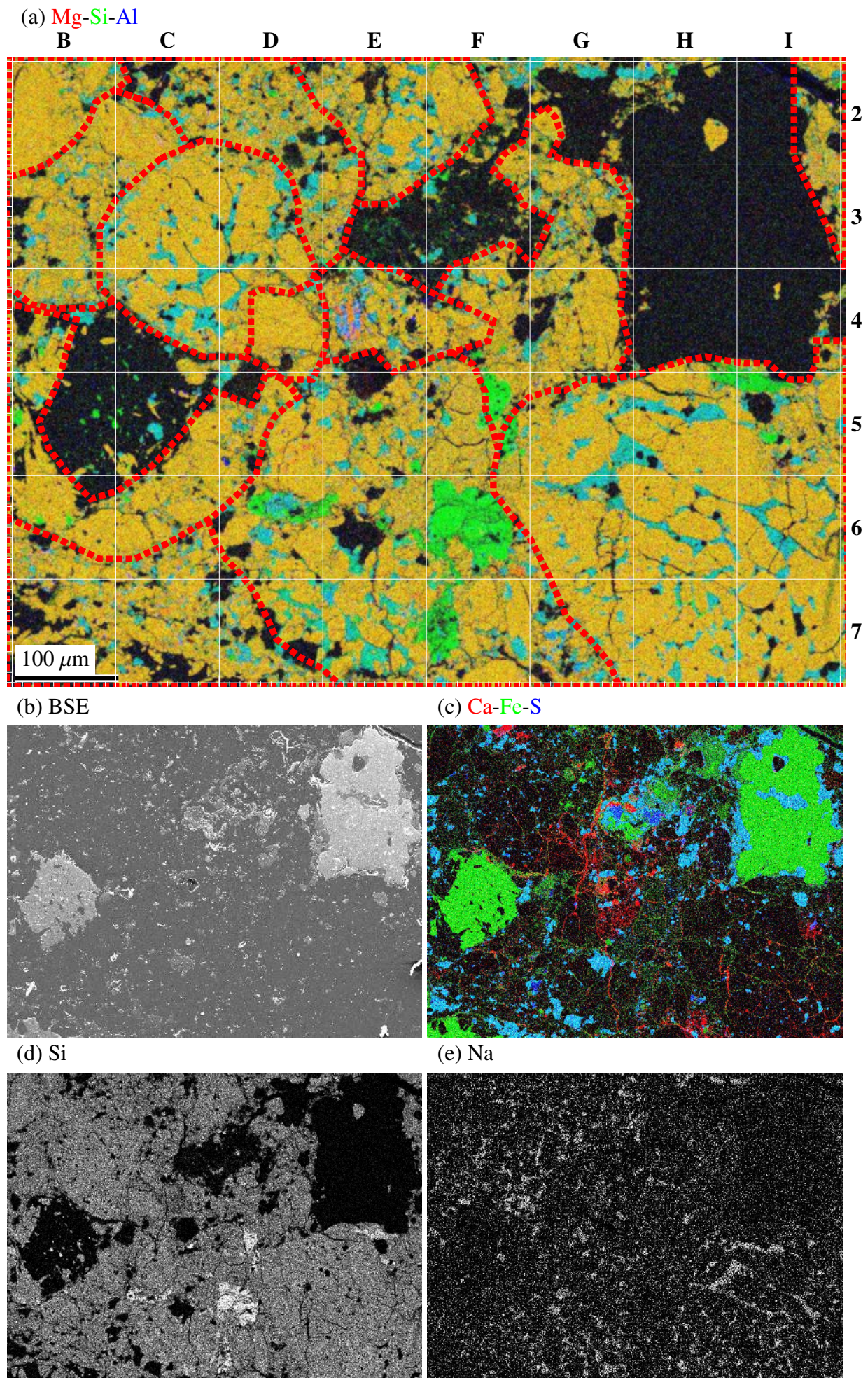


Figure 2.67: Site-3 of MAC02837 (EL3). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.65.

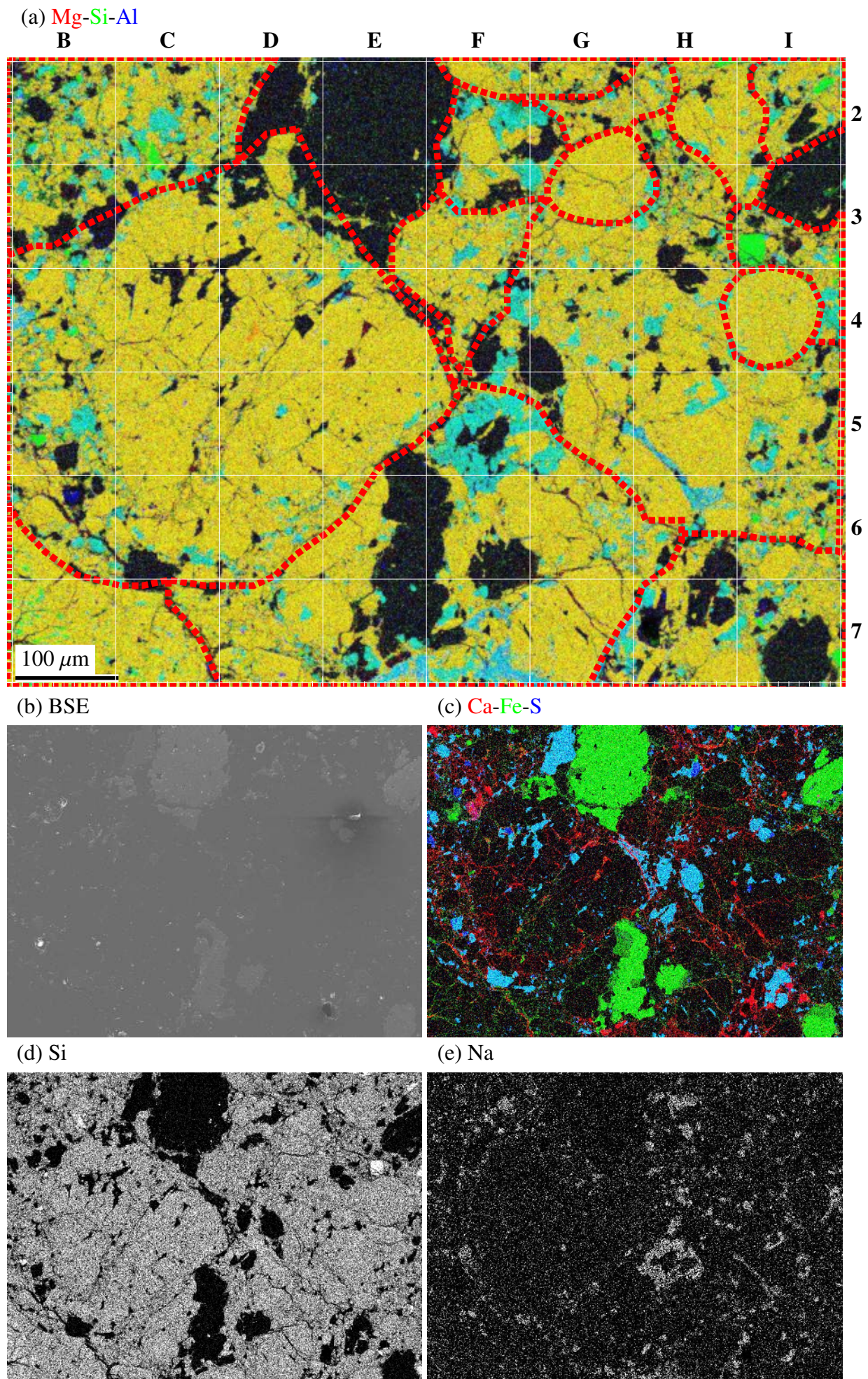


Figure 2.68: Site-4 of MAC02837 (EL3). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.65.

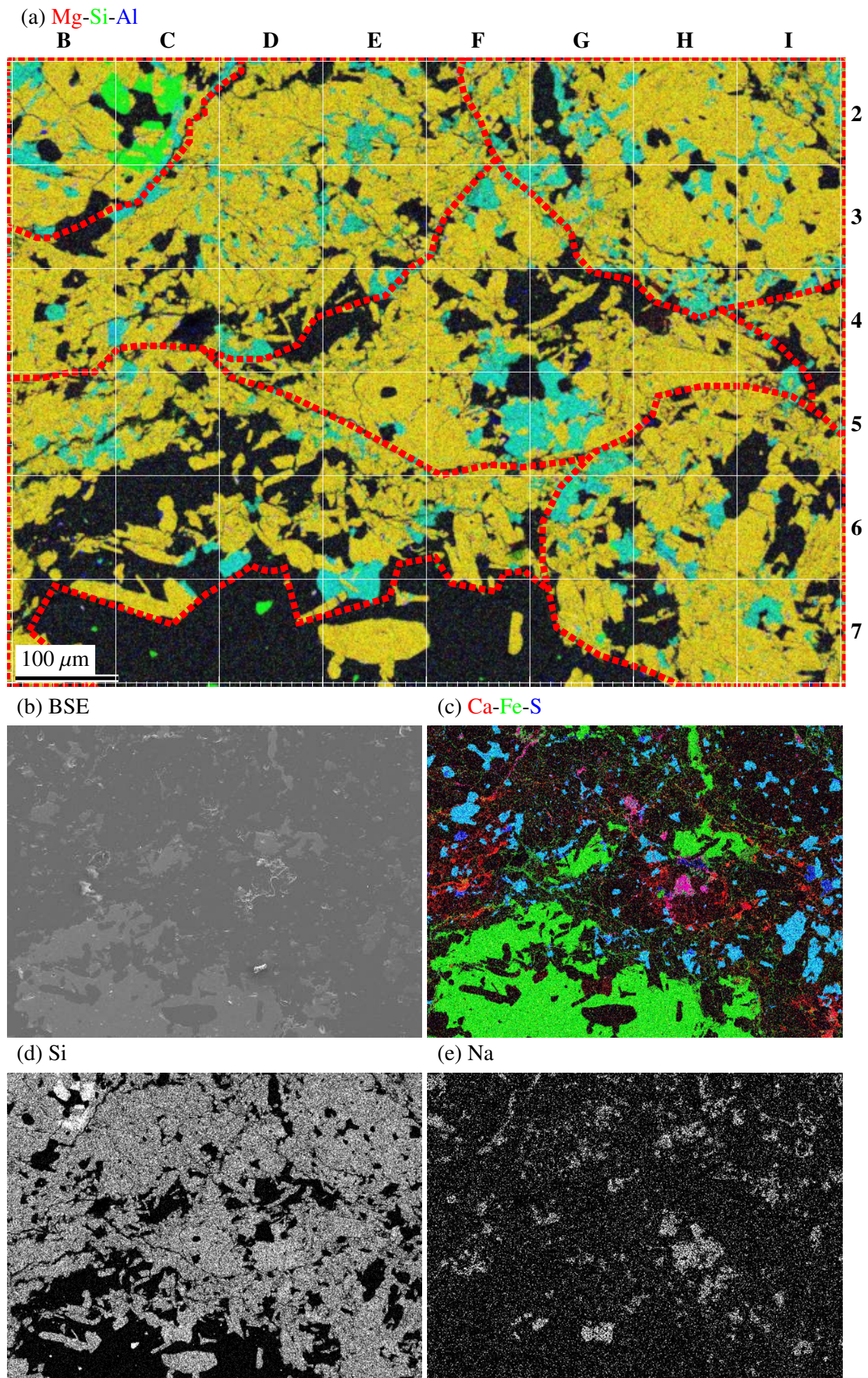


Figure 2.69: Site-5 of MAC02837 (EL3). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.65.

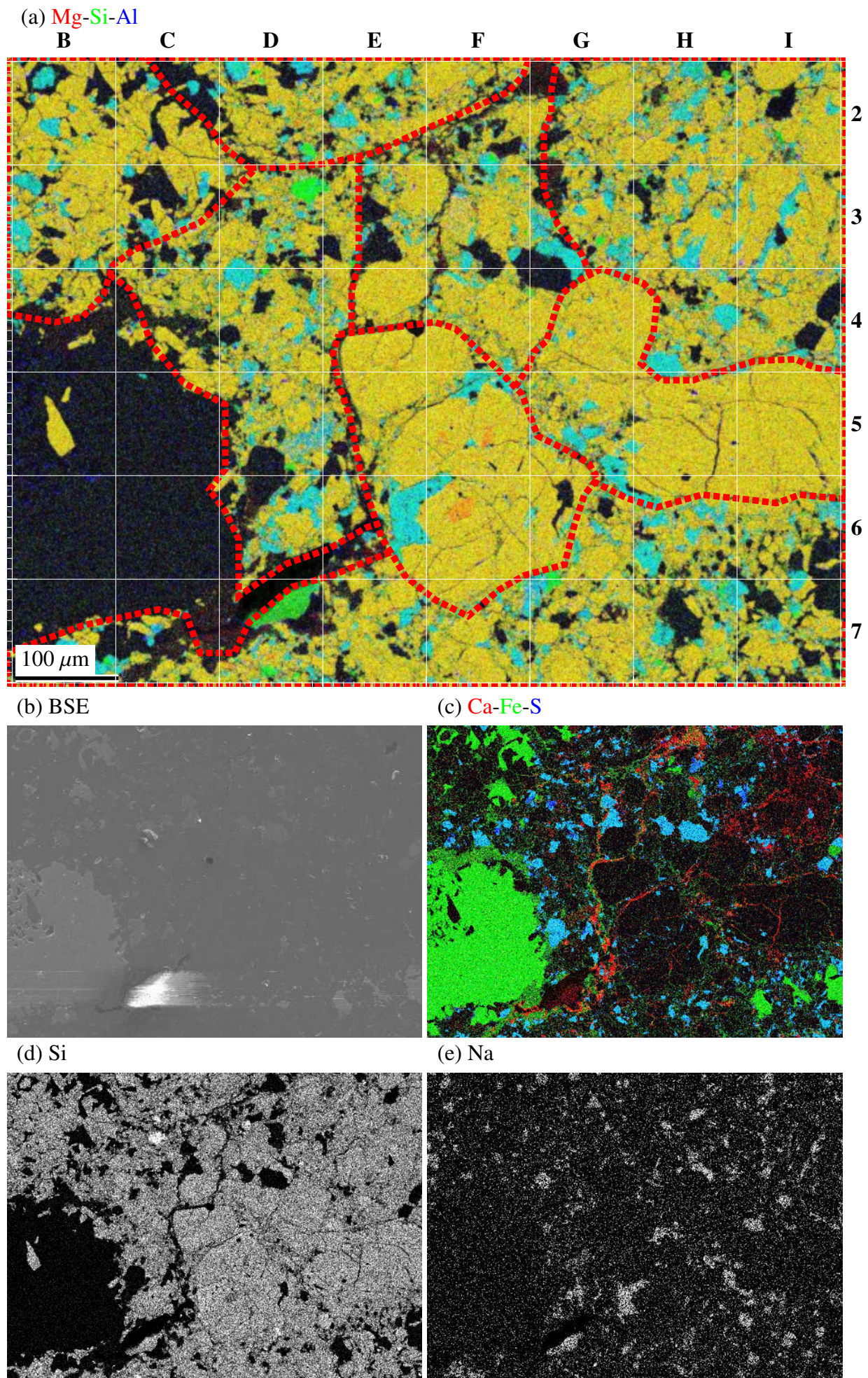


Figure 2.70: Site-6 of MAC02837 (EL3). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.65.

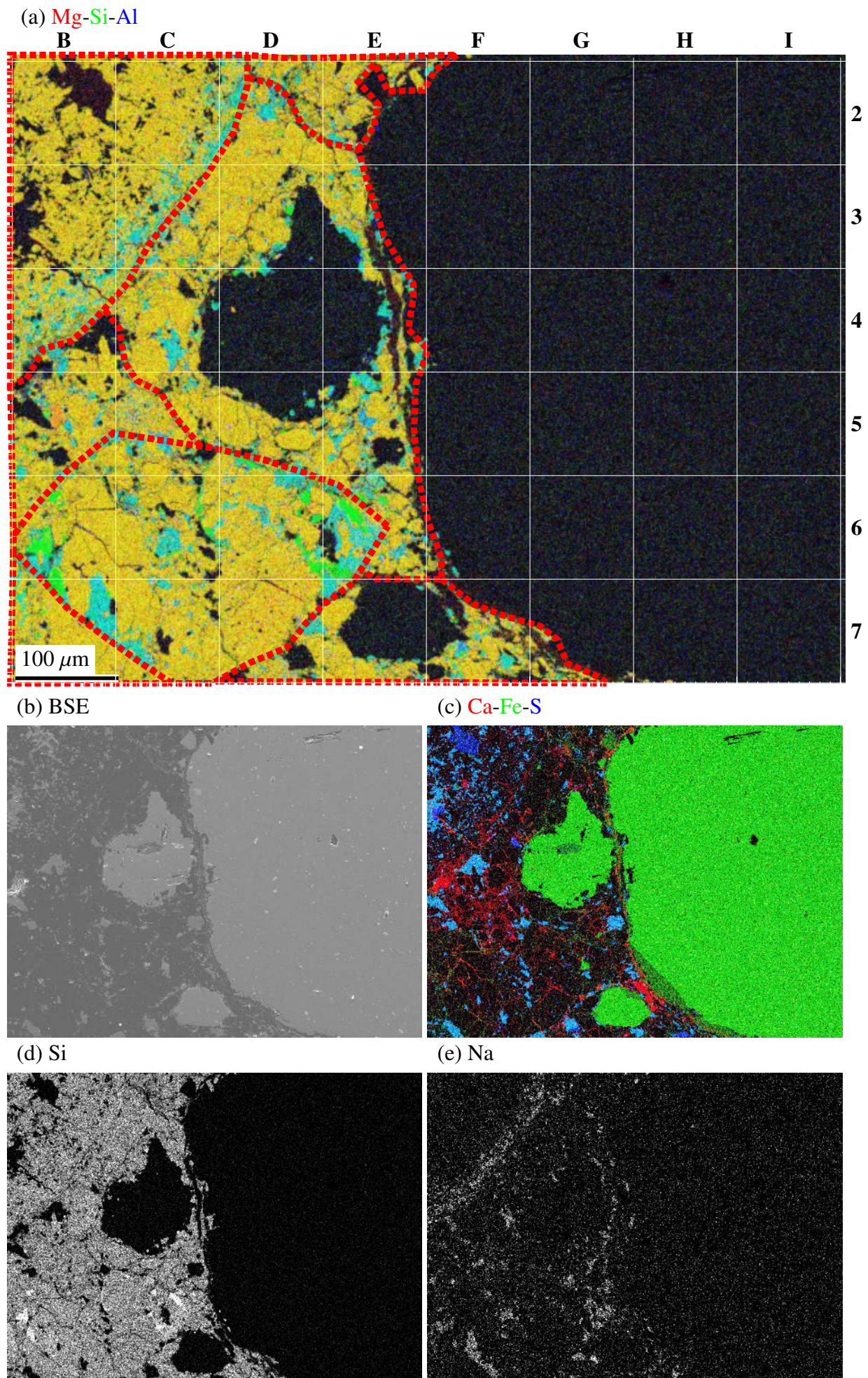


Figure 2.71: Site-7 of MAC02837 (EL3). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.65.

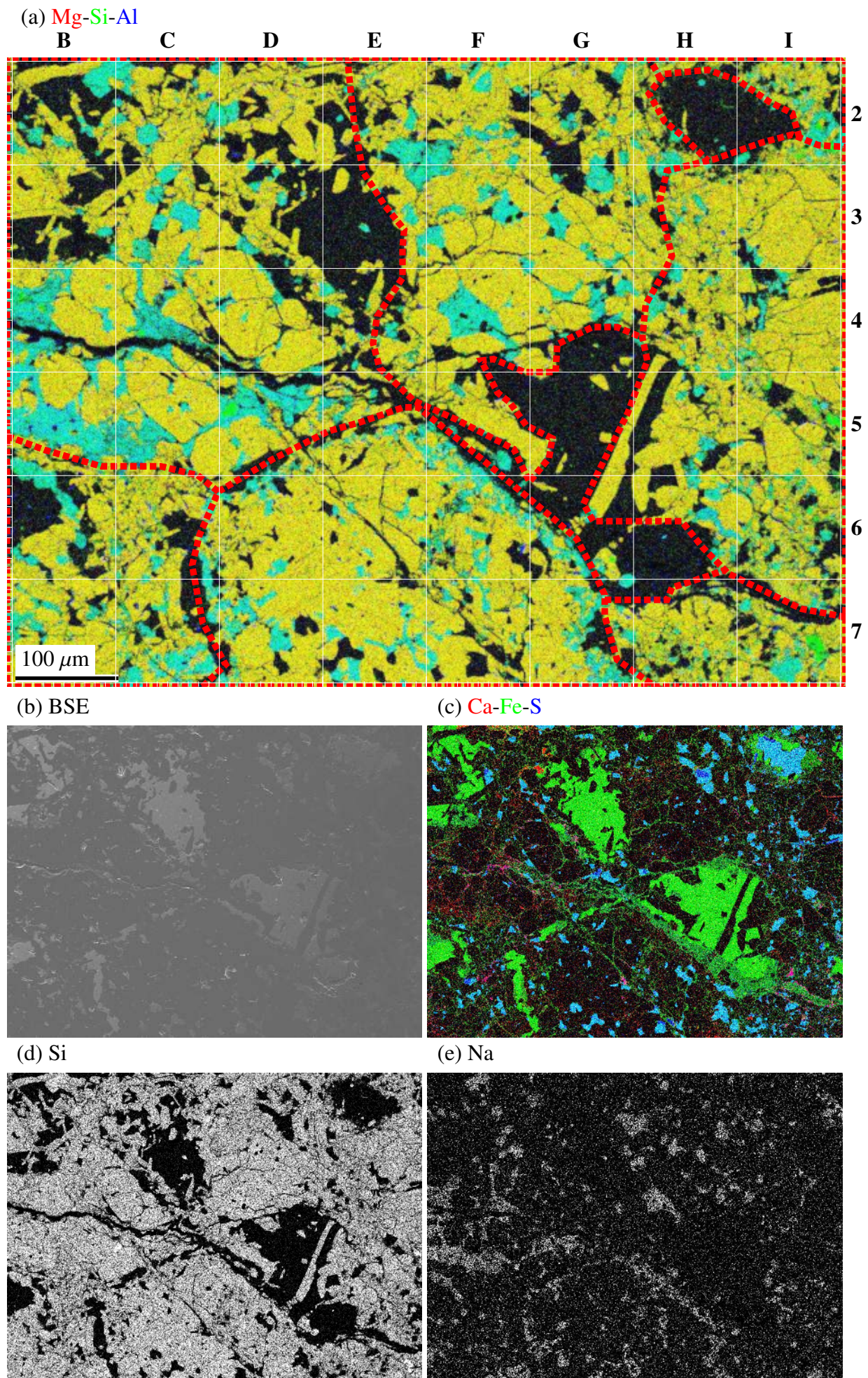


Figure 2.72: Site-8 of MAC02837 (EL3). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.65.

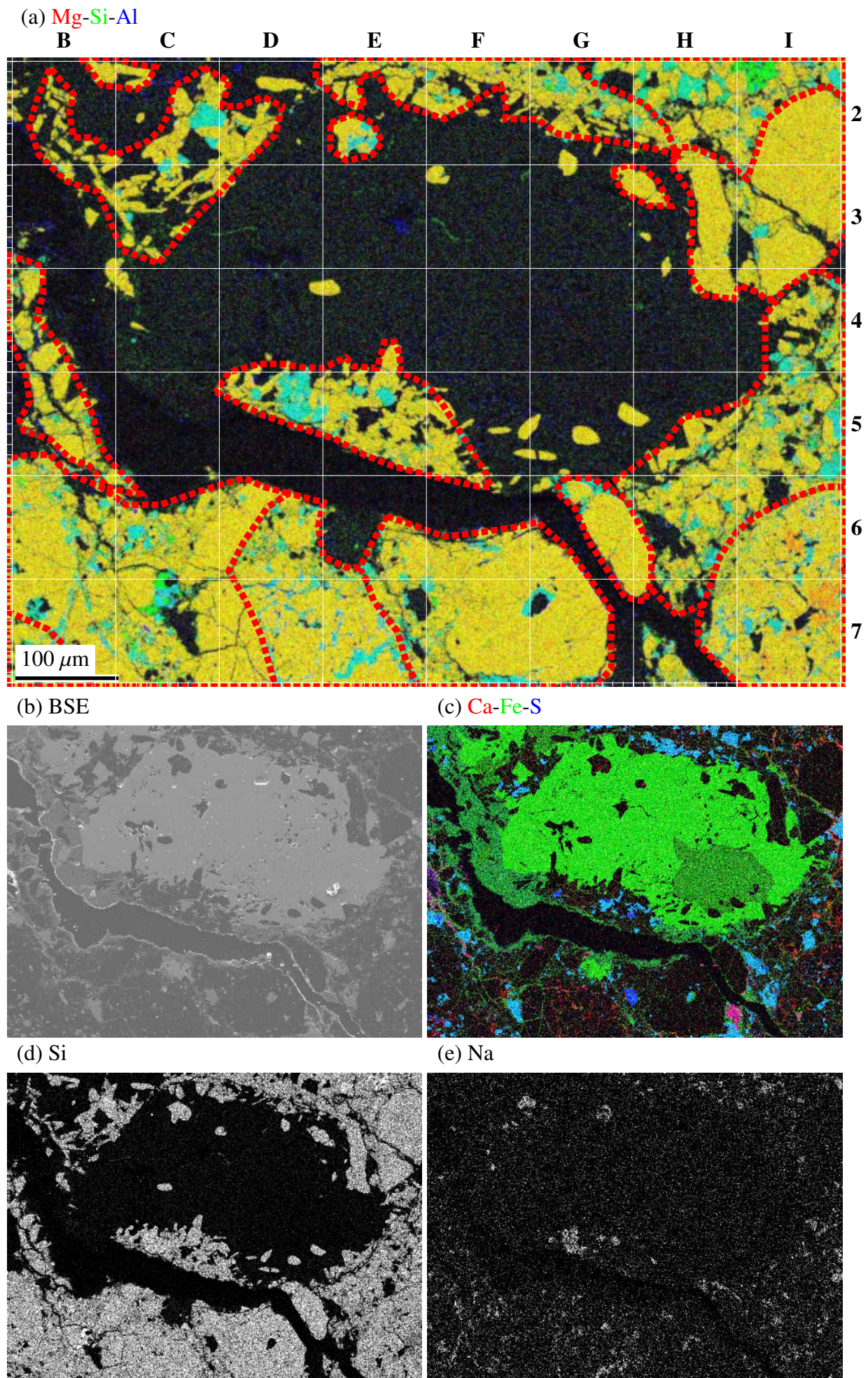


Figure 2.73: Site-9 of MAC02837 (EL3). (a) Mg:Si:Al image with chondrules and chondrule fragments outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.65.

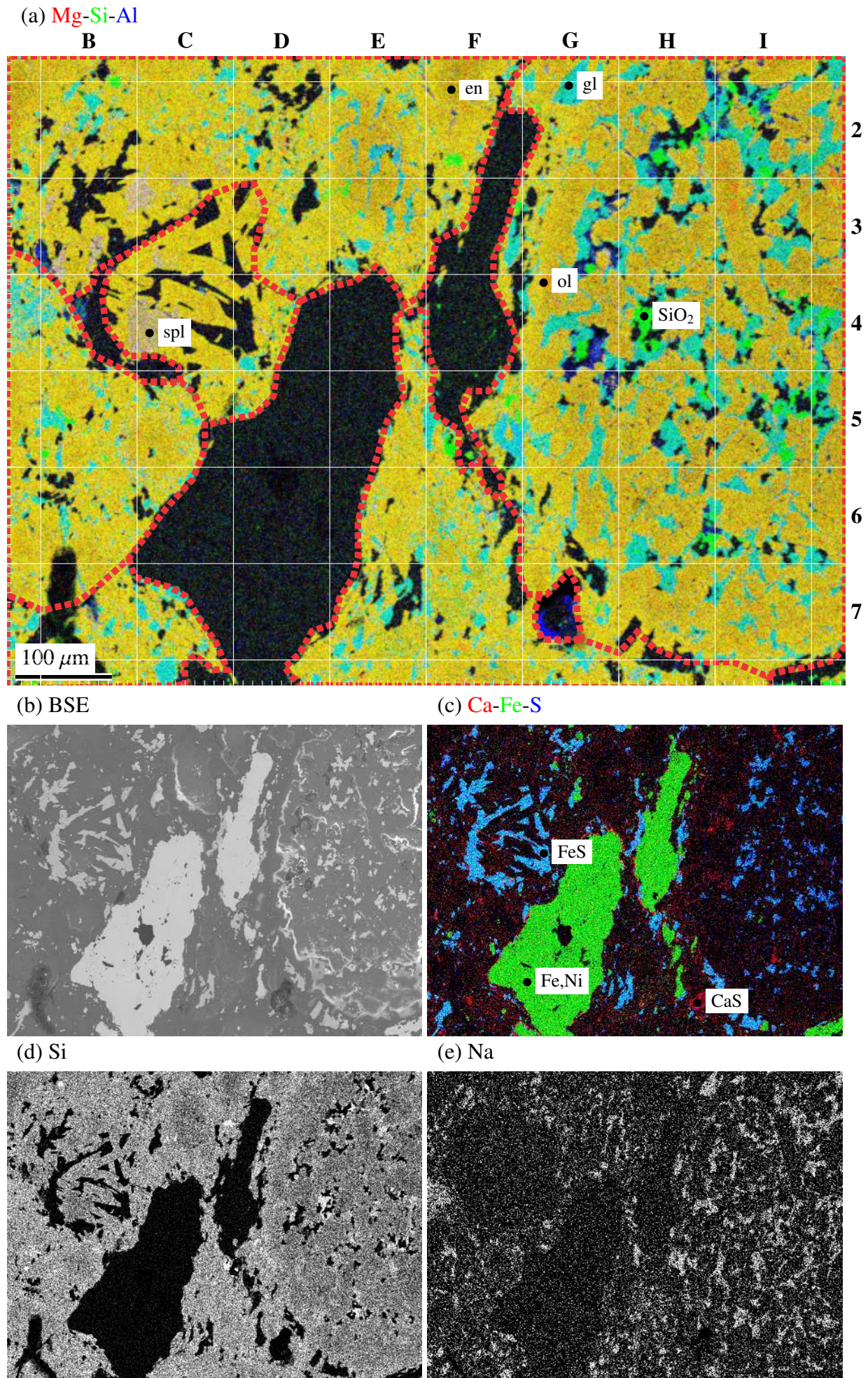


Figure 2.74: Site-1 of PCA91020 (EL3). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown.

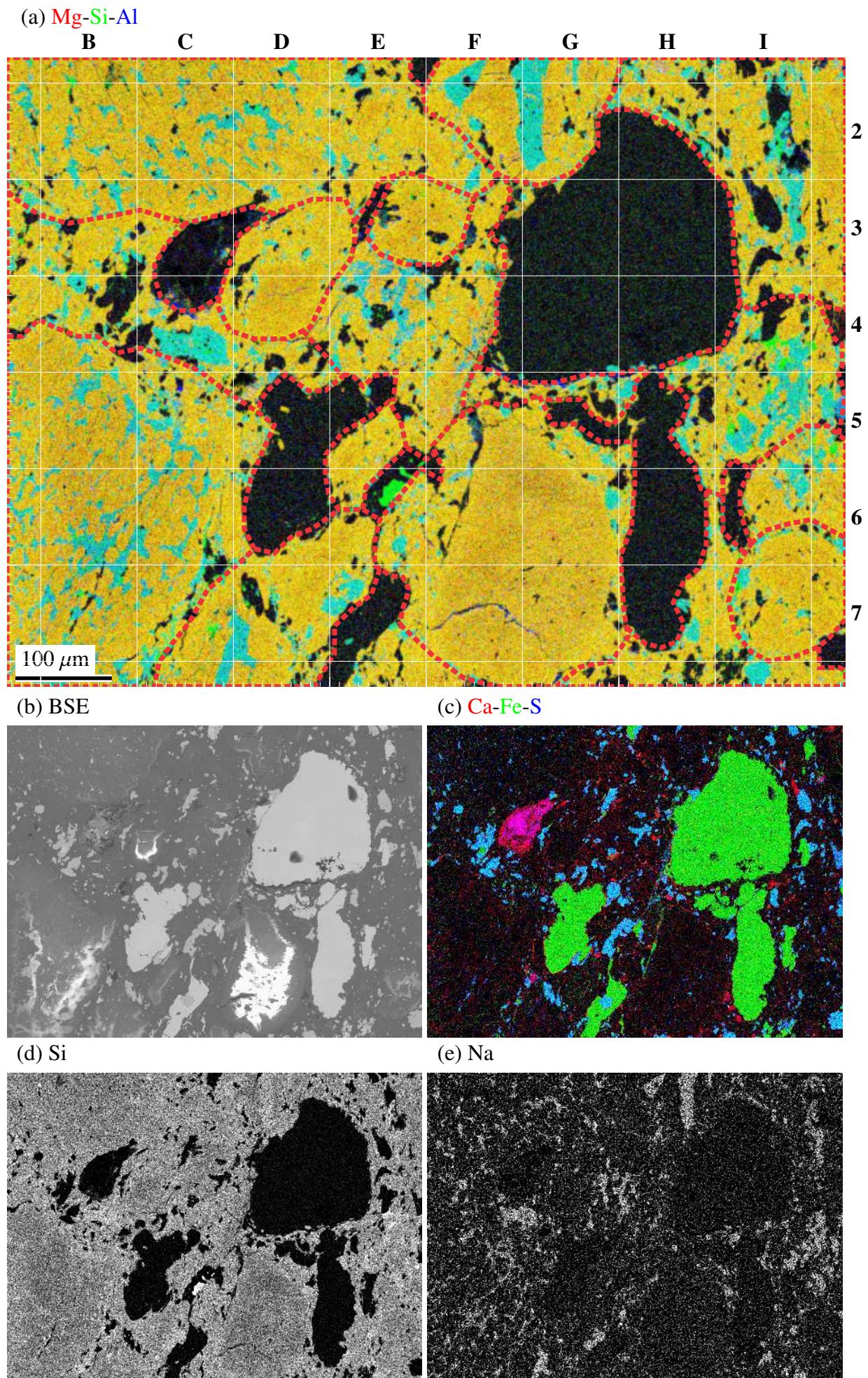


Figure 2.75: Site-2 of PCA91020 (EL3). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.74.

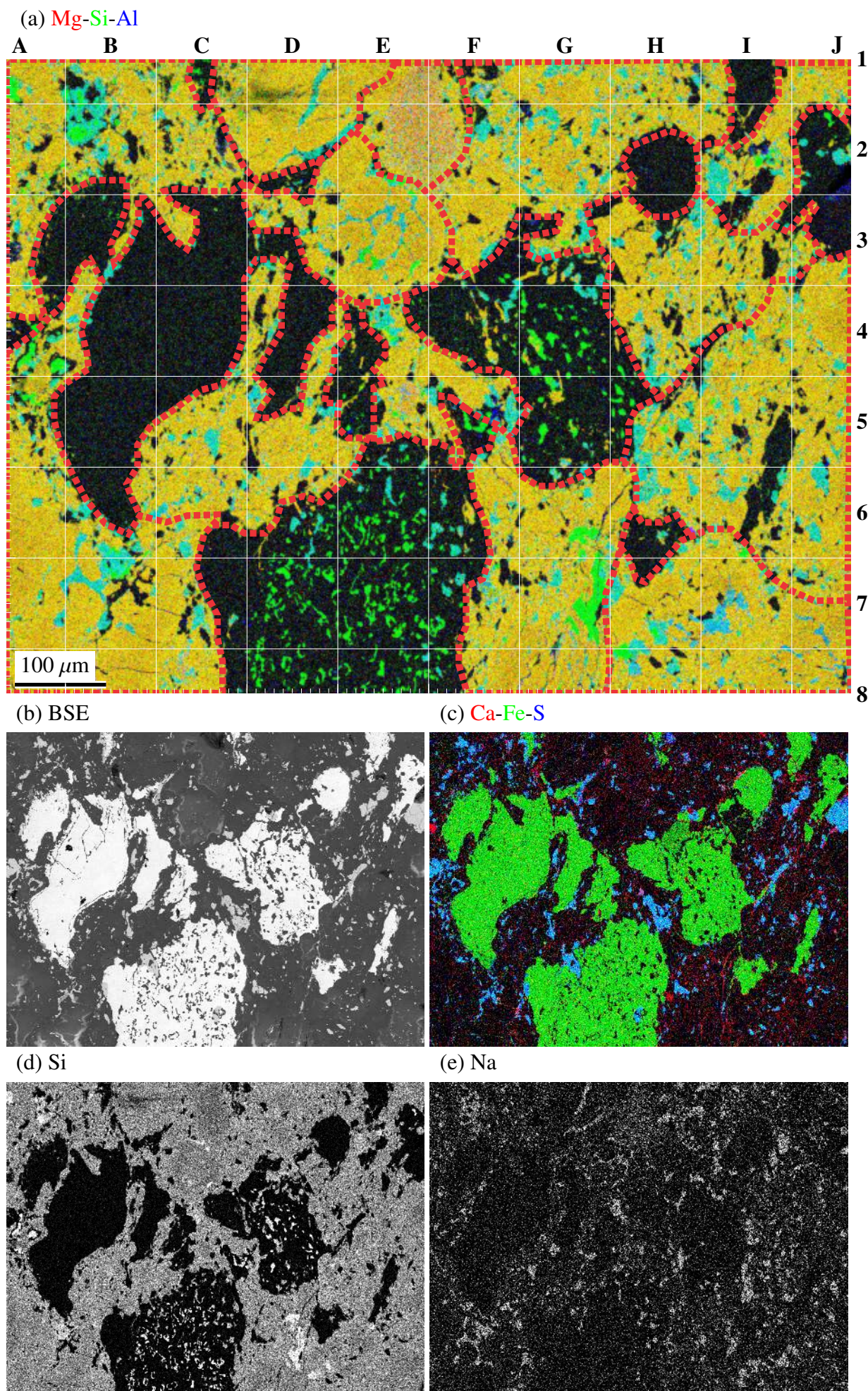


Figure 2.76: Site-3 of PCA91020 (EL3). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.74.

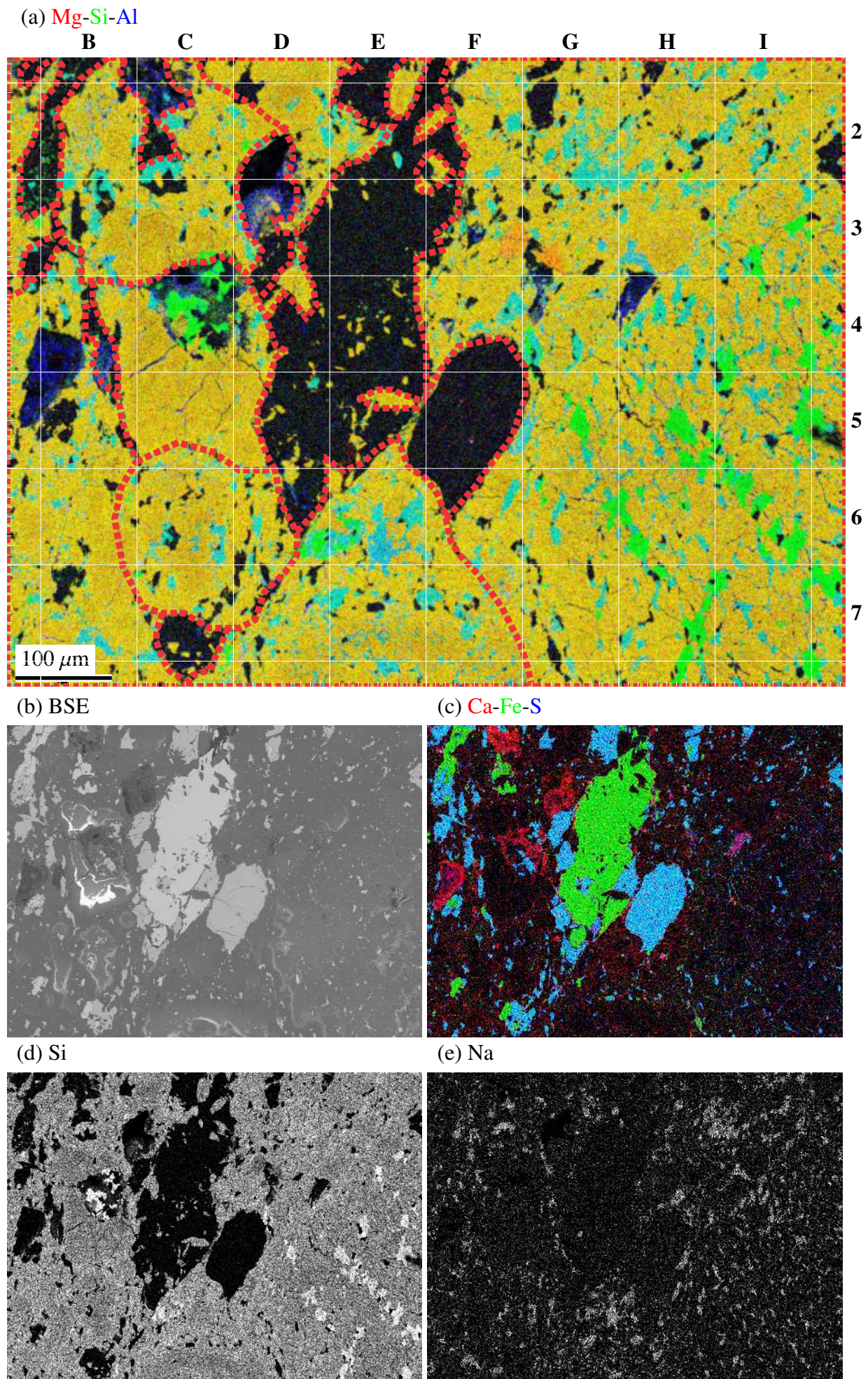


Figure 2.77: Site-4 of PCA91020 (EL3). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.74.

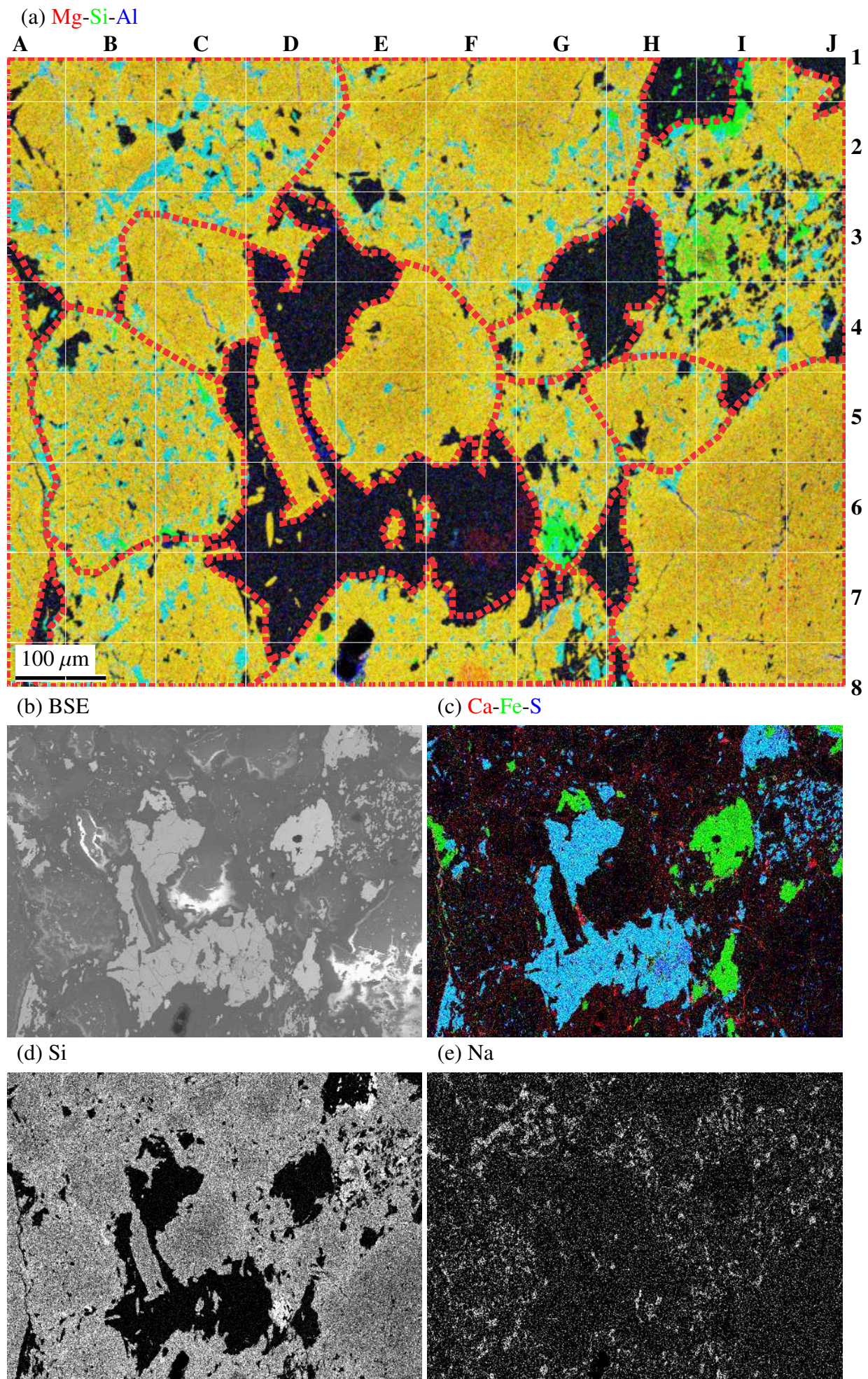


Figure 2.78: Site-5 of PCA91020 (EL3). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.74.

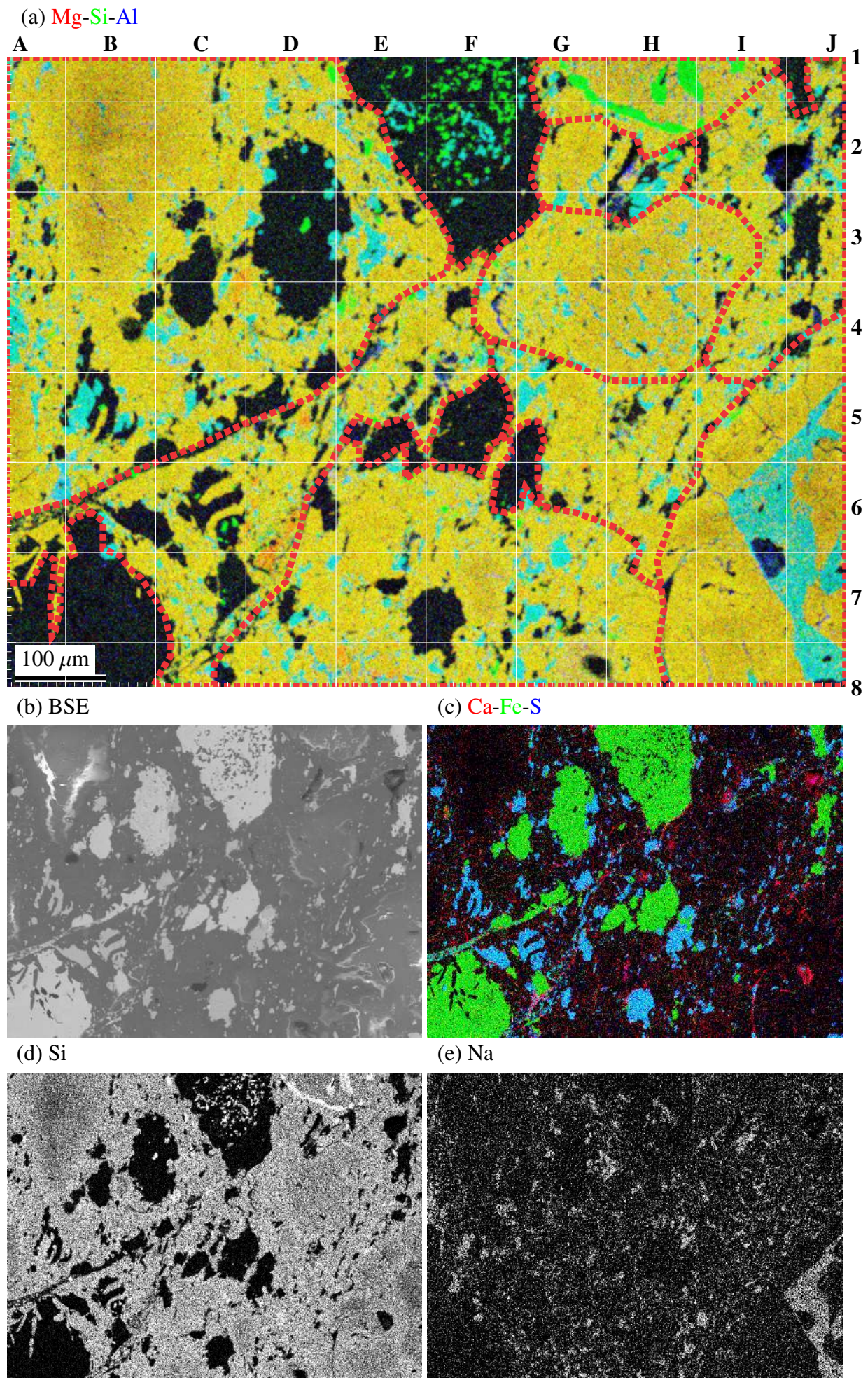


Figure 2.79: Site-6 of PCA91020 (EL3). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.74.

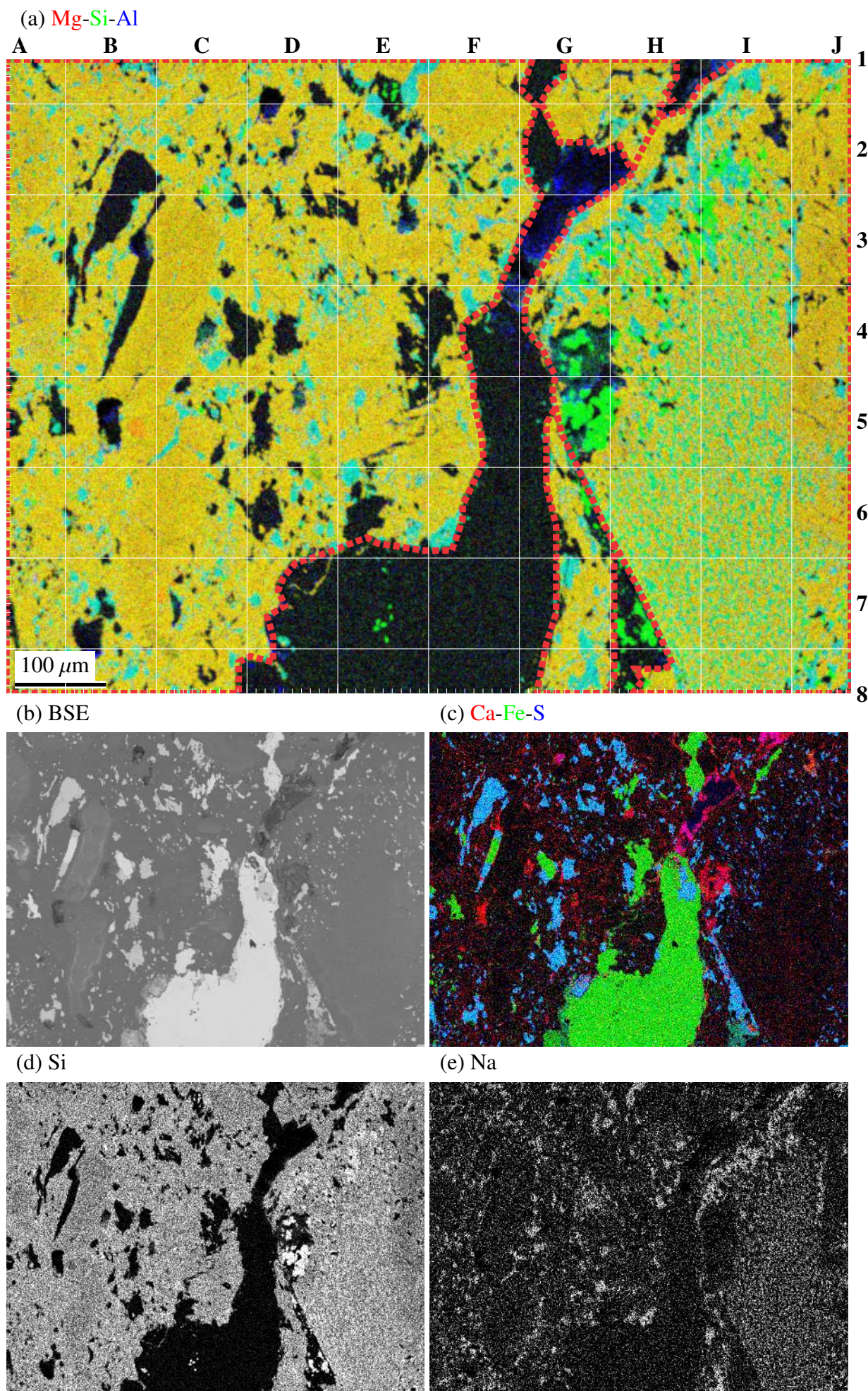


Figure 2.80: Site-7 of PCA91020 (EL3). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.74.

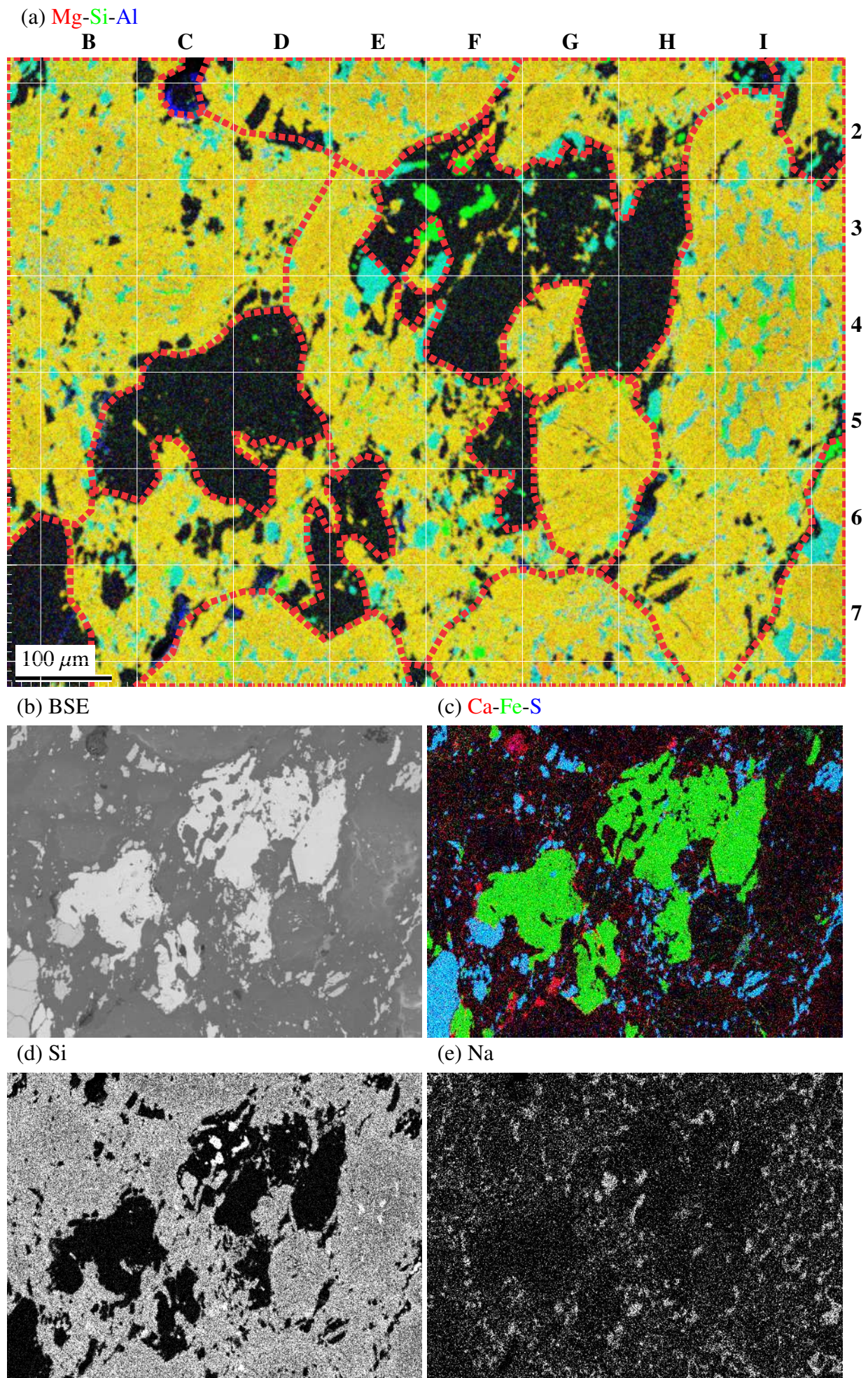


Figure 2.81: Site-8 of PCA91020 (EL3). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.74.

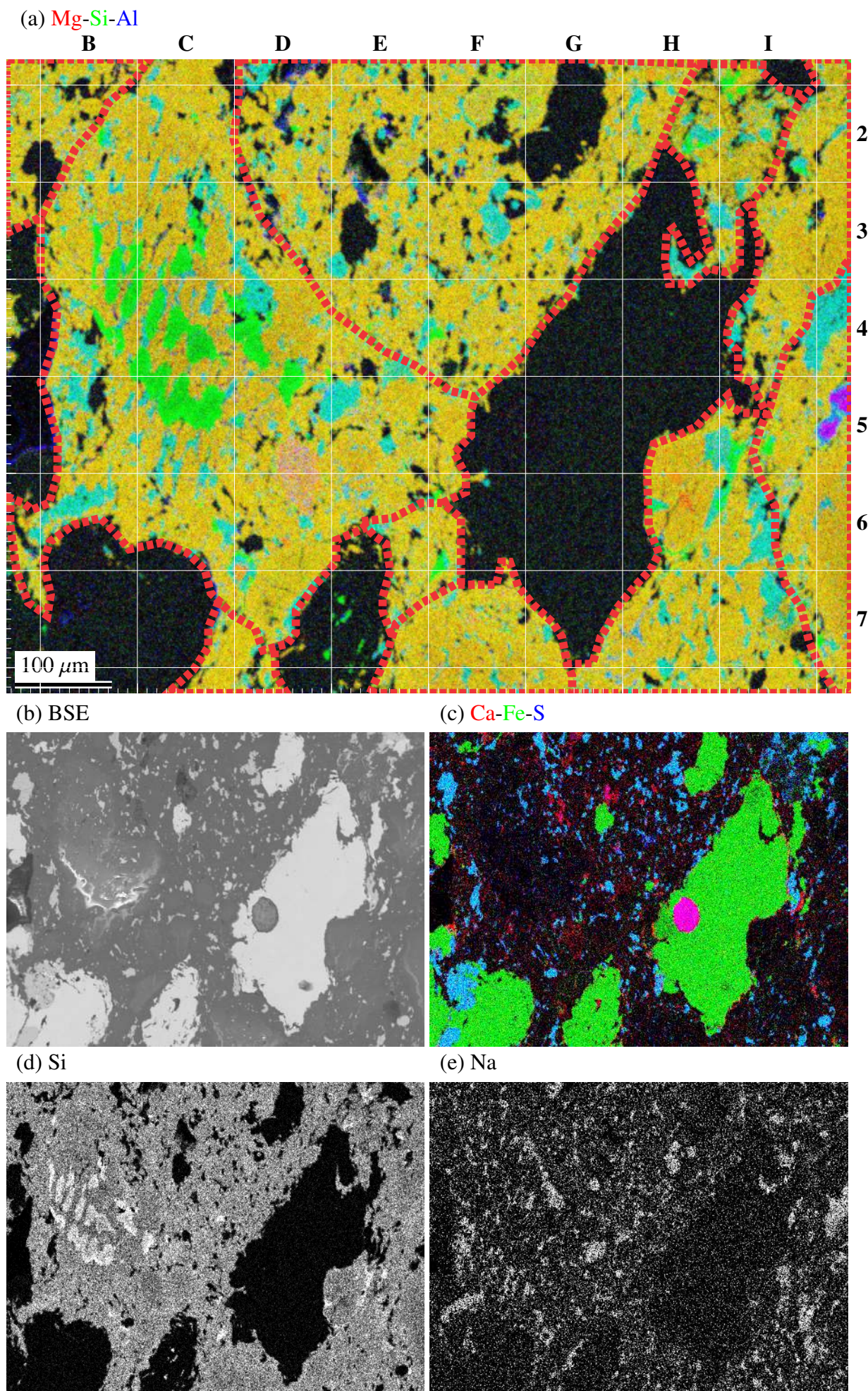


Figure 2.82: Site-9 of PCA91020 (EL3). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.74.

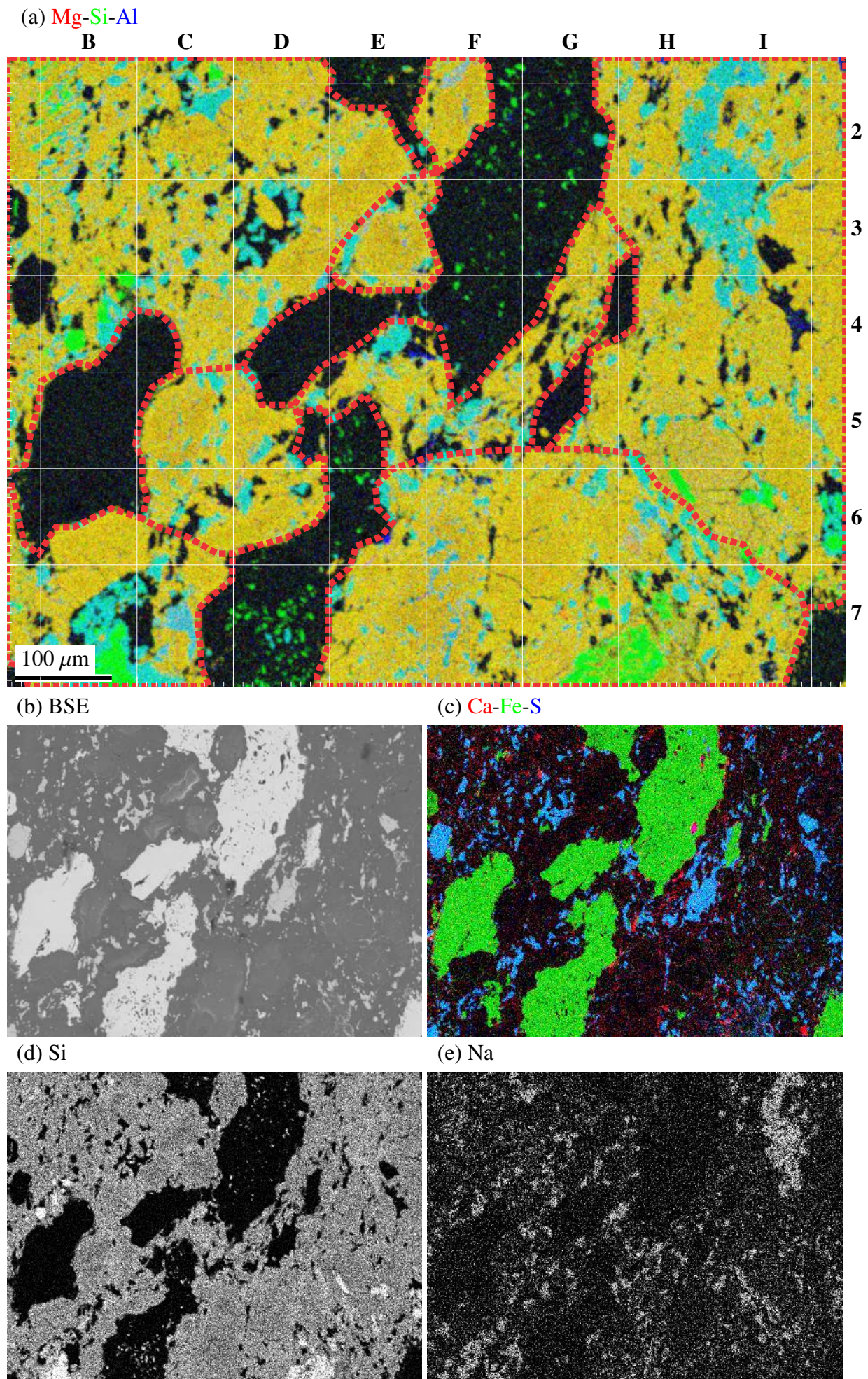


Figure 2.83: Site-10 of PCA91020 (EL3). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.74.

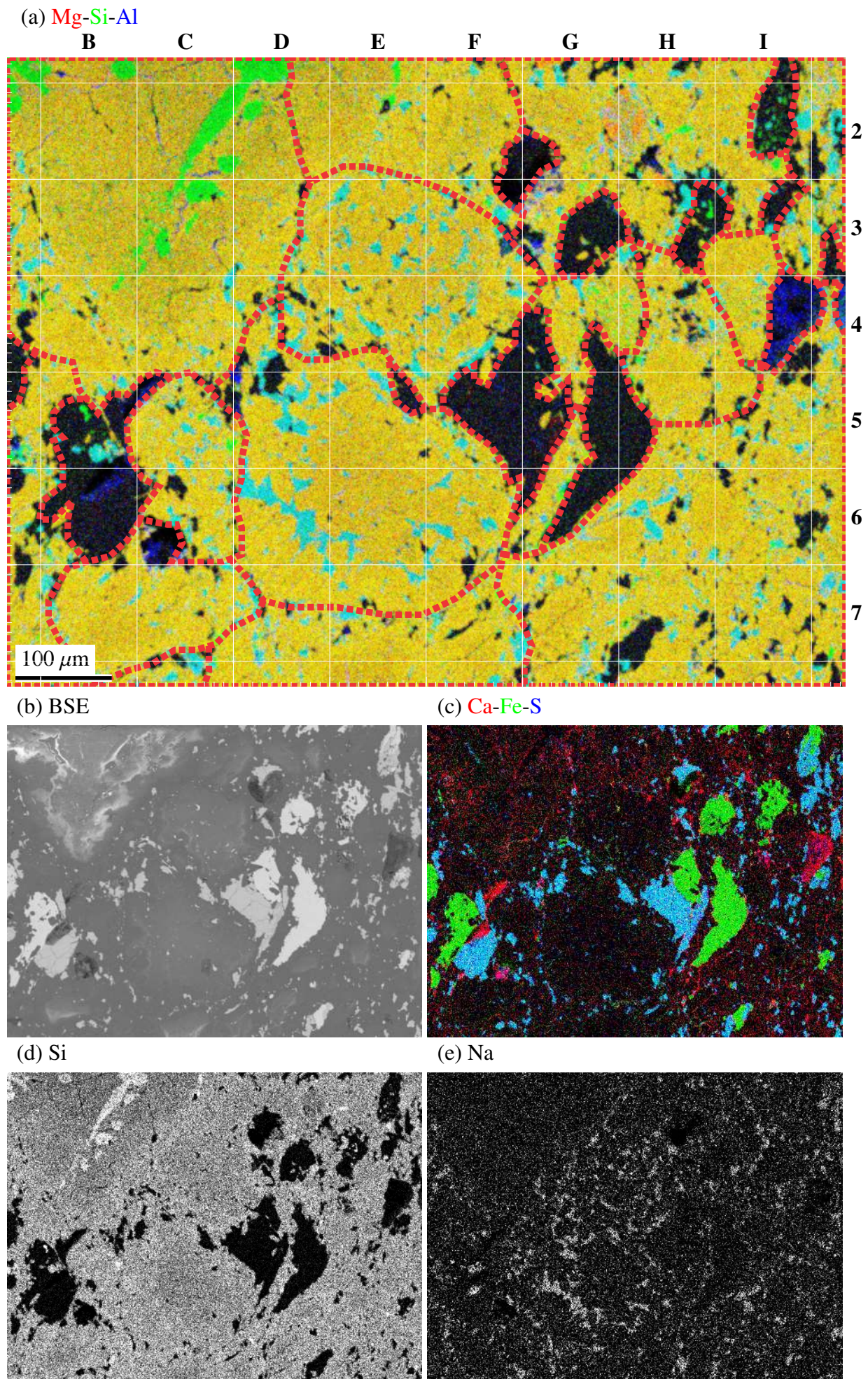


Figure 2.84: Site-11 of PCA91020 (EL3). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.74.

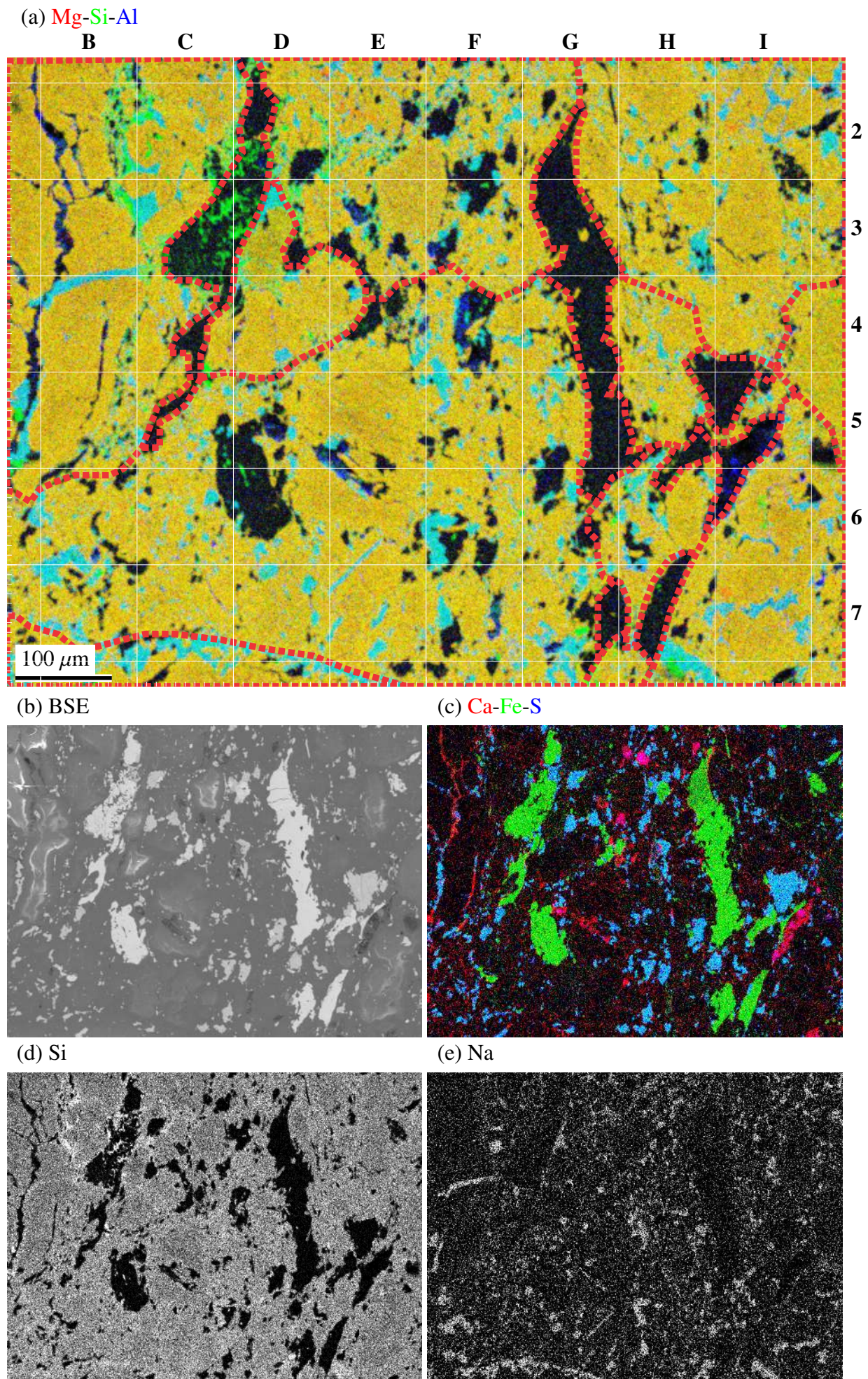


Figure 2.85: Site-12 of PCA91020 (EL3). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.74.

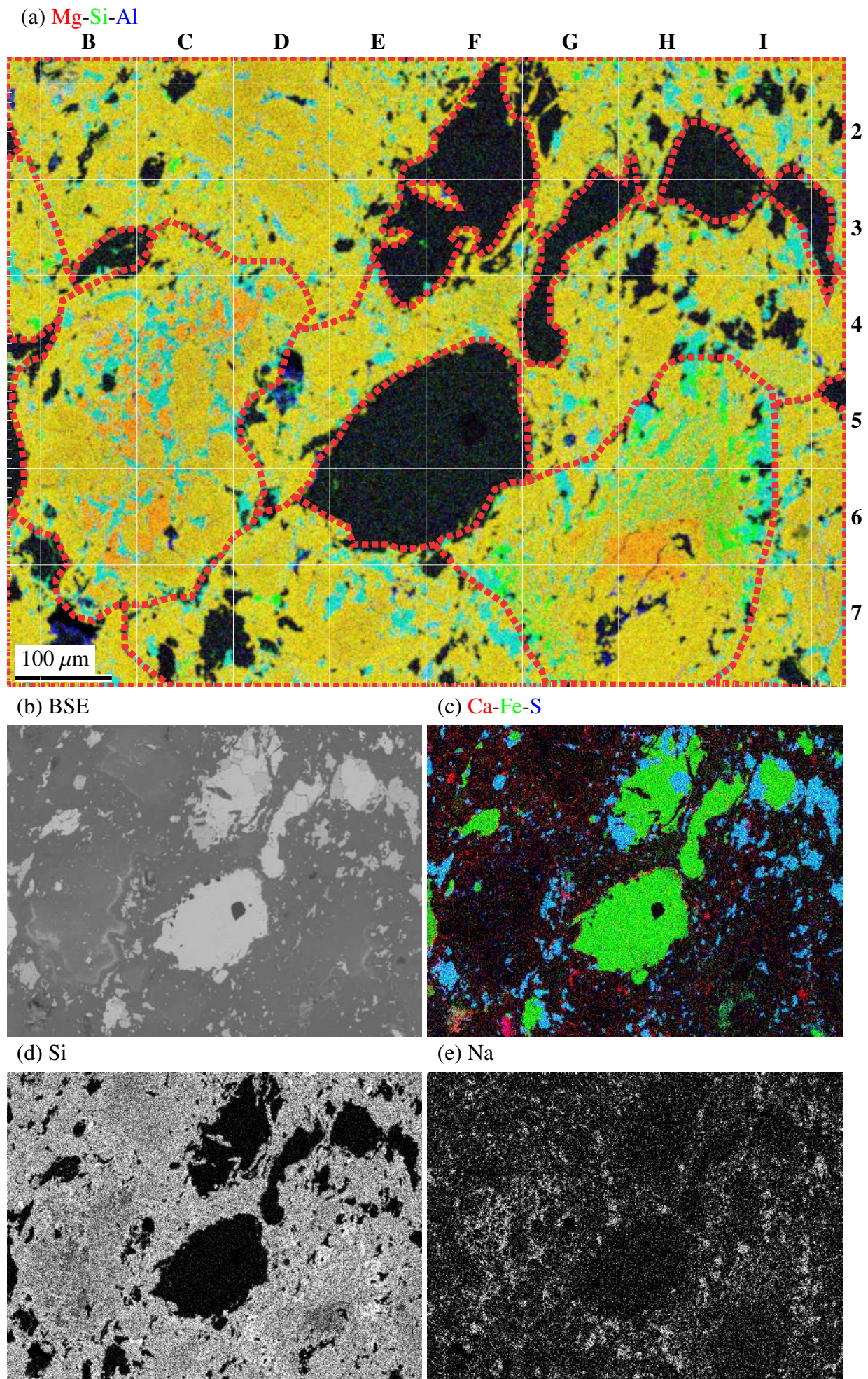


Figure 2.86: Site-13 of PCA91020 (EL3). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.74.

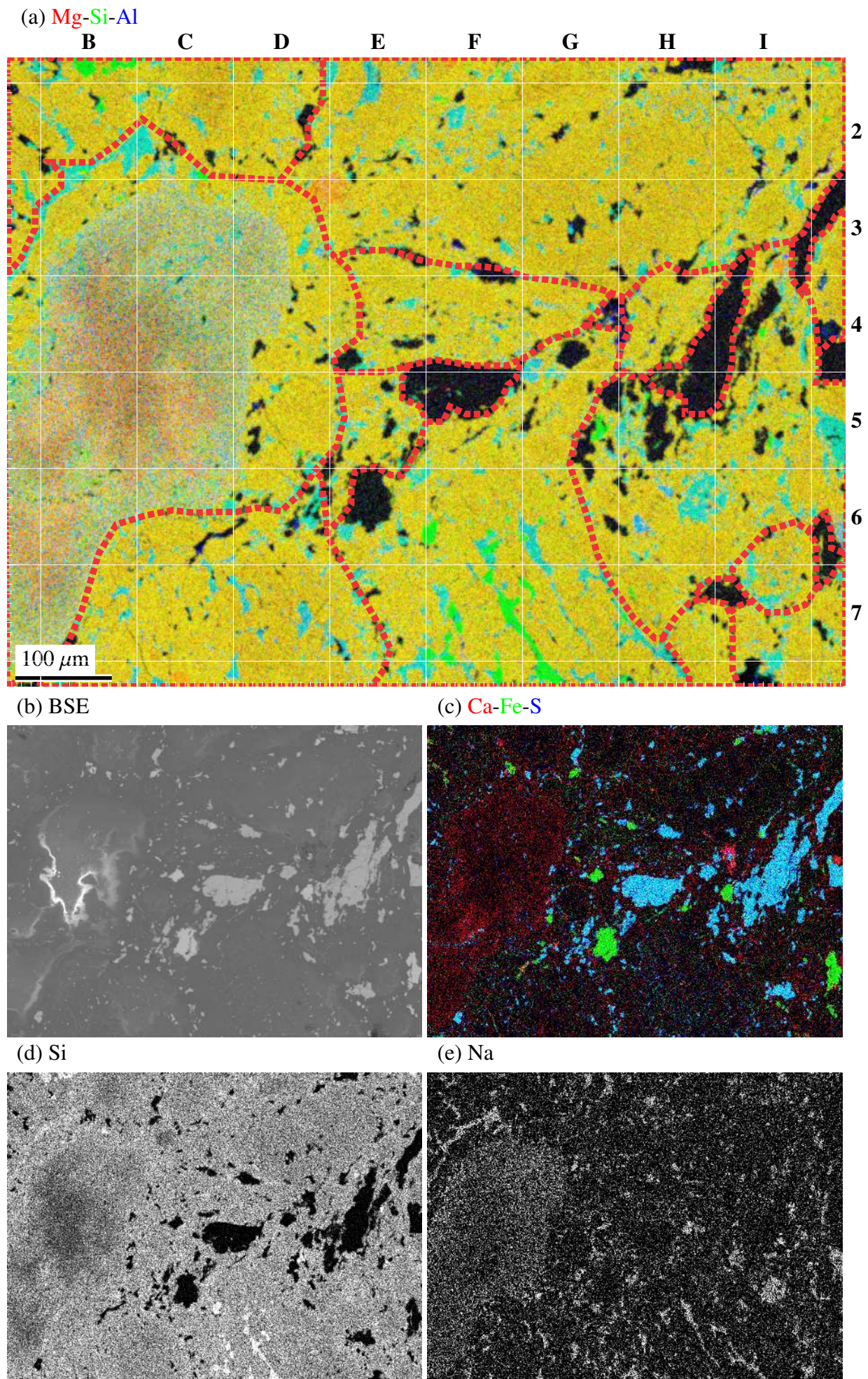


Figure 2.87: Site-14 of PCA91020 (EL3). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.74.

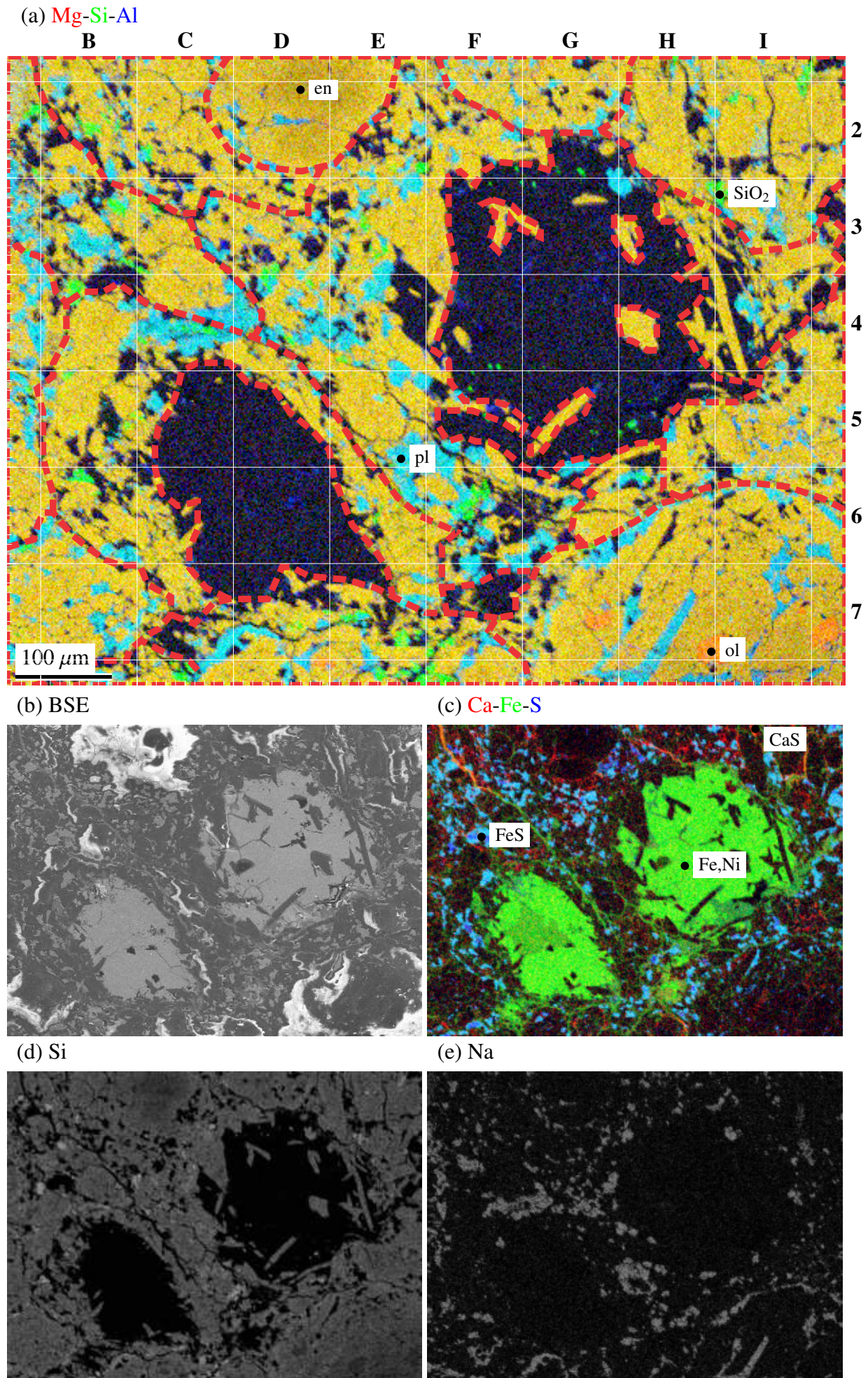


Figure 2.88: Site-1 of MAC02747 (EL4). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown.

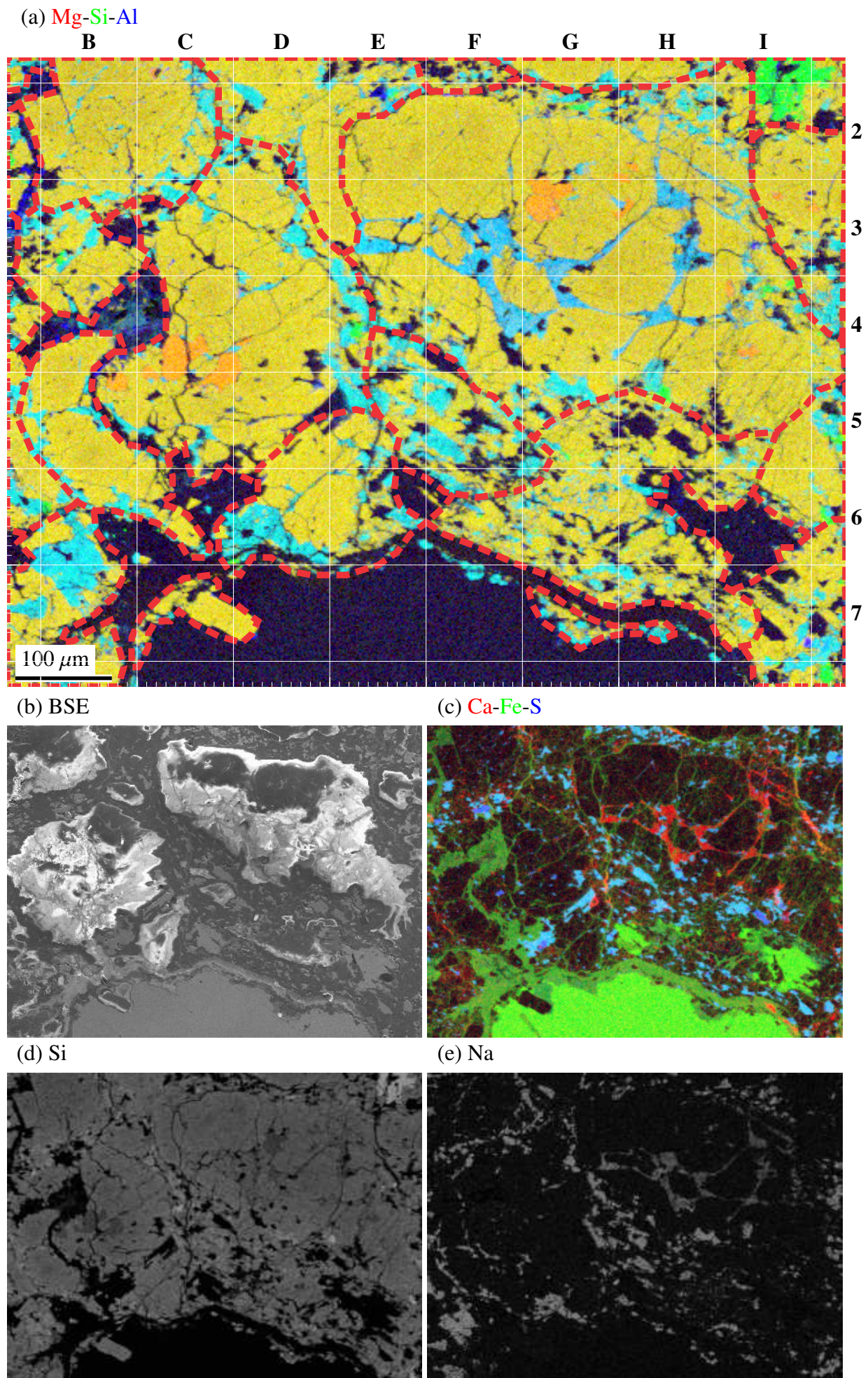


Figure 2.89: Site-2 of MAC02747 (EL4). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.88.

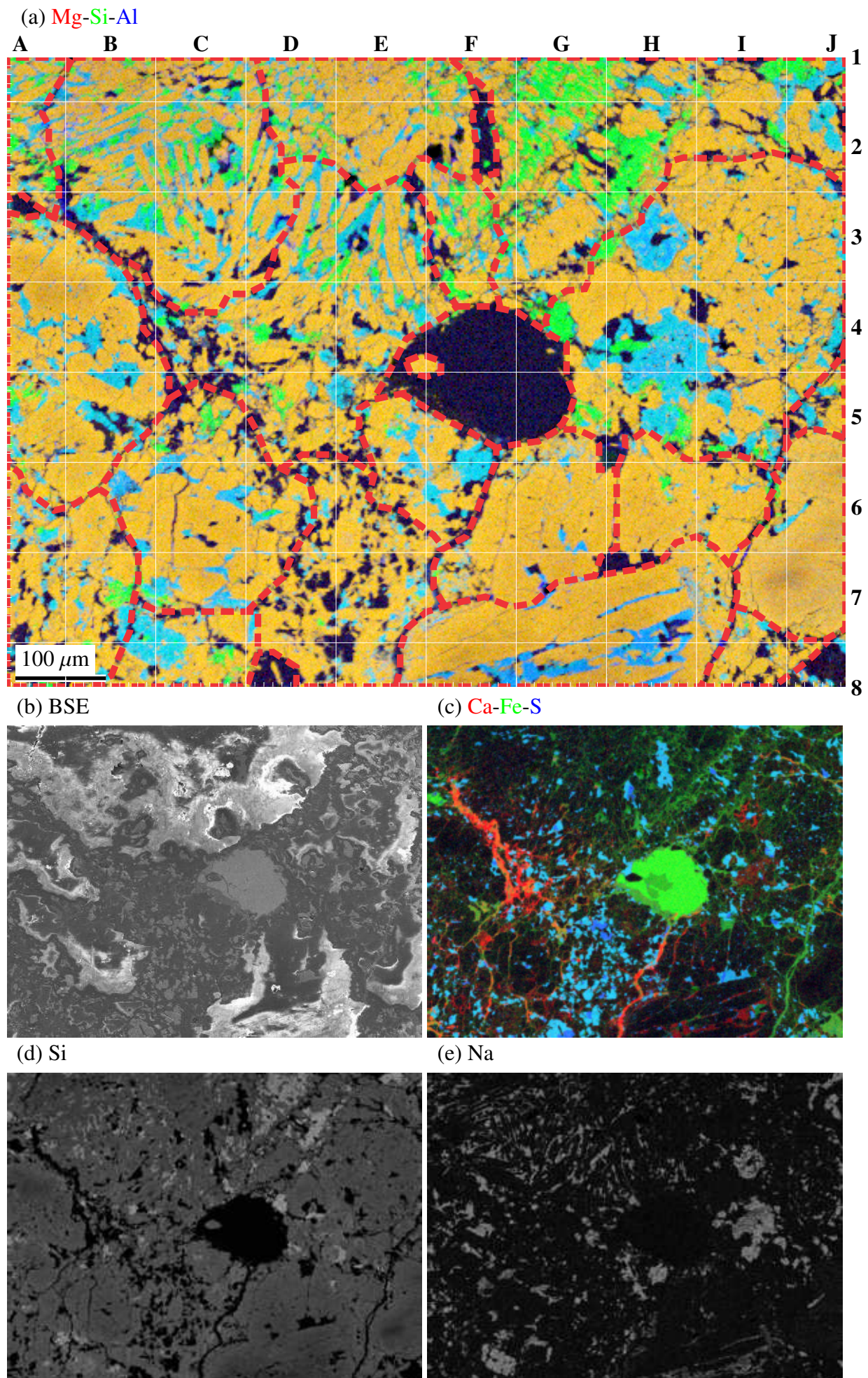


Figure 2.90: Site-3 of MAC02747 (EL4). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.88.

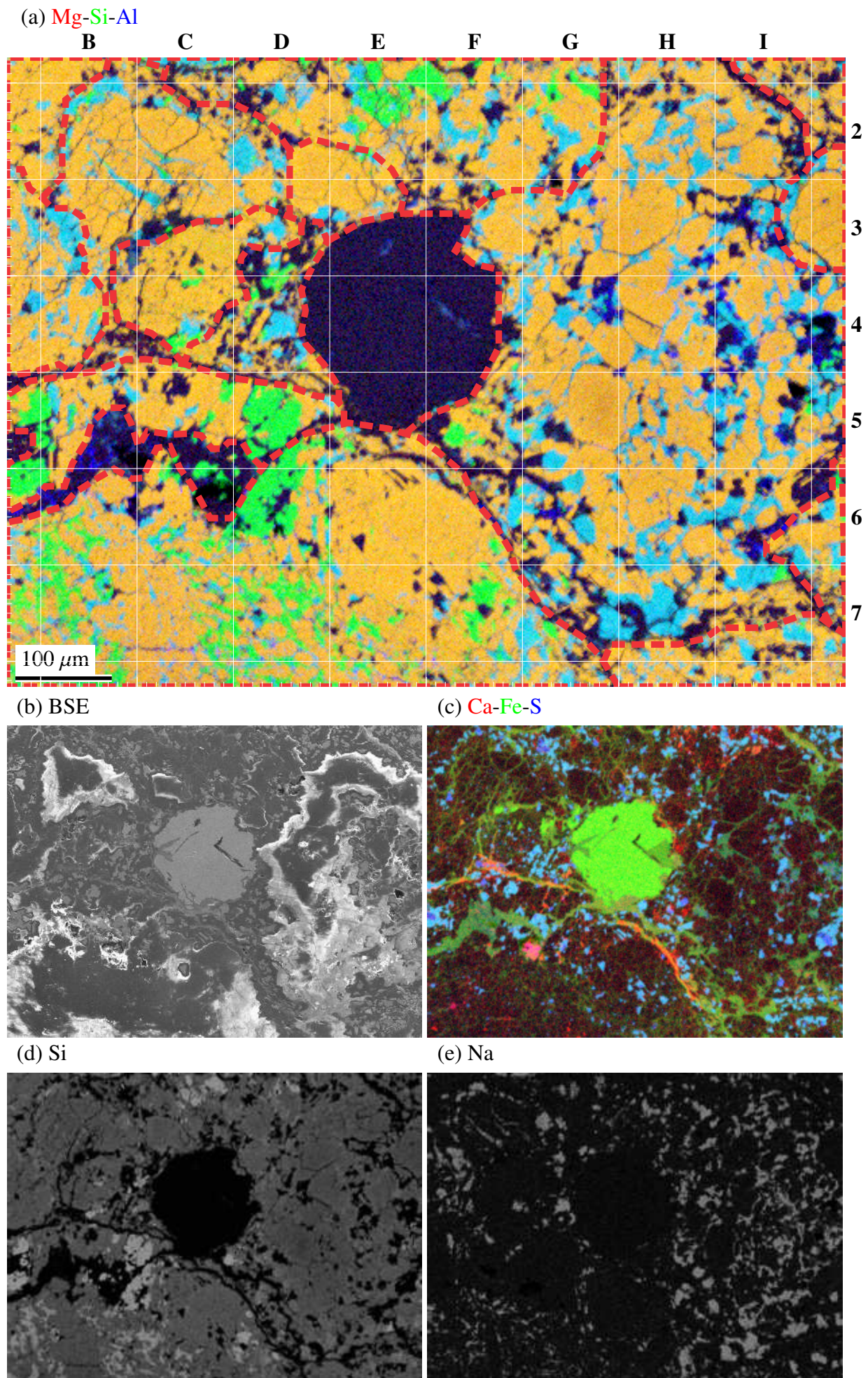


Figure 2.91: Site-4 of MAC02747 (EL4). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.88.

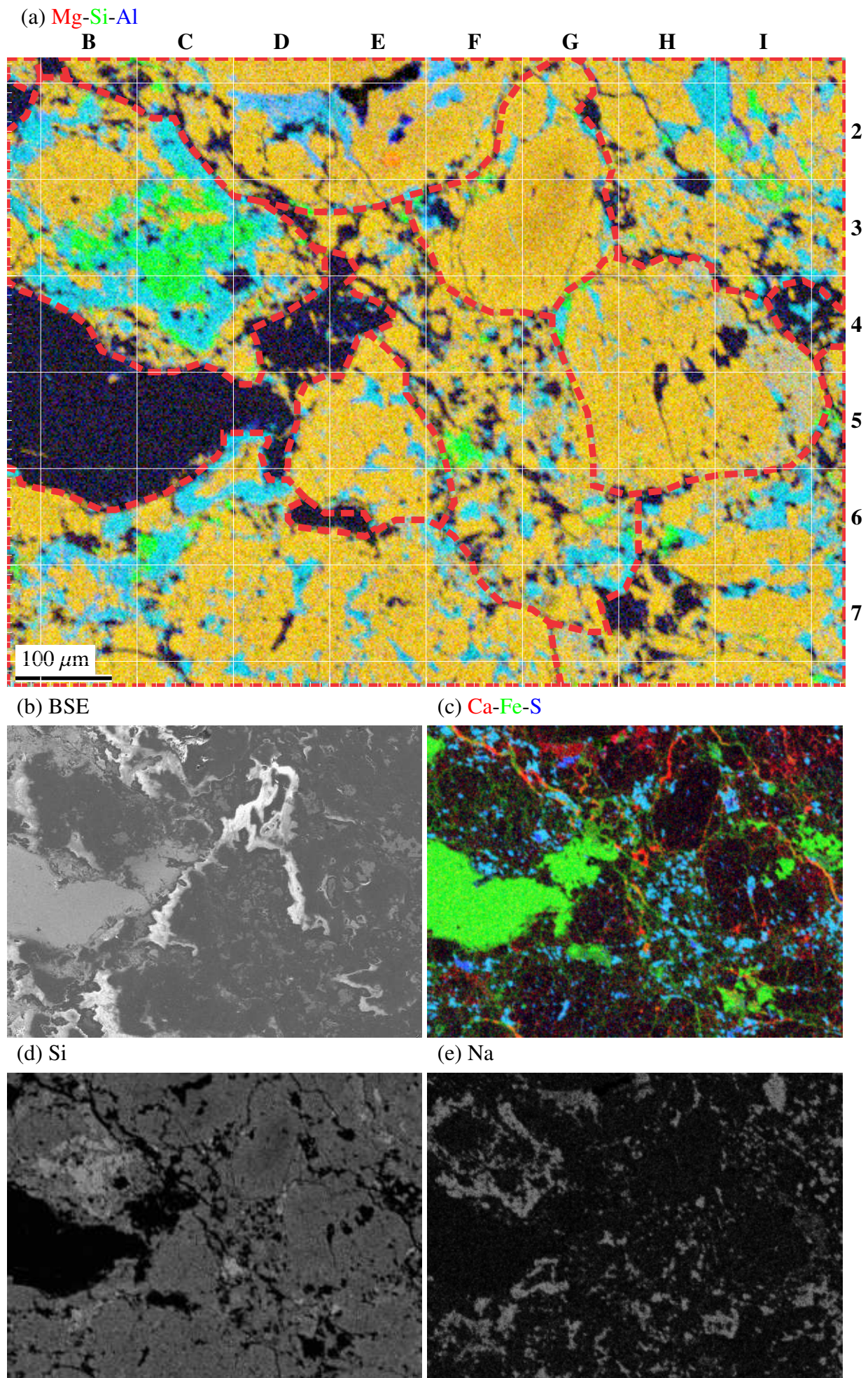


Figure 2.92: Site-5 of MAC02747 (EL4). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.88.

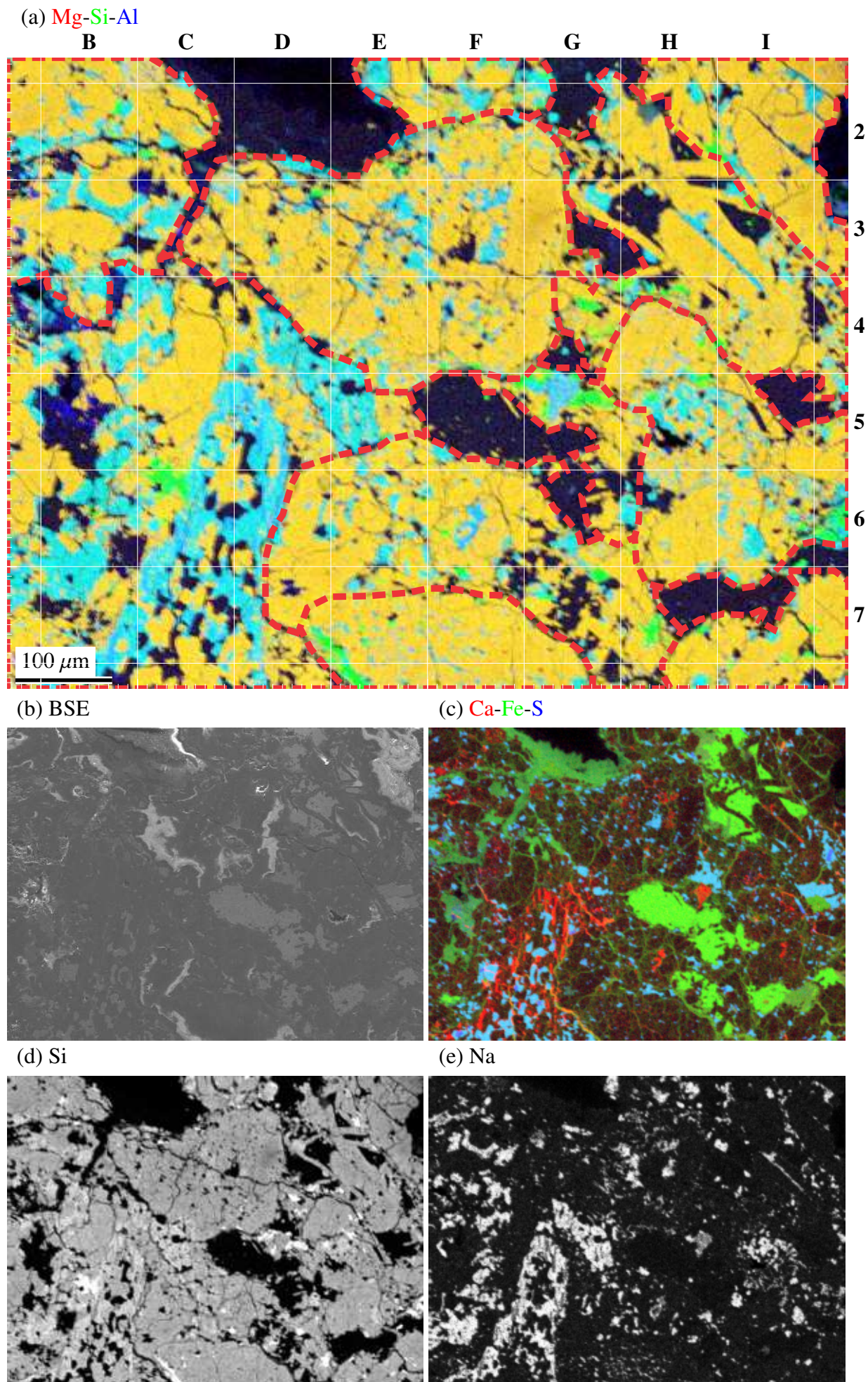


Figure 2.93: Site-6 of MAC02747 (EL4). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.88.

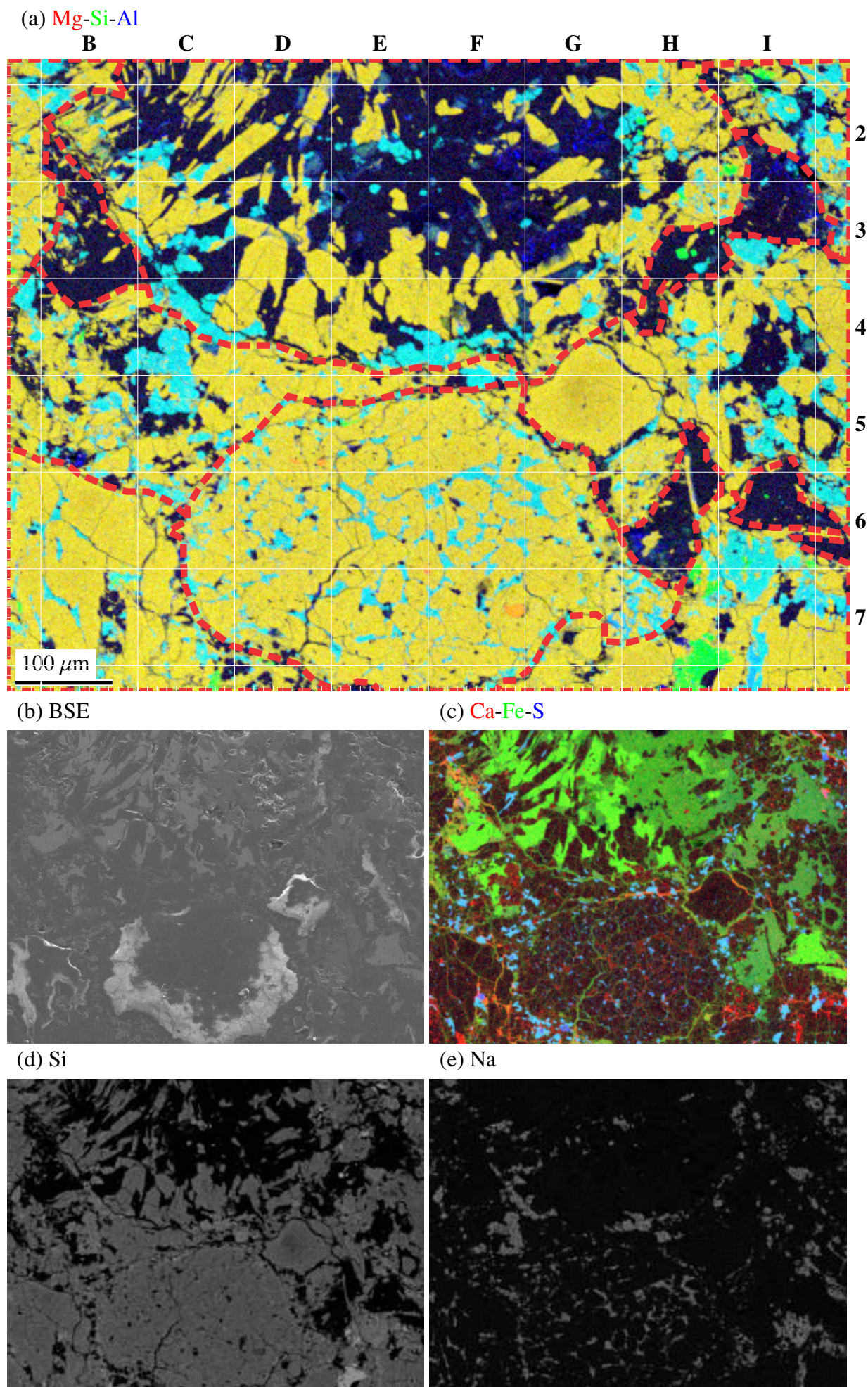


Figure 2.94: Site-7 of MAC02747 (EL4). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.88.

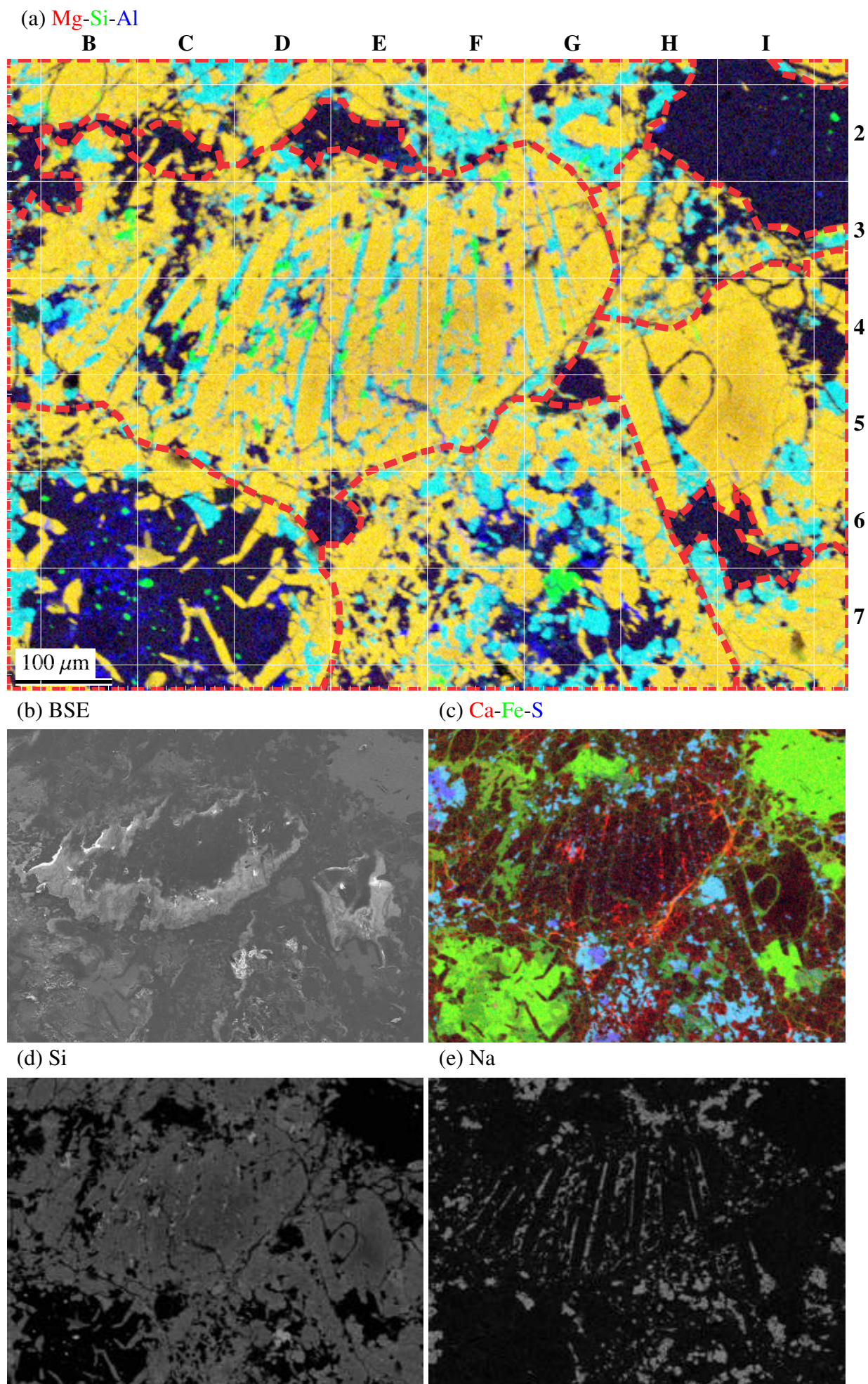


Figure 2.95: Site-8 of MAC02747 (EL4). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.88.

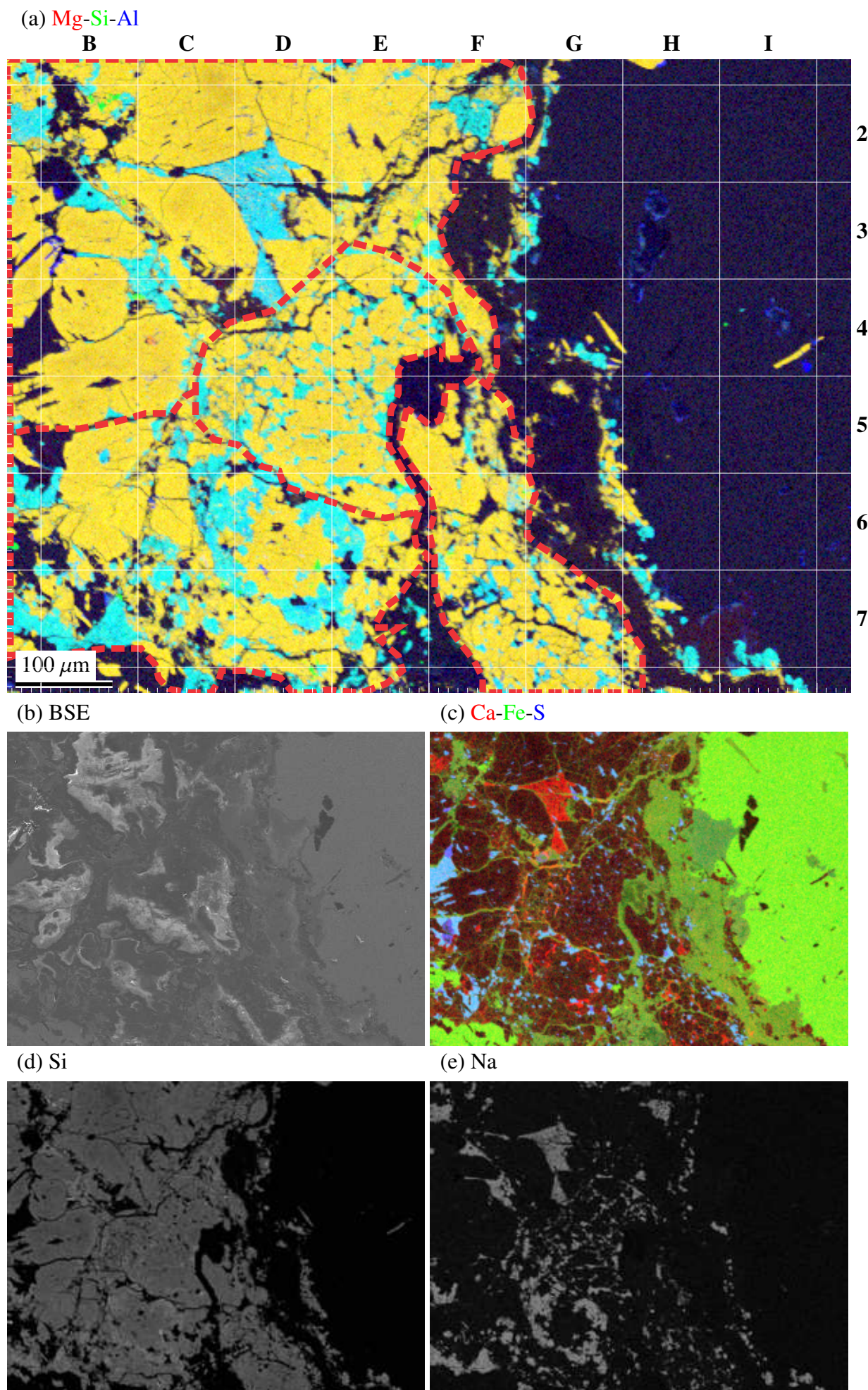


Figure 2.96: Site-9 of MAC02747 (EL4). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.88.

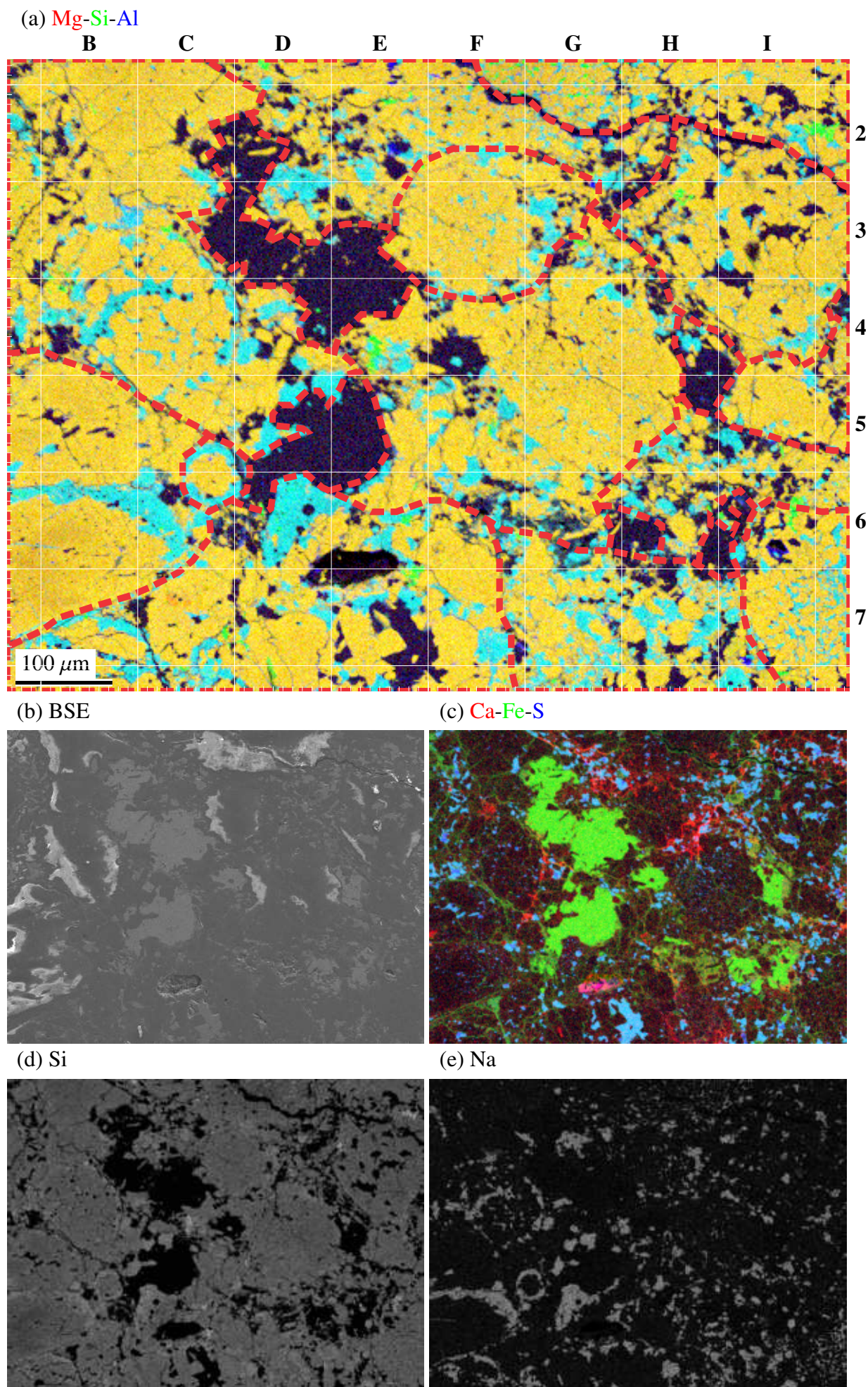


Figure 2.97: Site-10 of MAC02747 (EL4). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.88.

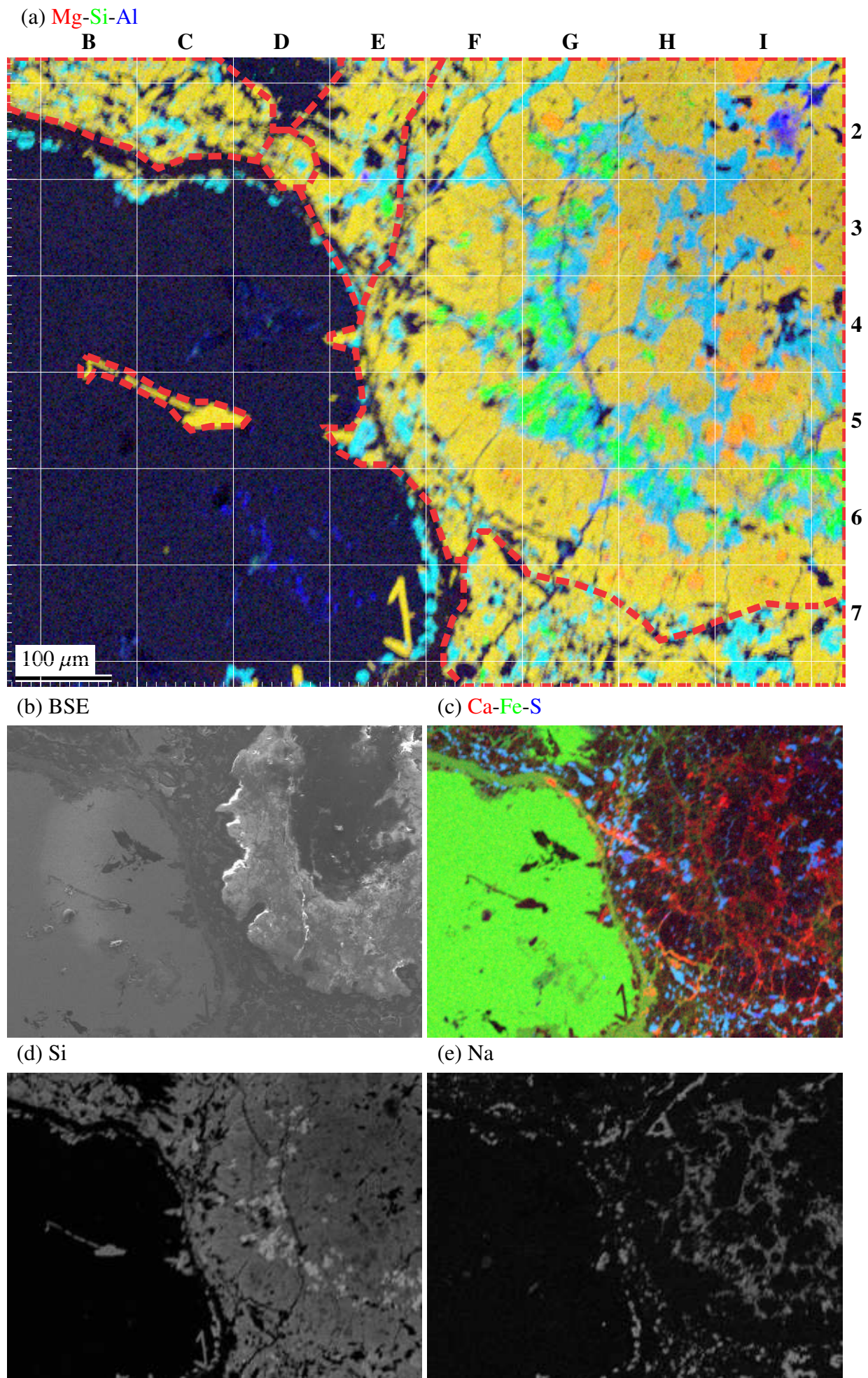


Figure 2.98: Site-11 of MAC02747 (EL4). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.88.

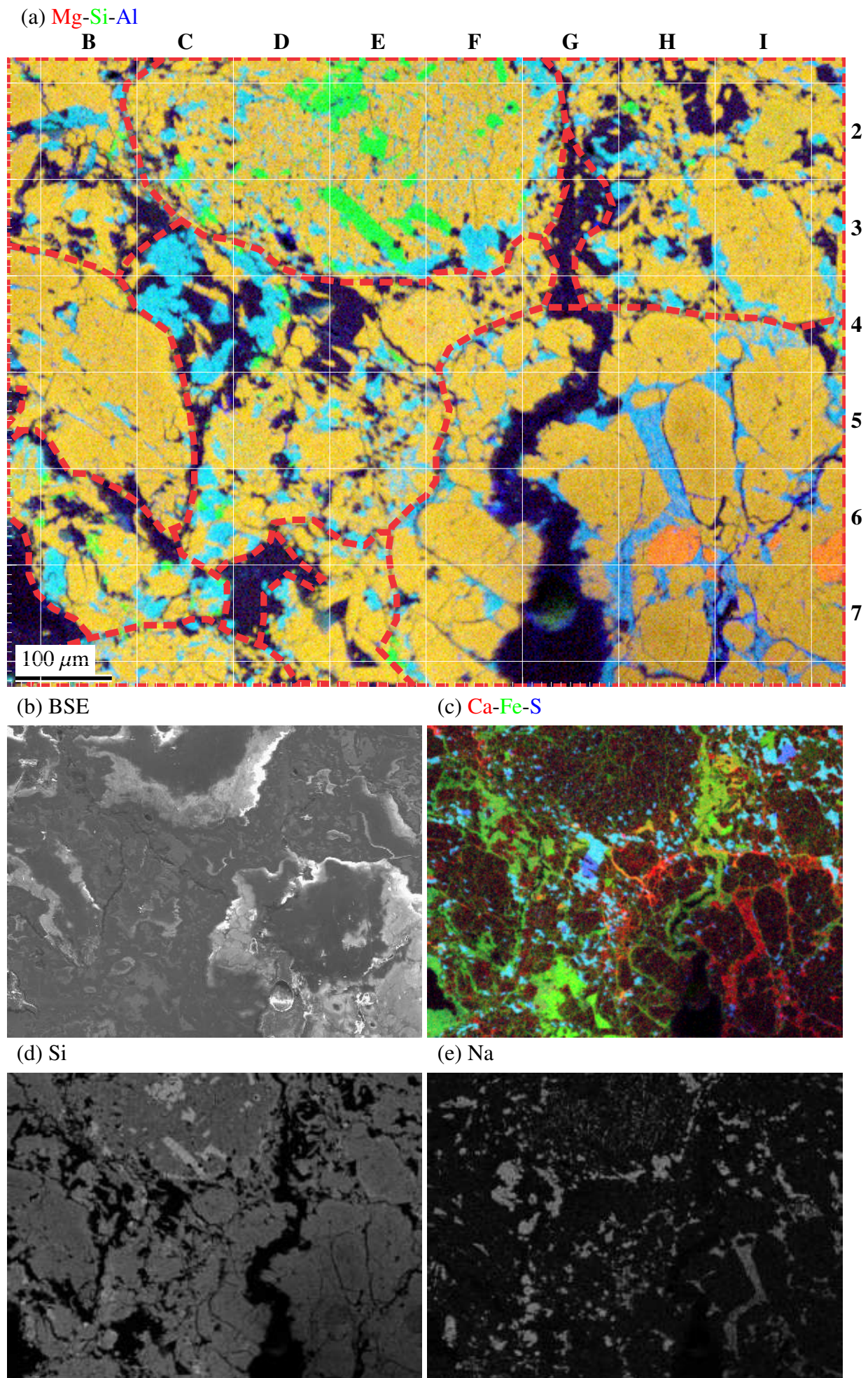


Figure 2.99: Site-12 of MAC02747 (EL4). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.88.

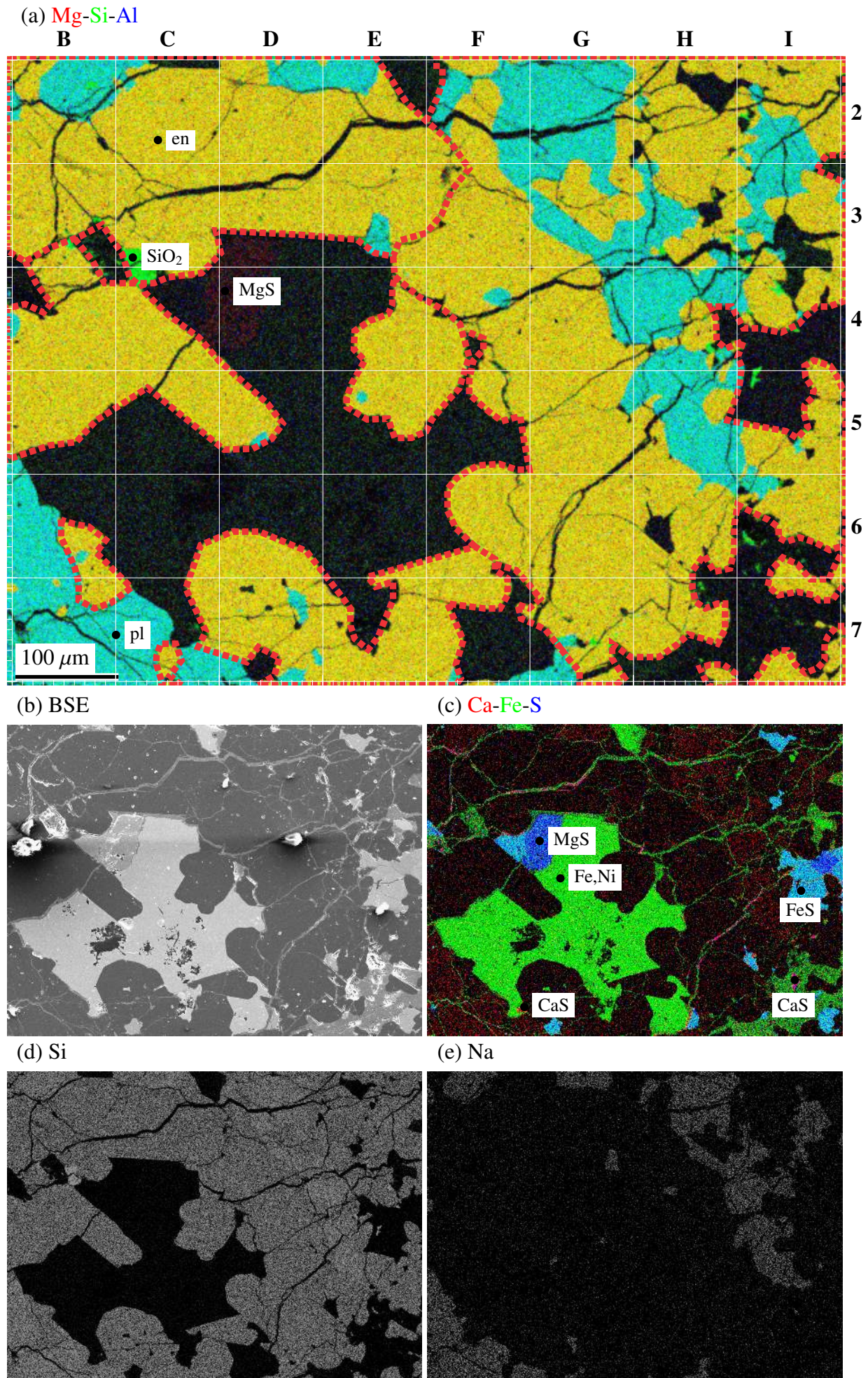


Figure 2.100: Site-1 of TIL91714 (EL5). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown.

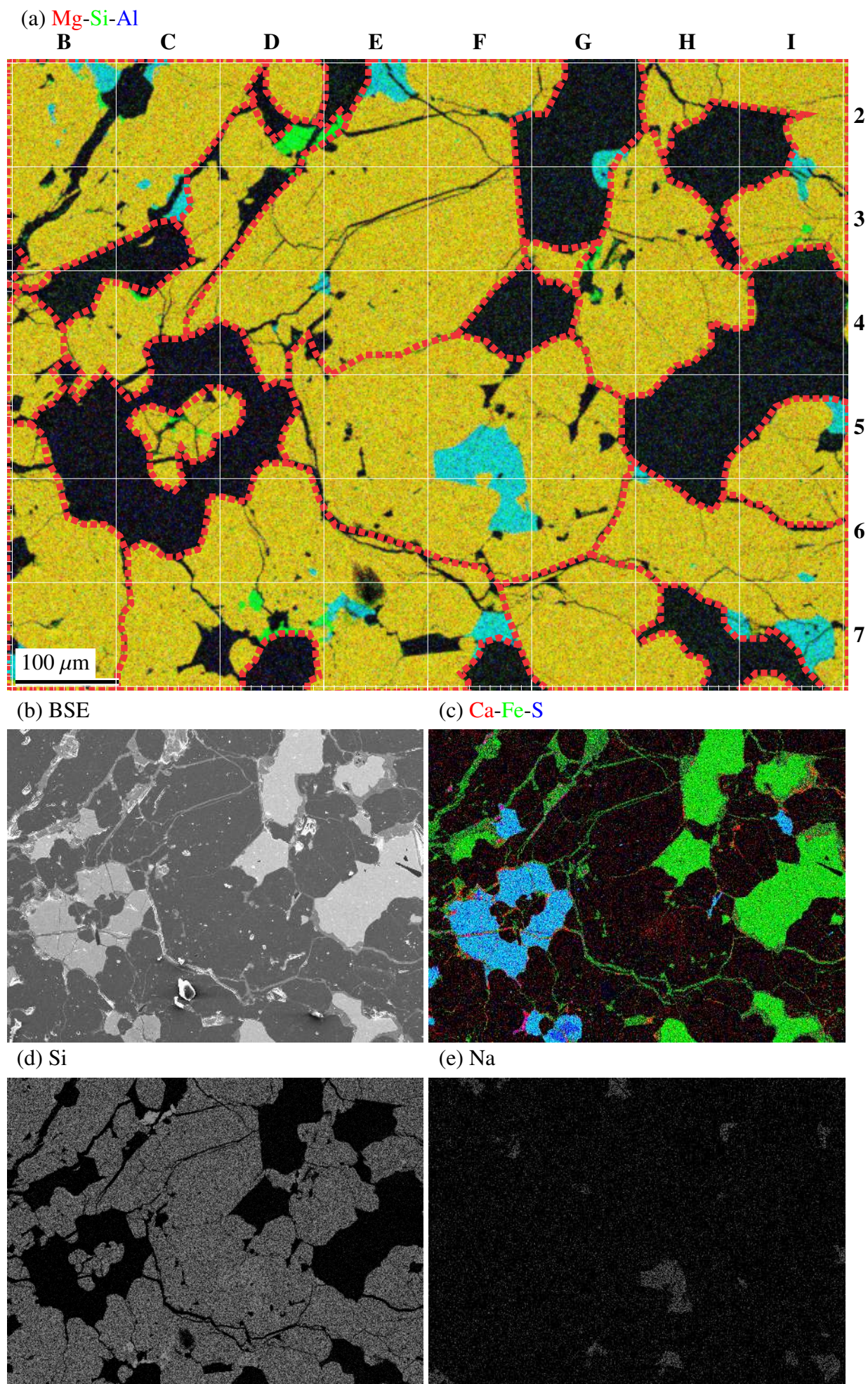


Figure 2.101: Site-2 of TIL91714 (EL5). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.100.

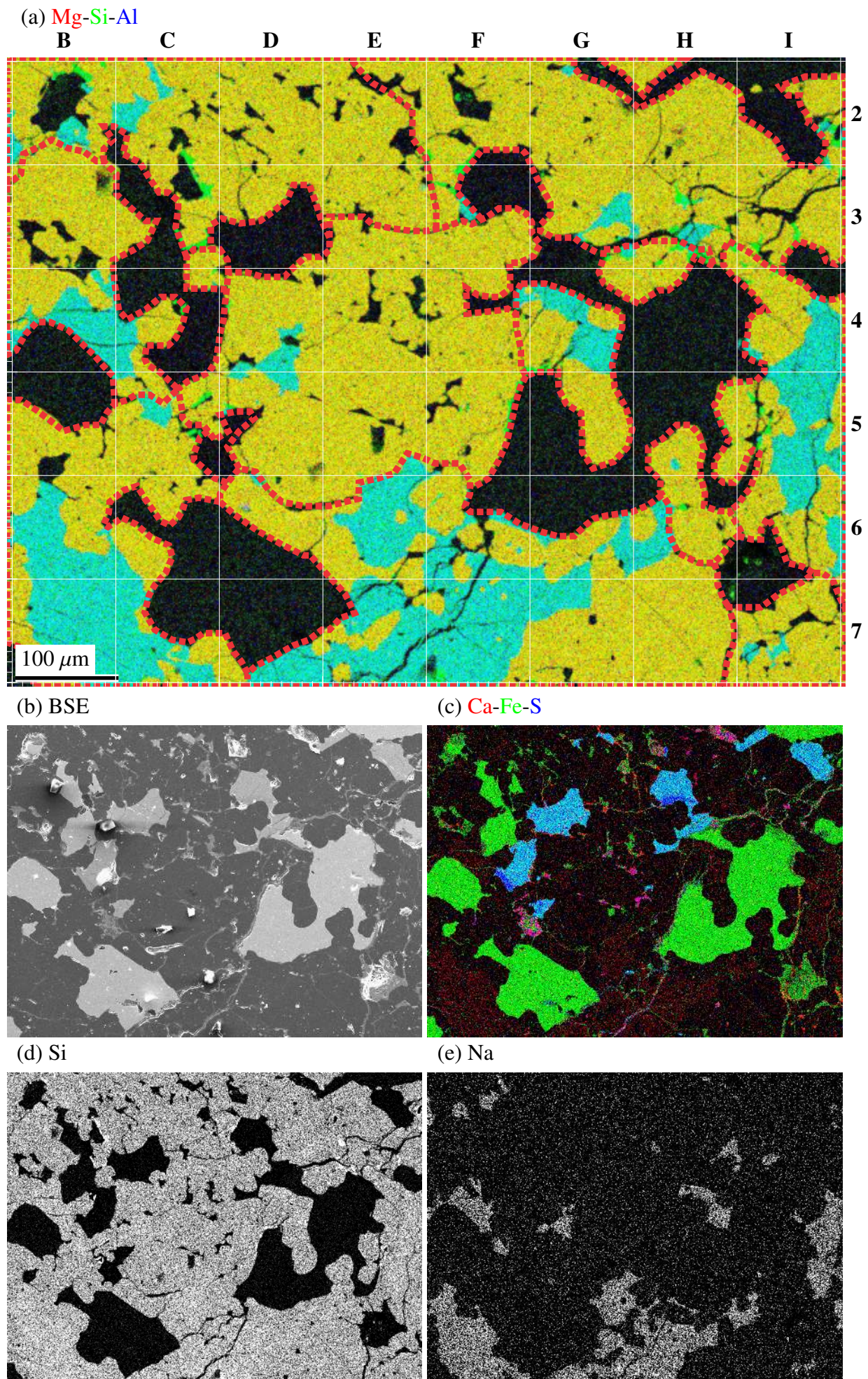


Figure 2.102: Site-3 of TIL91714 (EL5). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.100.

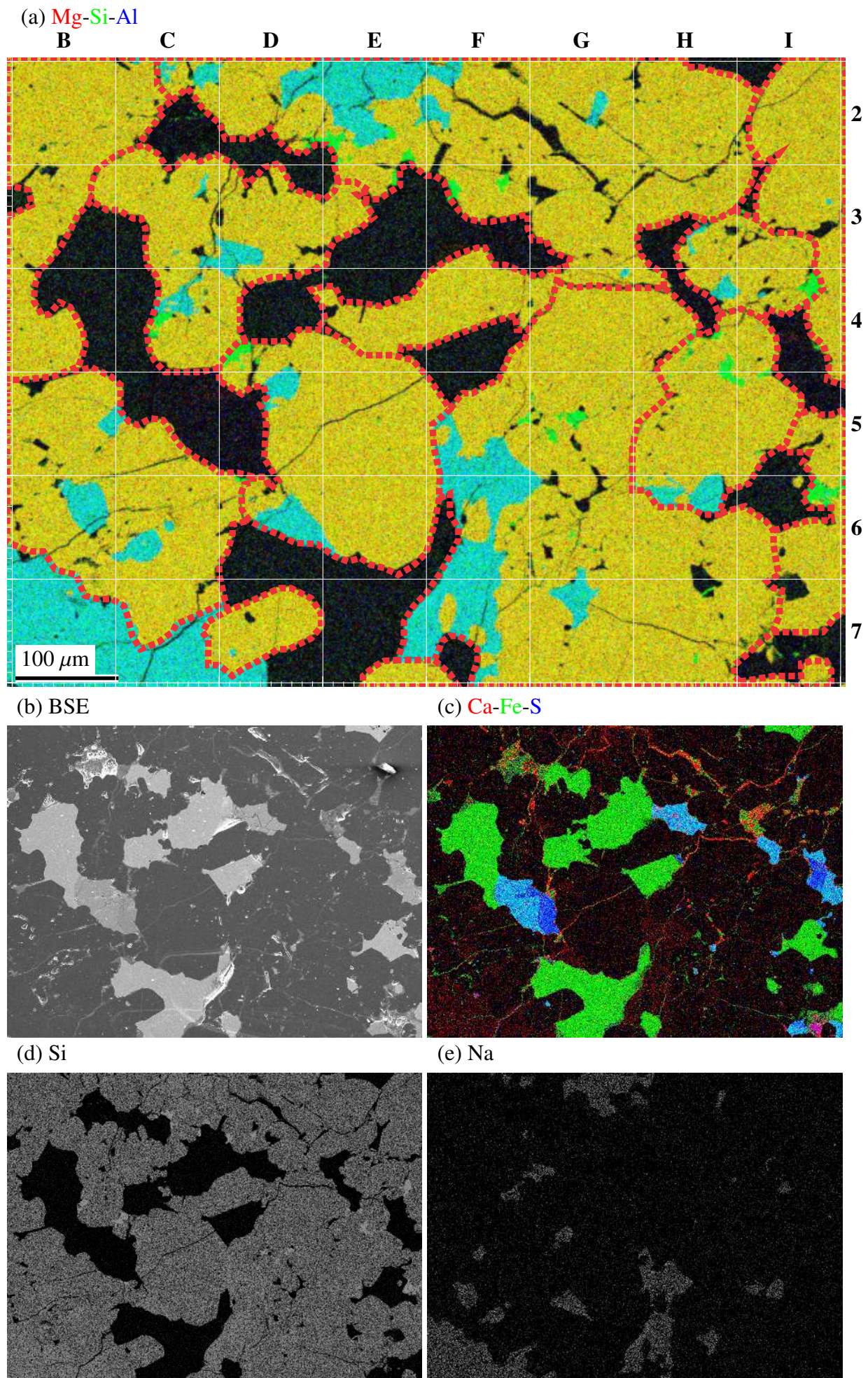


Figure 2.103: Site-4 of TIL91714 (EL5). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.100.

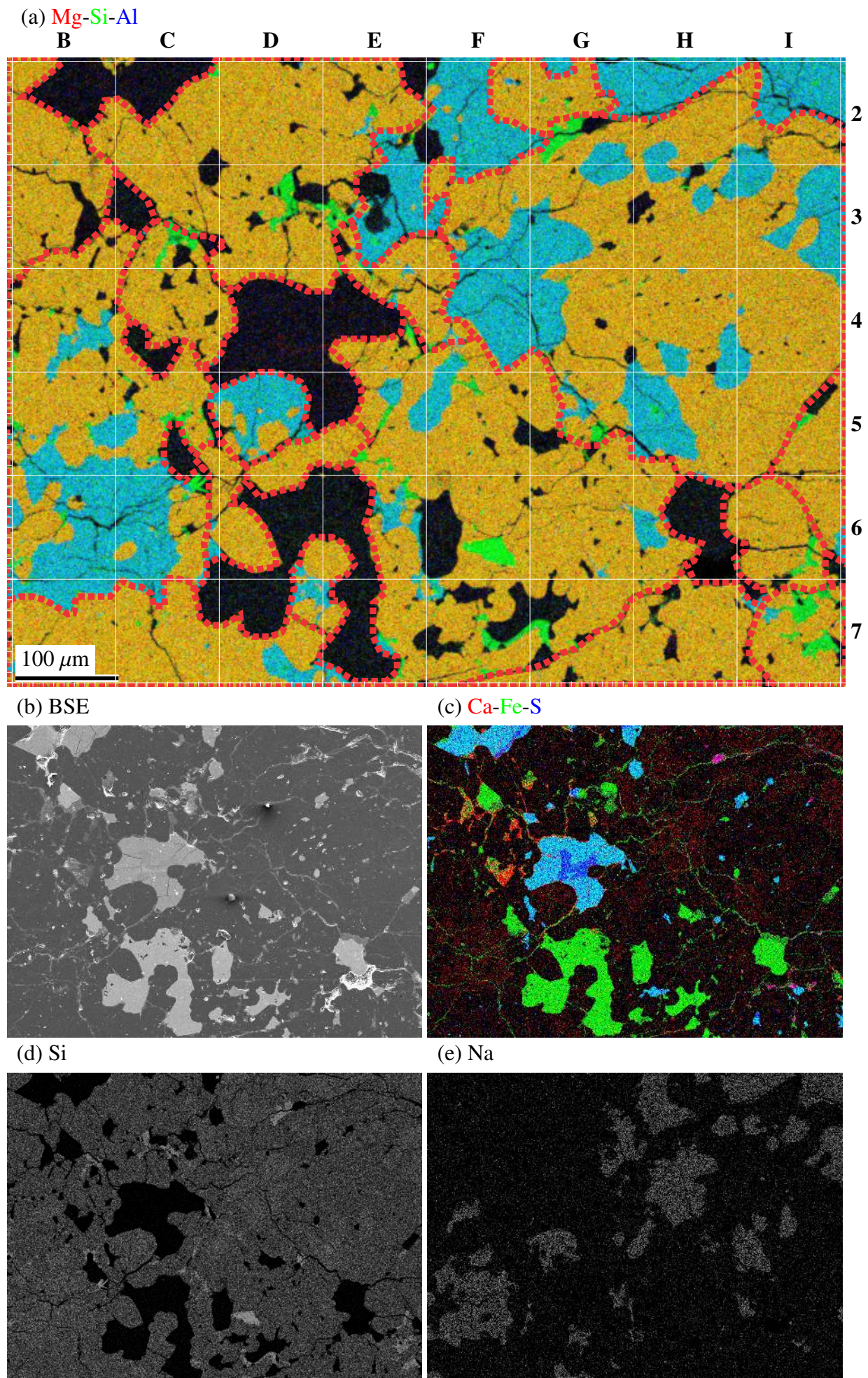


Figure 2.104: Site-5 of TIL91714 (EL5). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.100.

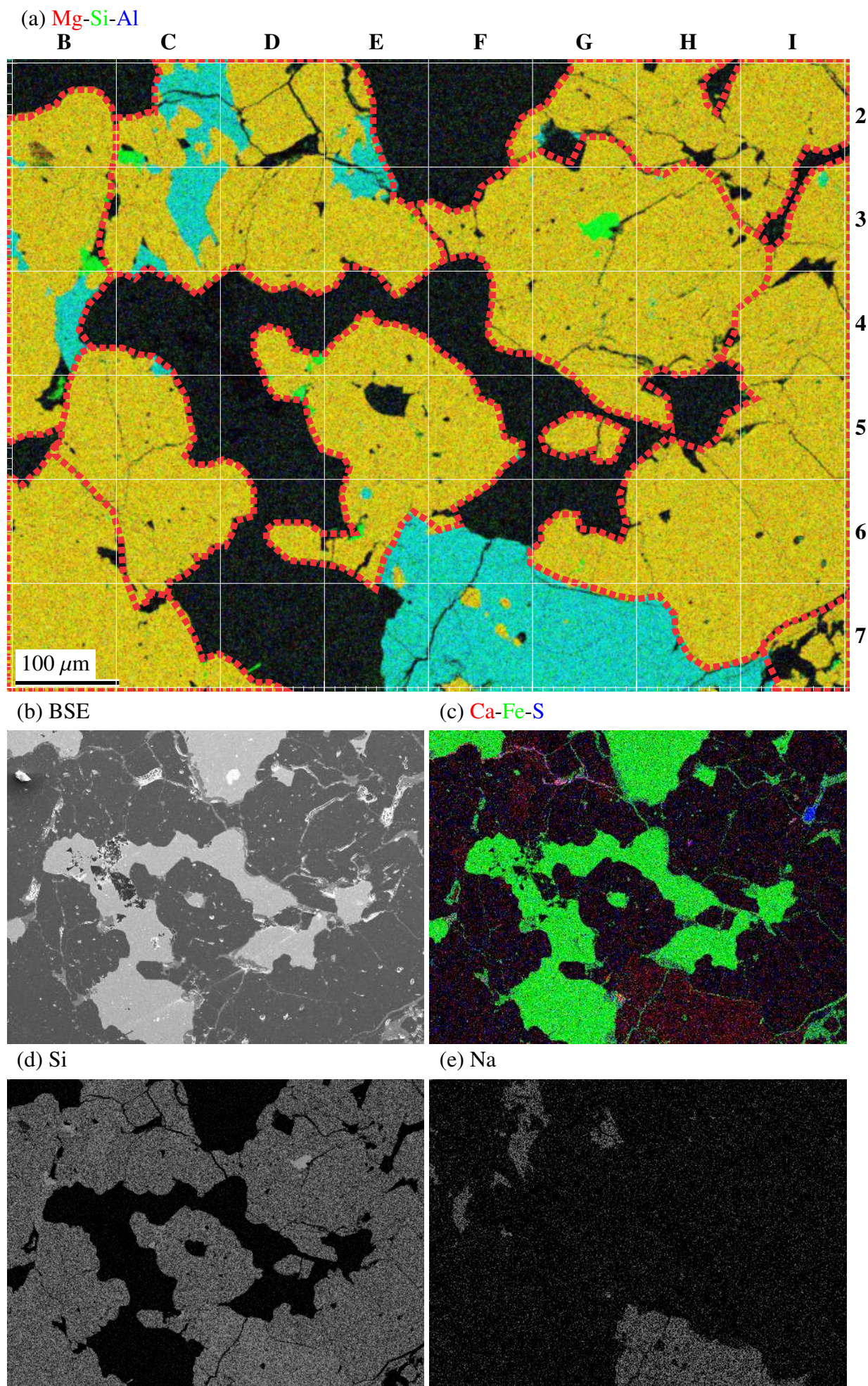


Figure 2.105: Site-6 of TIL91714 (EL5). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.100.

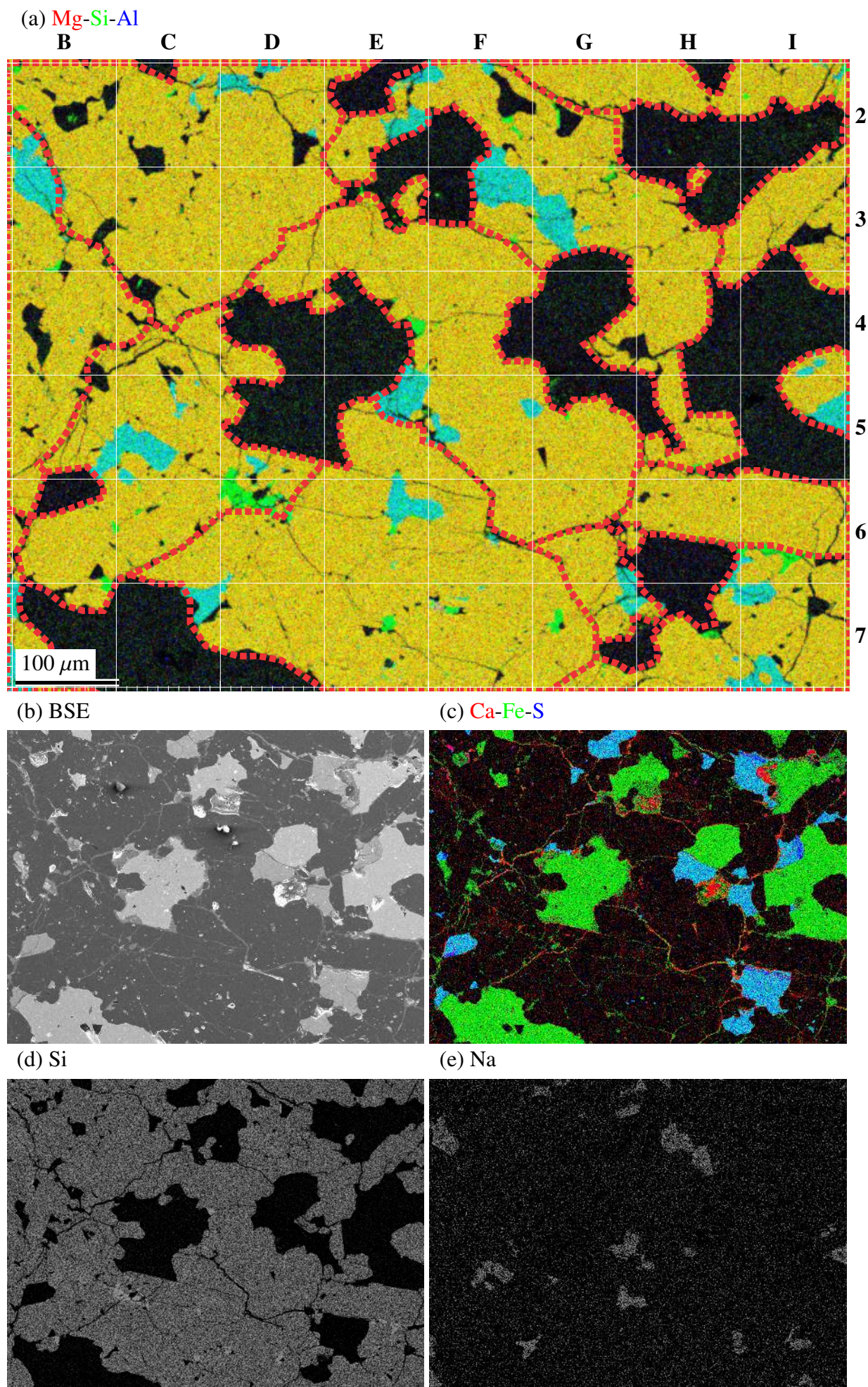


Figure 2.106: Site-7 of TIL91714 (EL5). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.100.

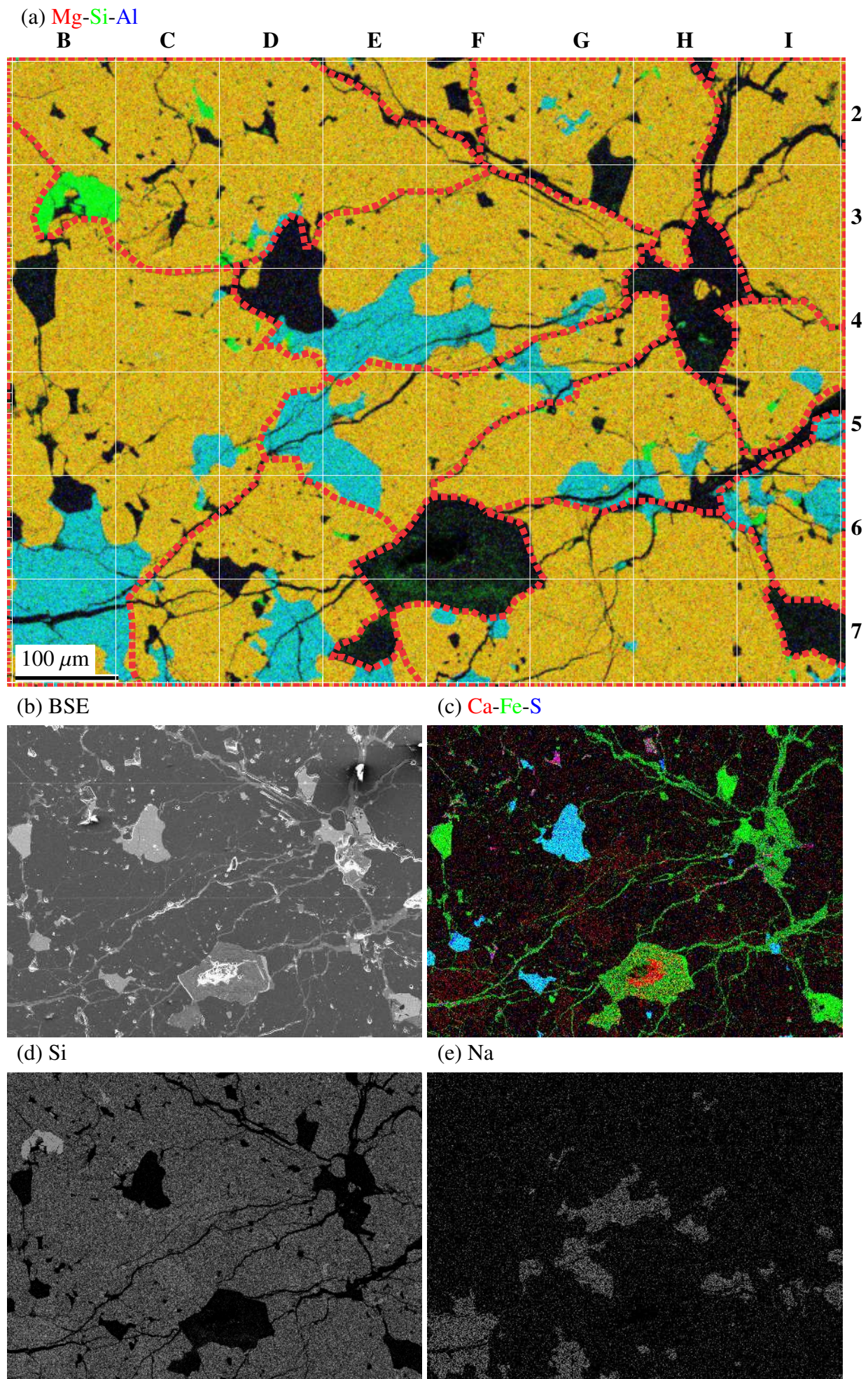


Figure 2.107: Site-8 of TIL91714 (EL5). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.100.

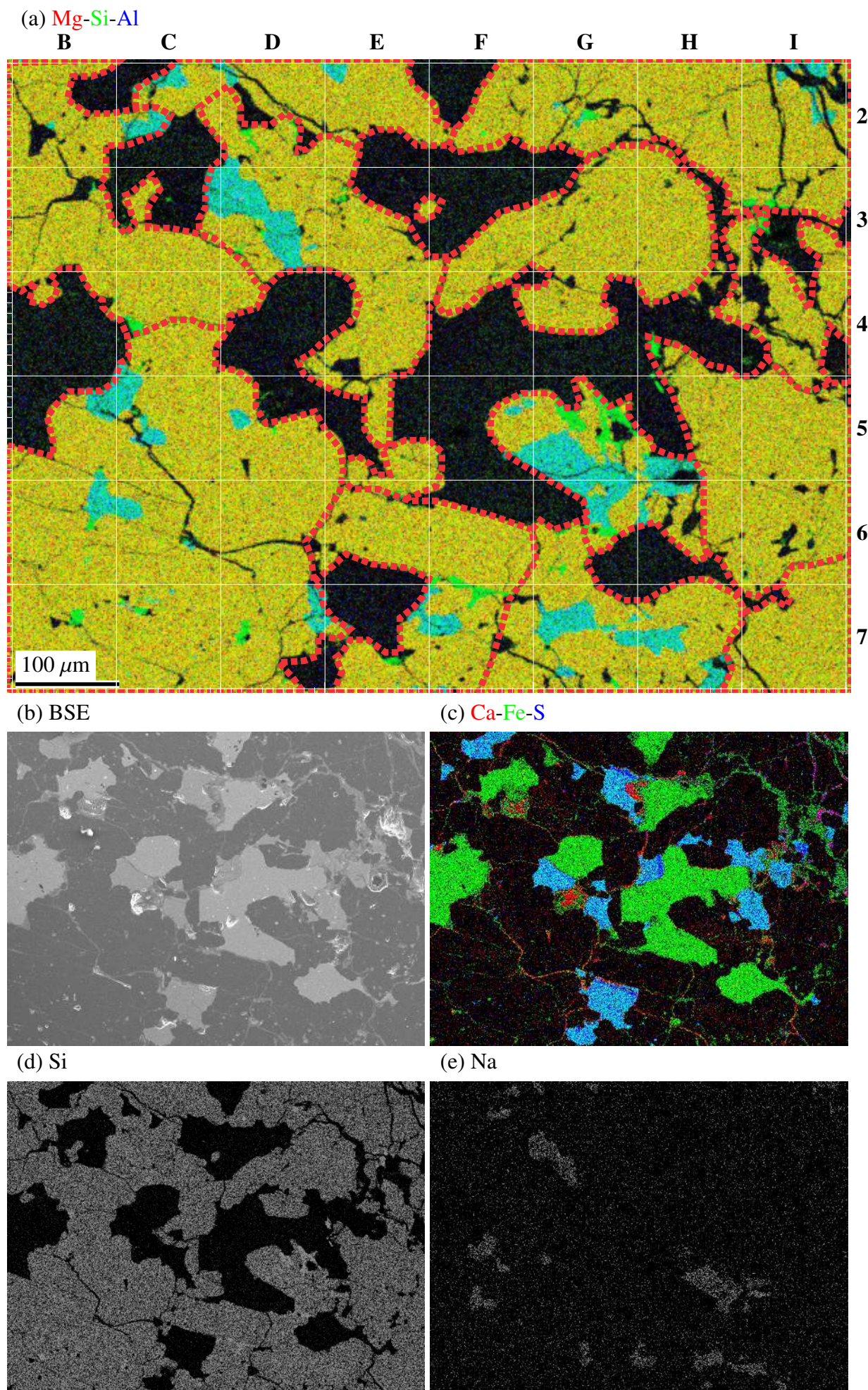


Figure 2.108: Site-9 of TIL91714 (EL5). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.100.

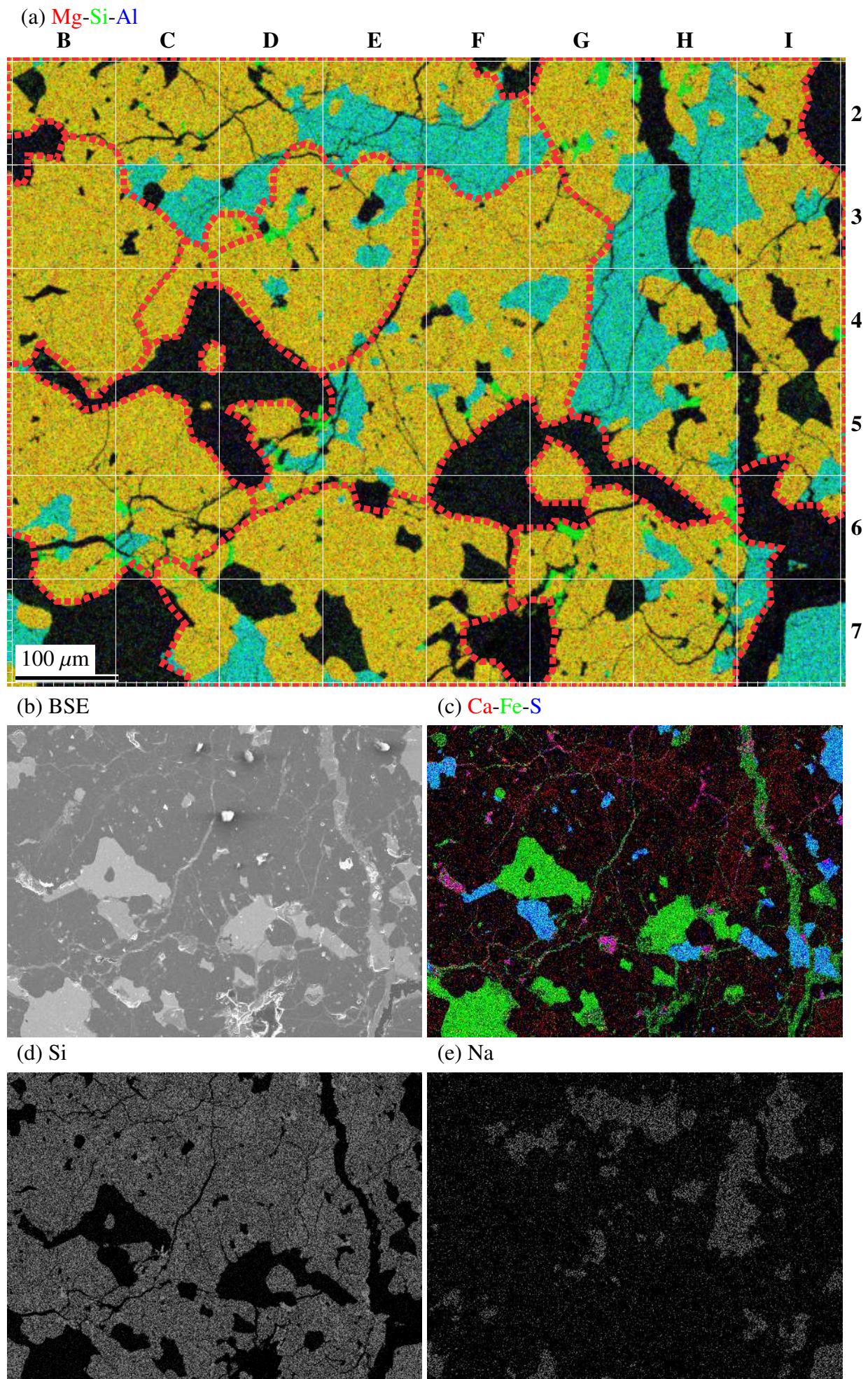


Figure 2.109: Site-10 of TIL91714 (EL5). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.100.

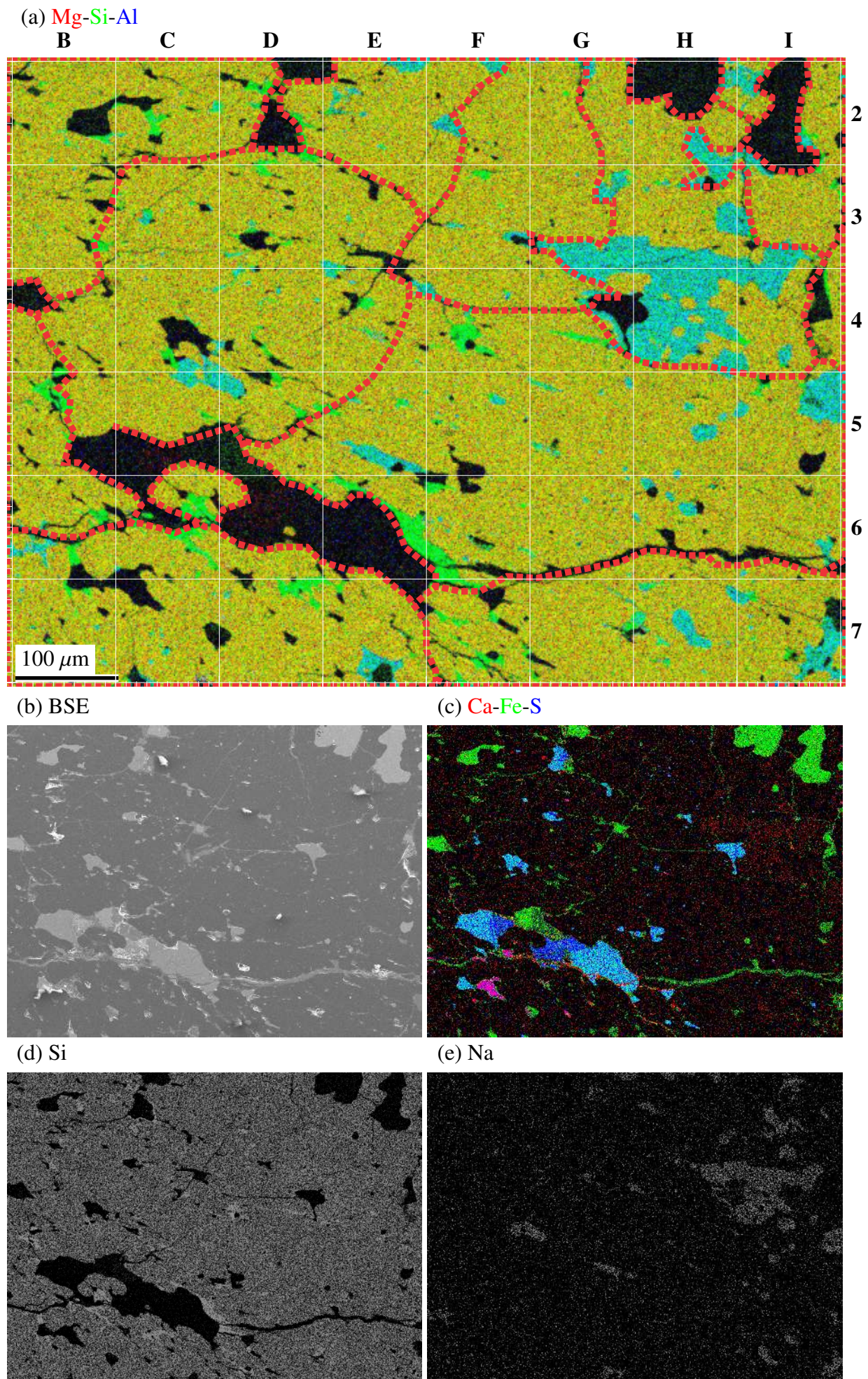


Figure 2.110: Site-11 of TIL91714 (EL5). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.100.

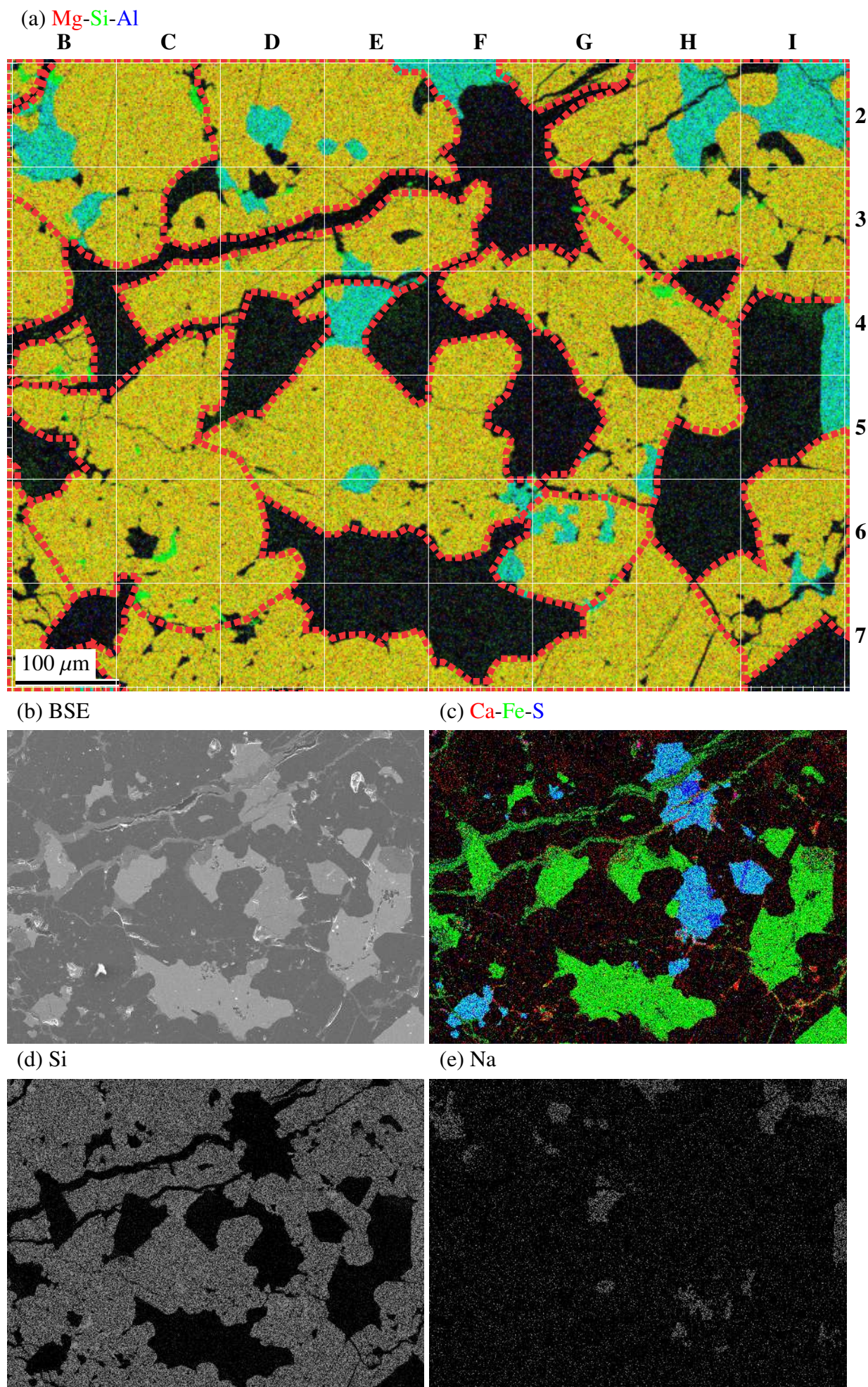


Figure 2.111: Site-12 of TIL91714 (EL5). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.100.

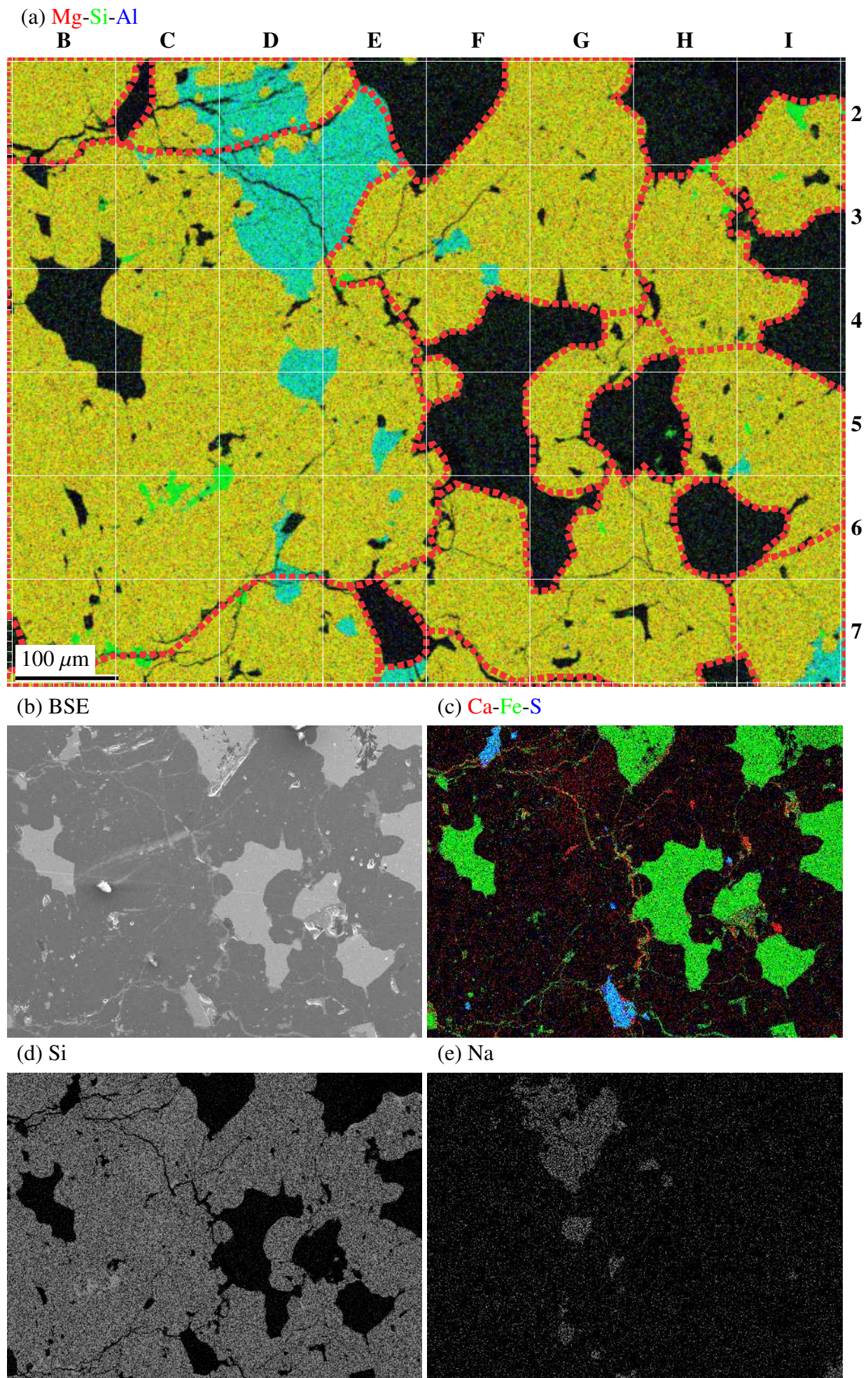


Figure 2.112: Site-13 of TIL91714 (EL5). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.100.

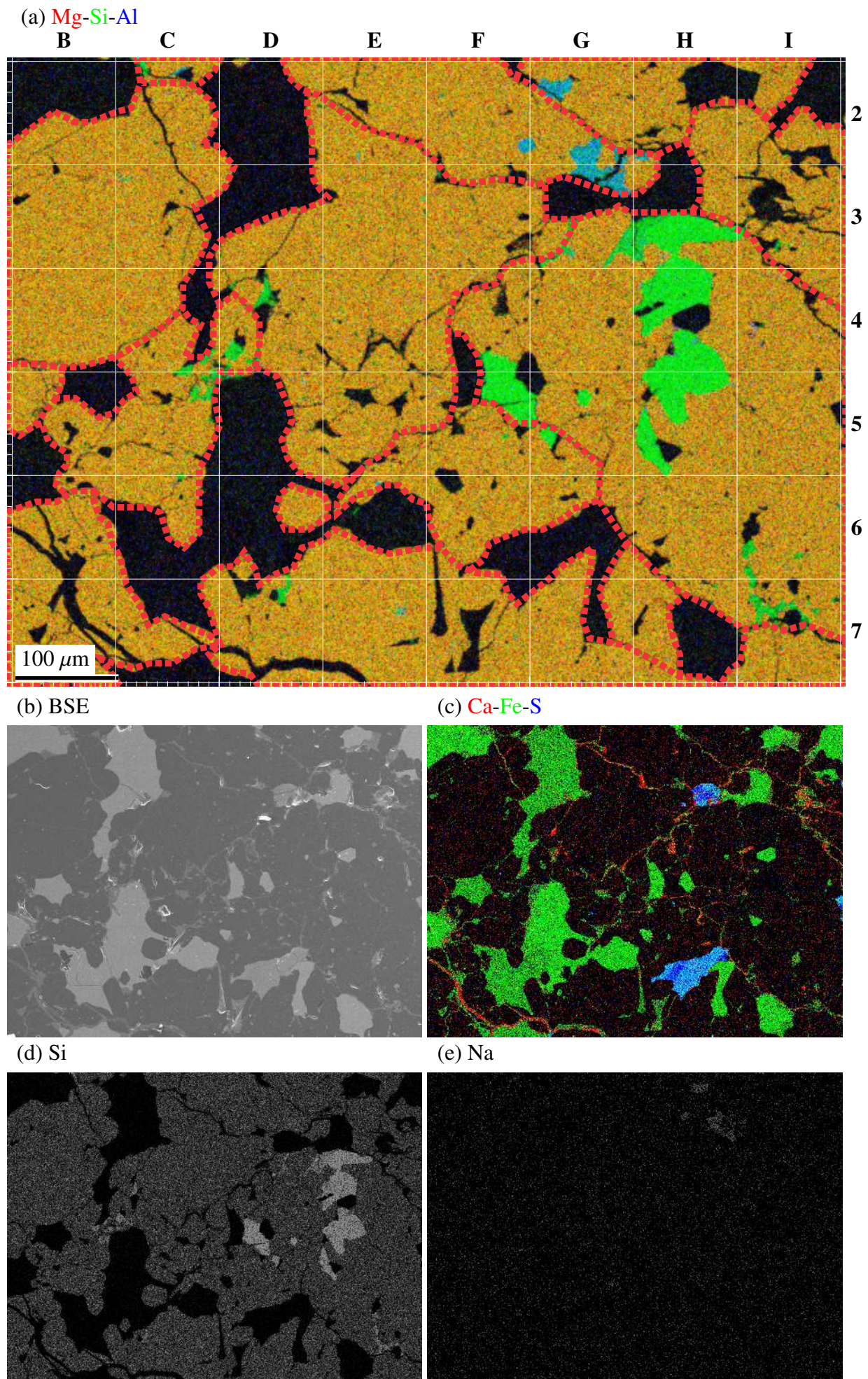


Figure 2.113: Site-14 of TIL91714 (EL5). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.100.

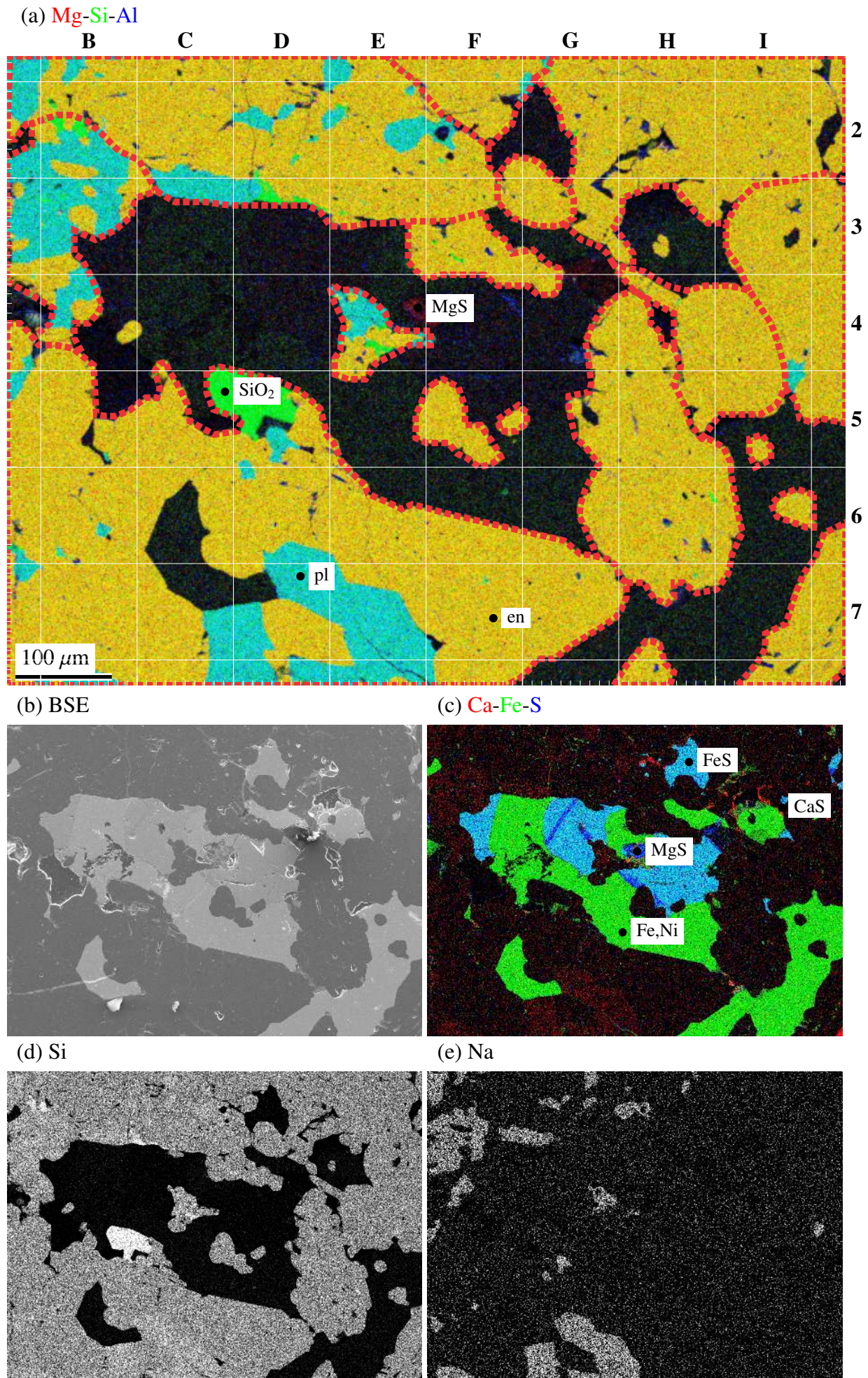


Figure 2.114: Site-1 of ALHA81021 (EL6). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown.

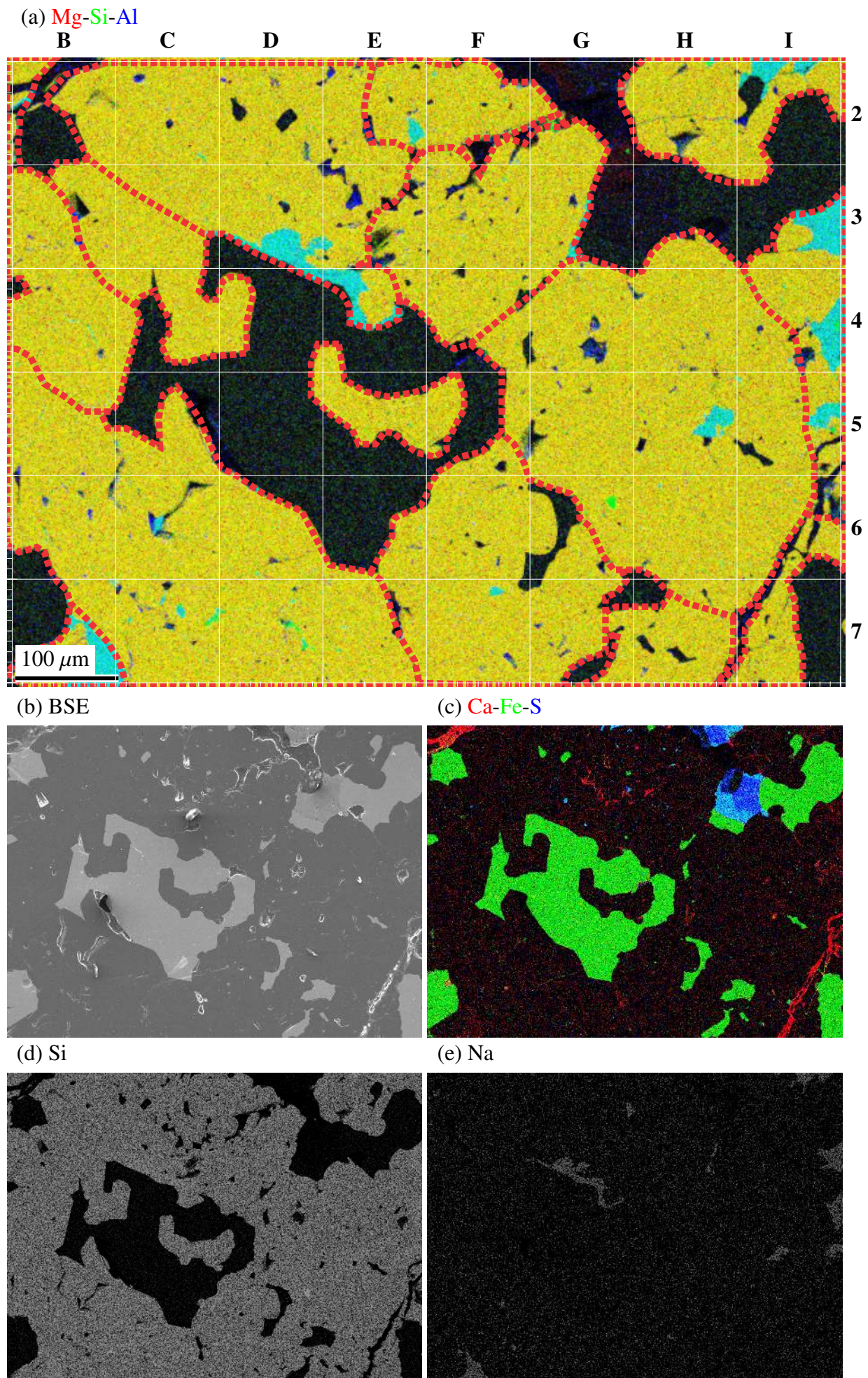


Figure 2.115: Site-2 of ALHA81021 (EL6). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.114.

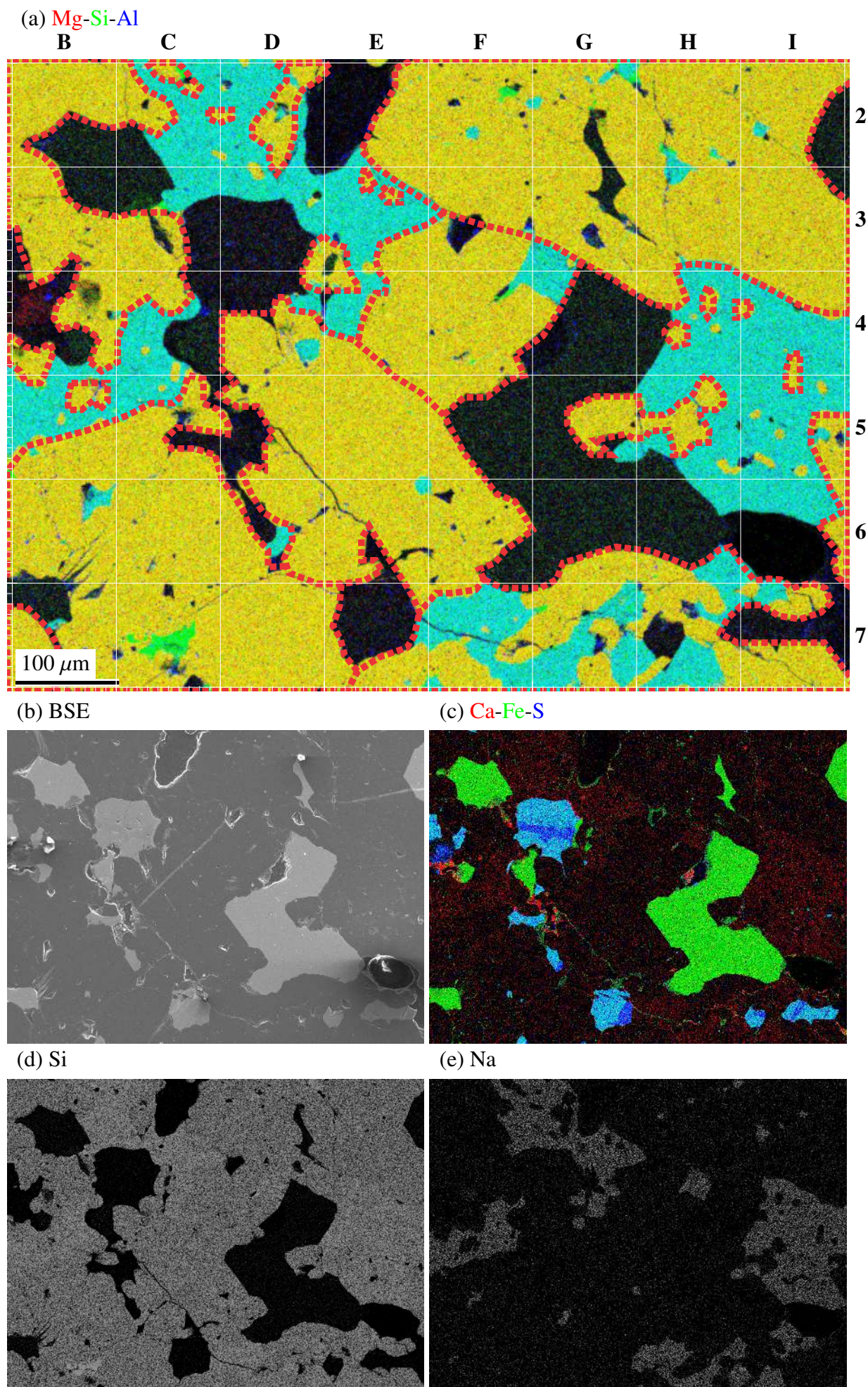


Figure 2.116: Site-3 of ALHA81021 (EL6). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.114.

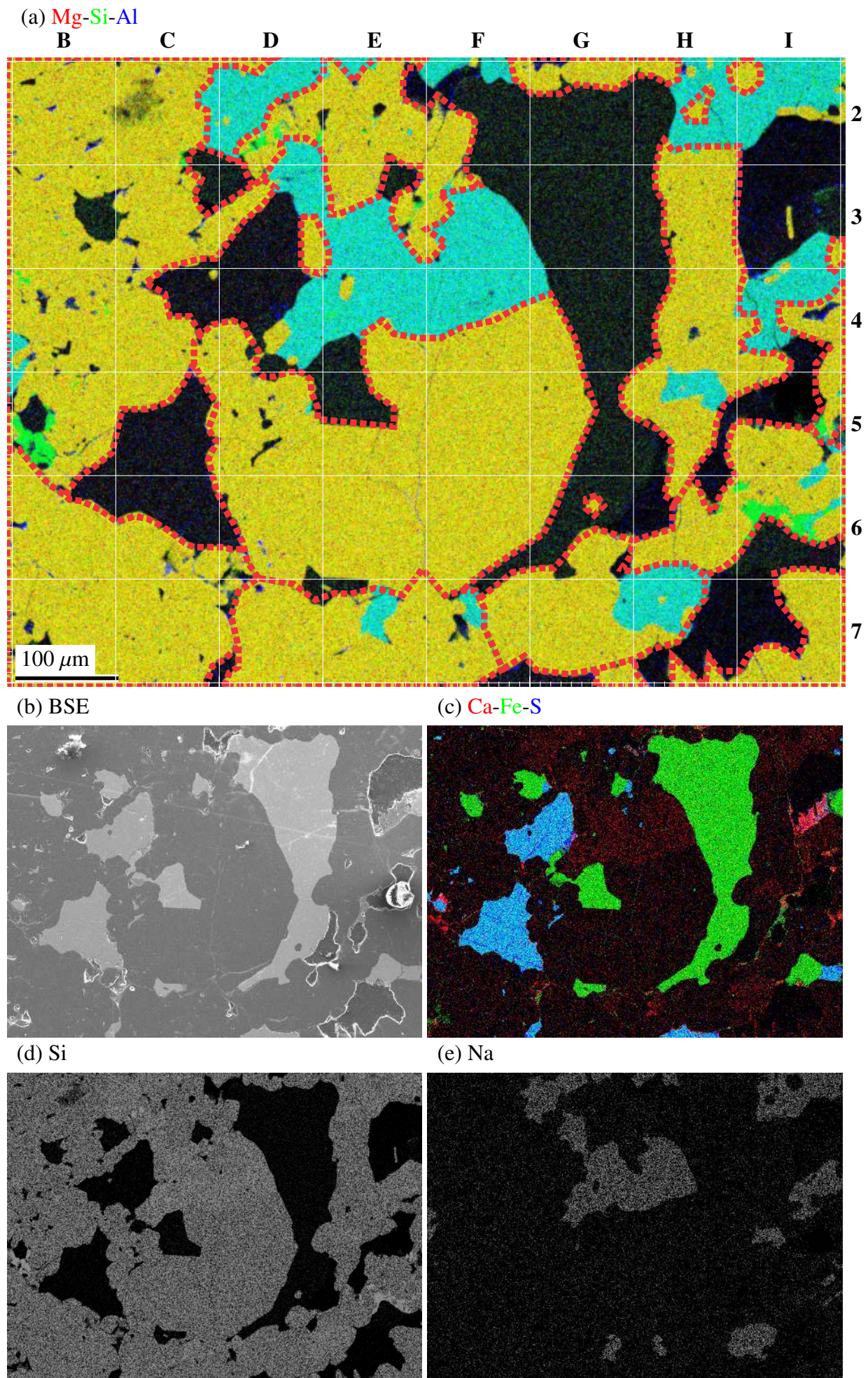


Figure 2.117: Site-4 of ALHA81021 (EL6). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.114.

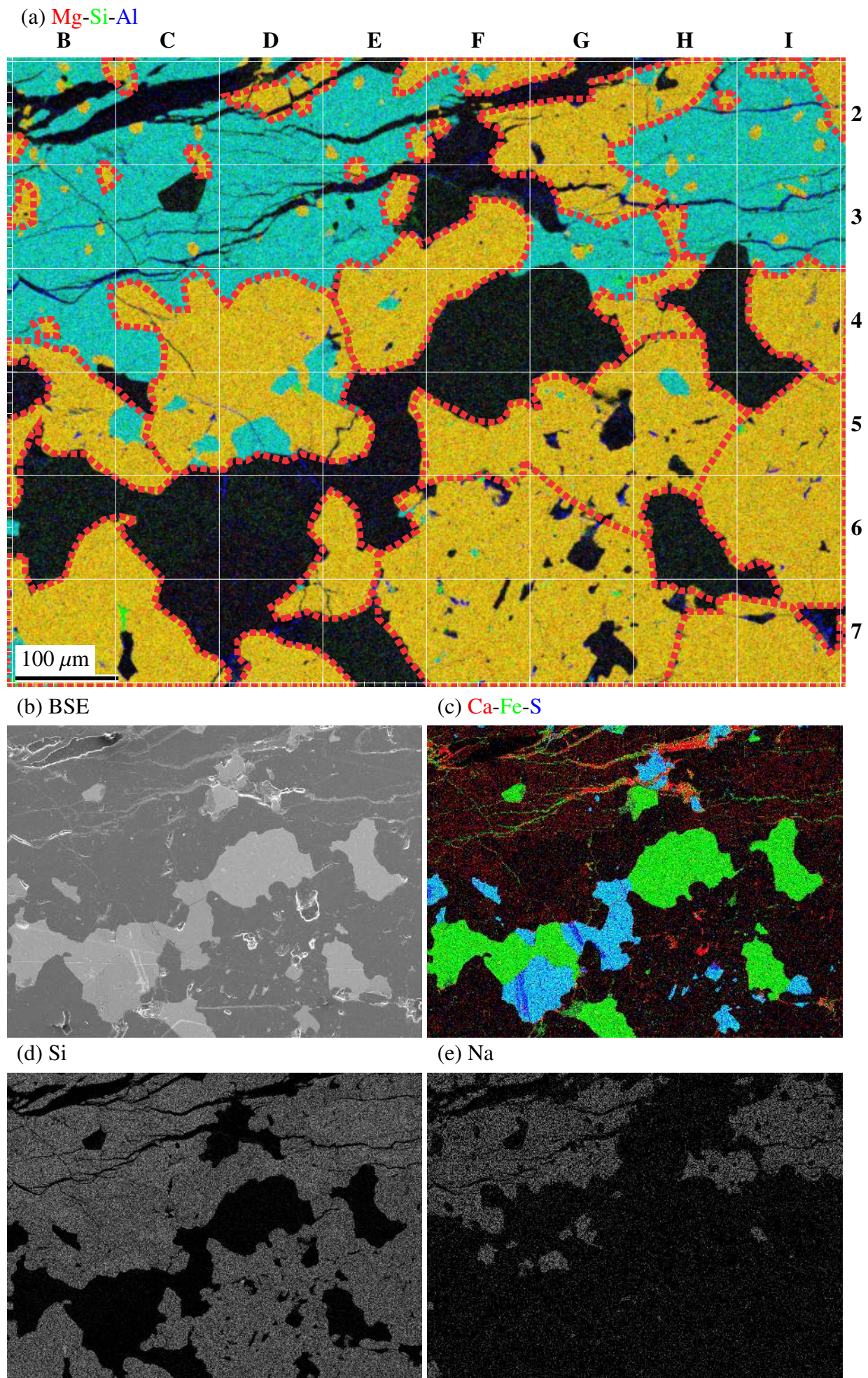


Figure 2.118: Site-5 of ALHA81021 (EL6). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.114.

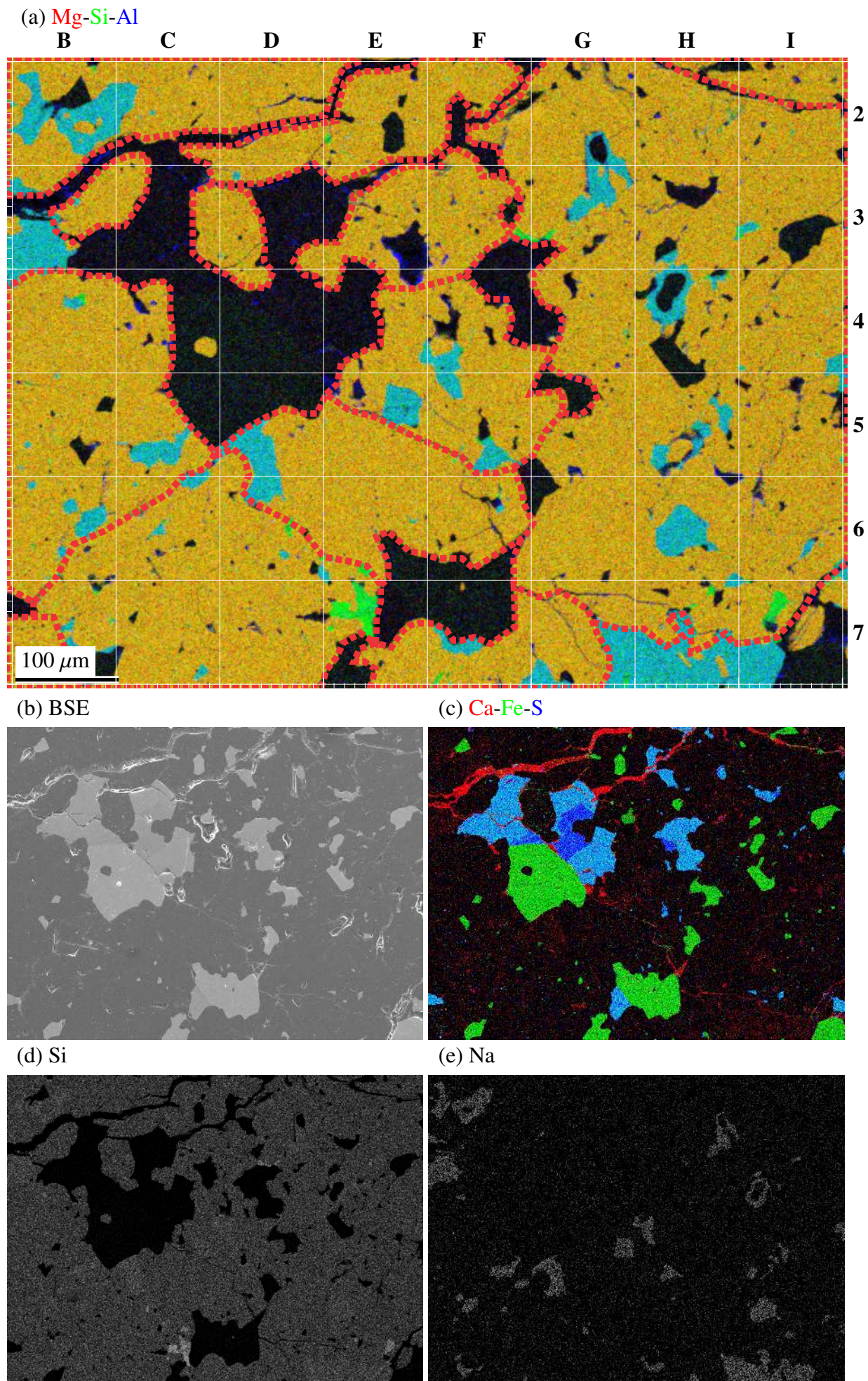


Figure 2.119: Site-6 of ALHA81021 (EL6). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.114.

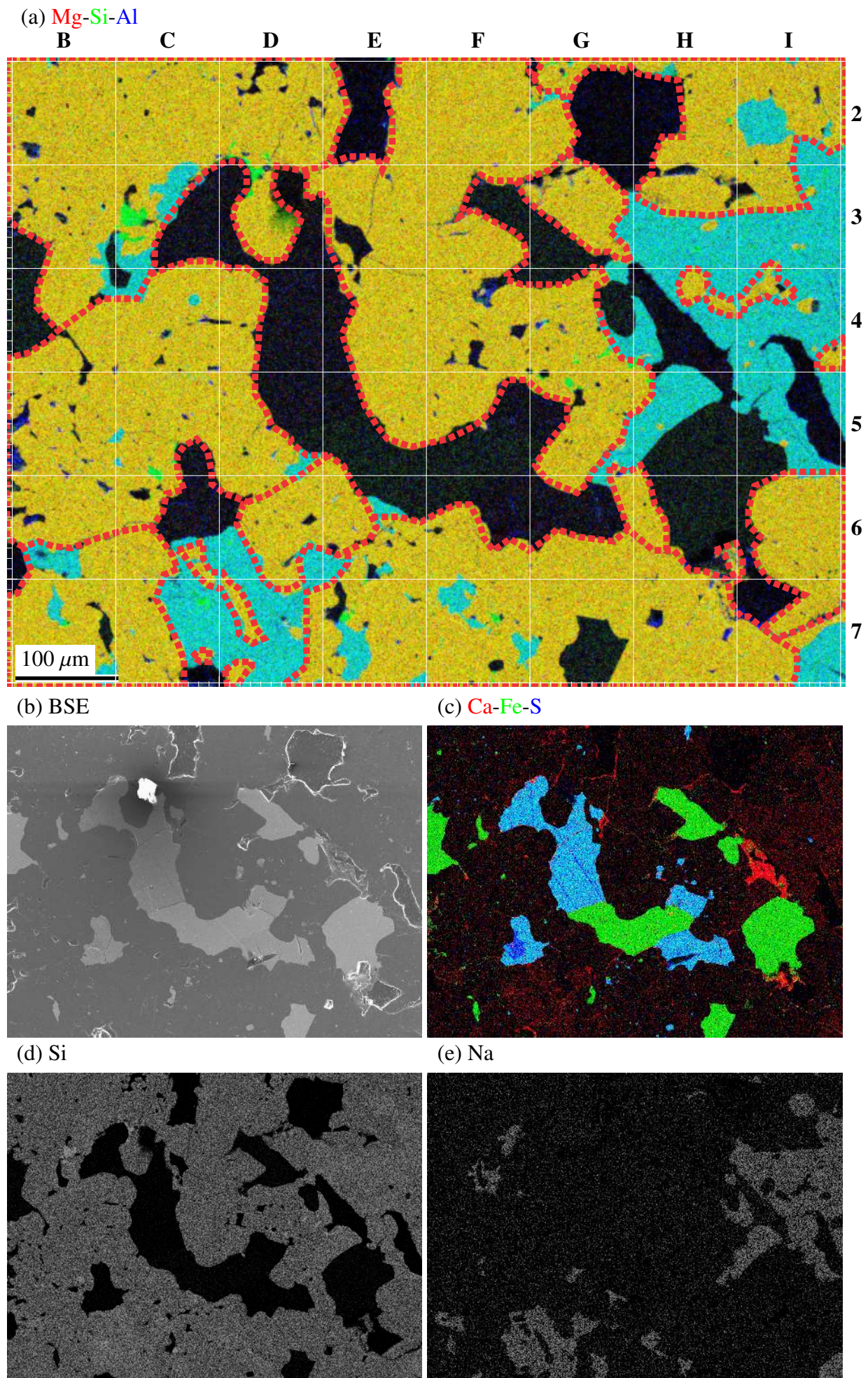


Figure 2.120: Site-7 of ALHA81021 (EL6). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.114.

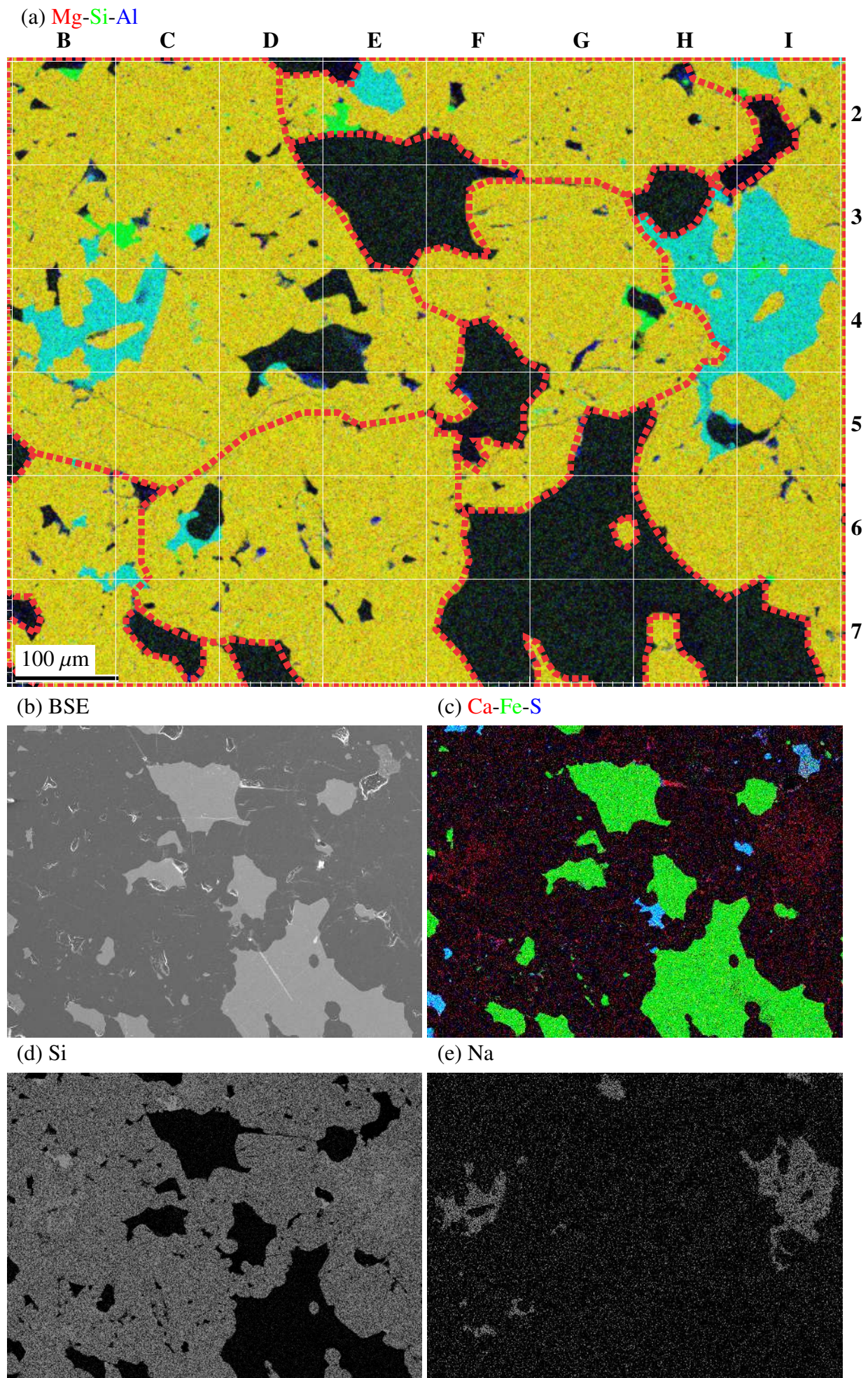


Figure 2.121: Site-8 of ALHA81021 (EL6). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.114.

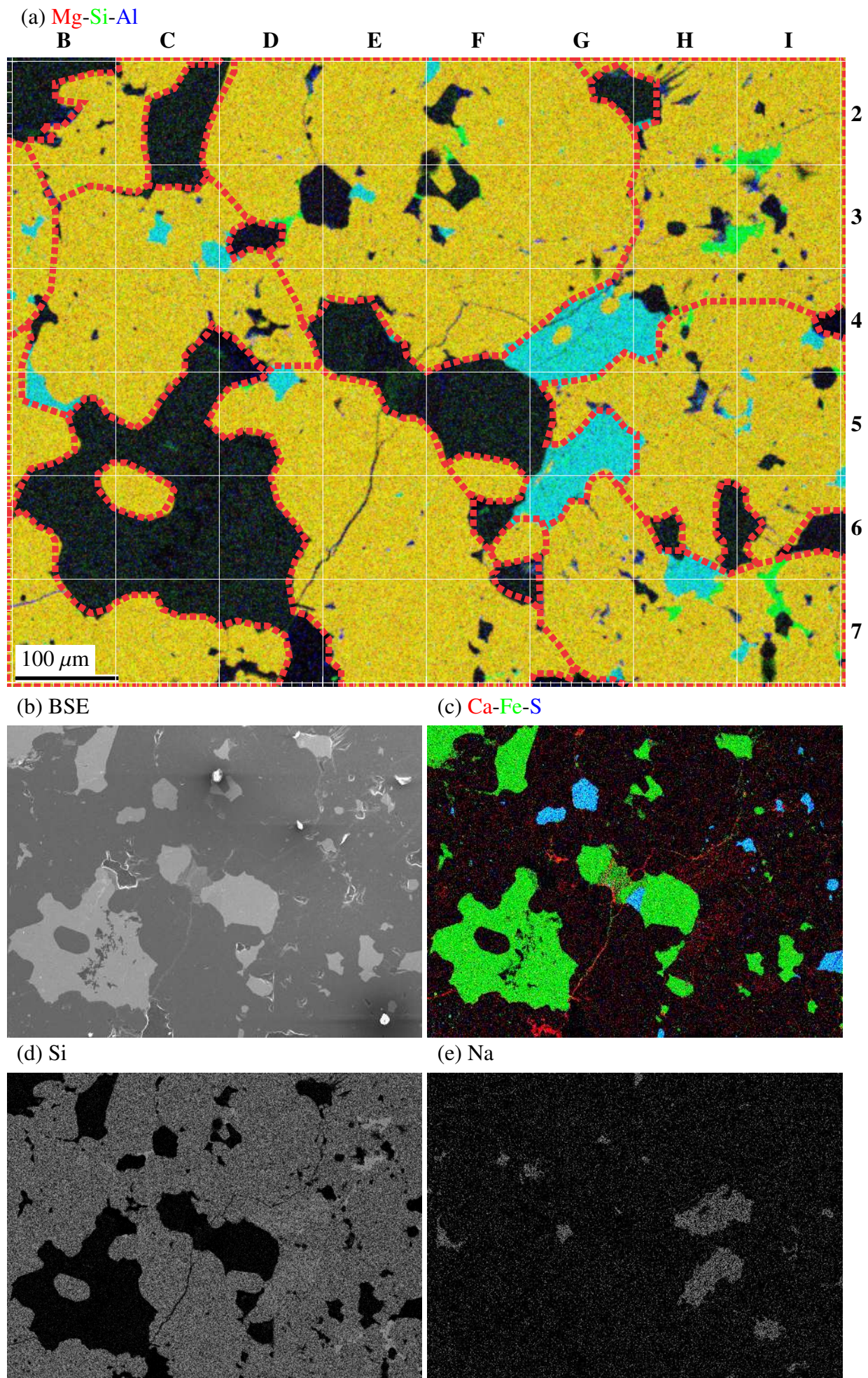


Figure 2.122: Site-9 of ALHA81021 (EL6). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.114.

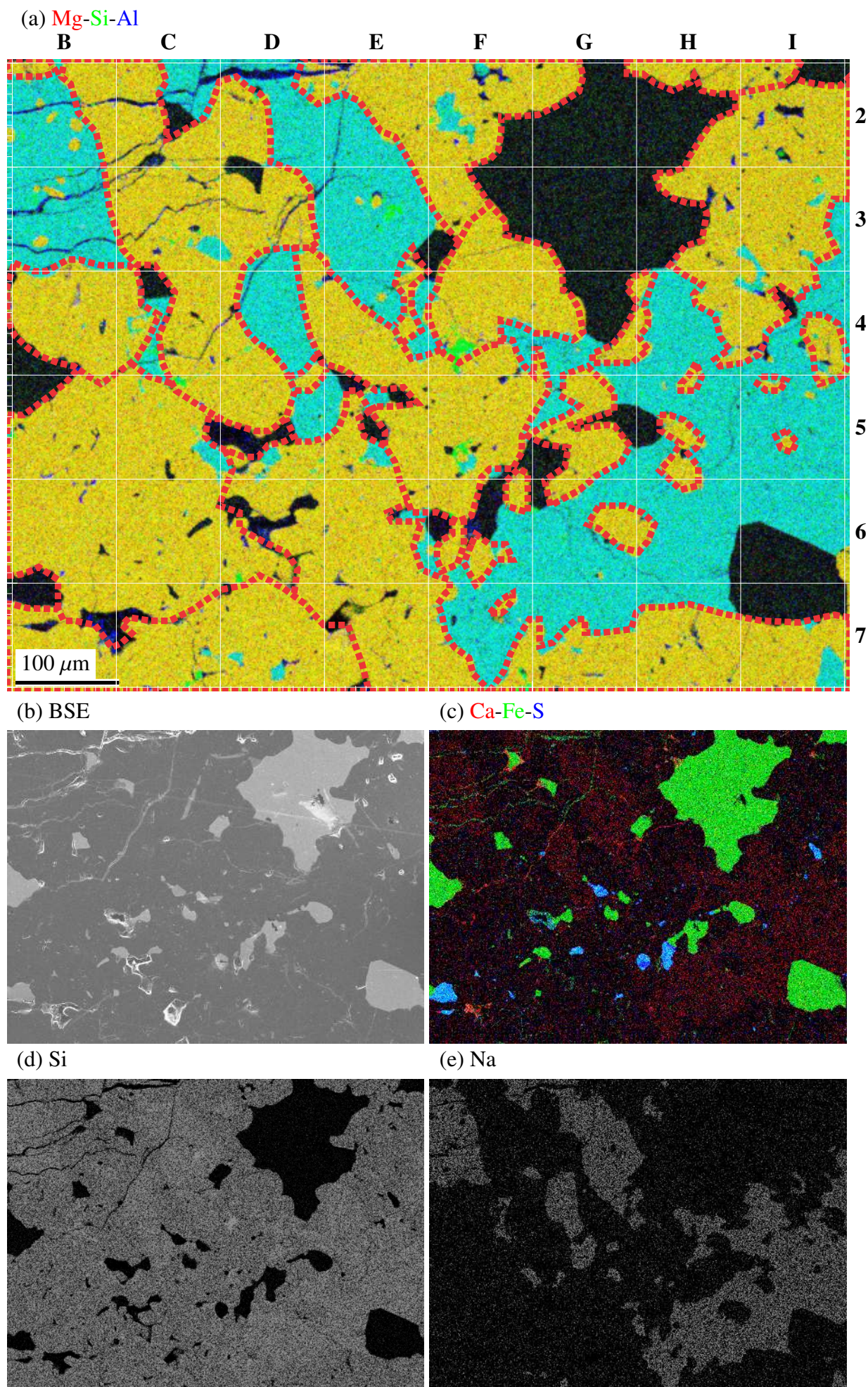


Figure 2.123: Site-10 of ALHA81021 (EL6). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.114.

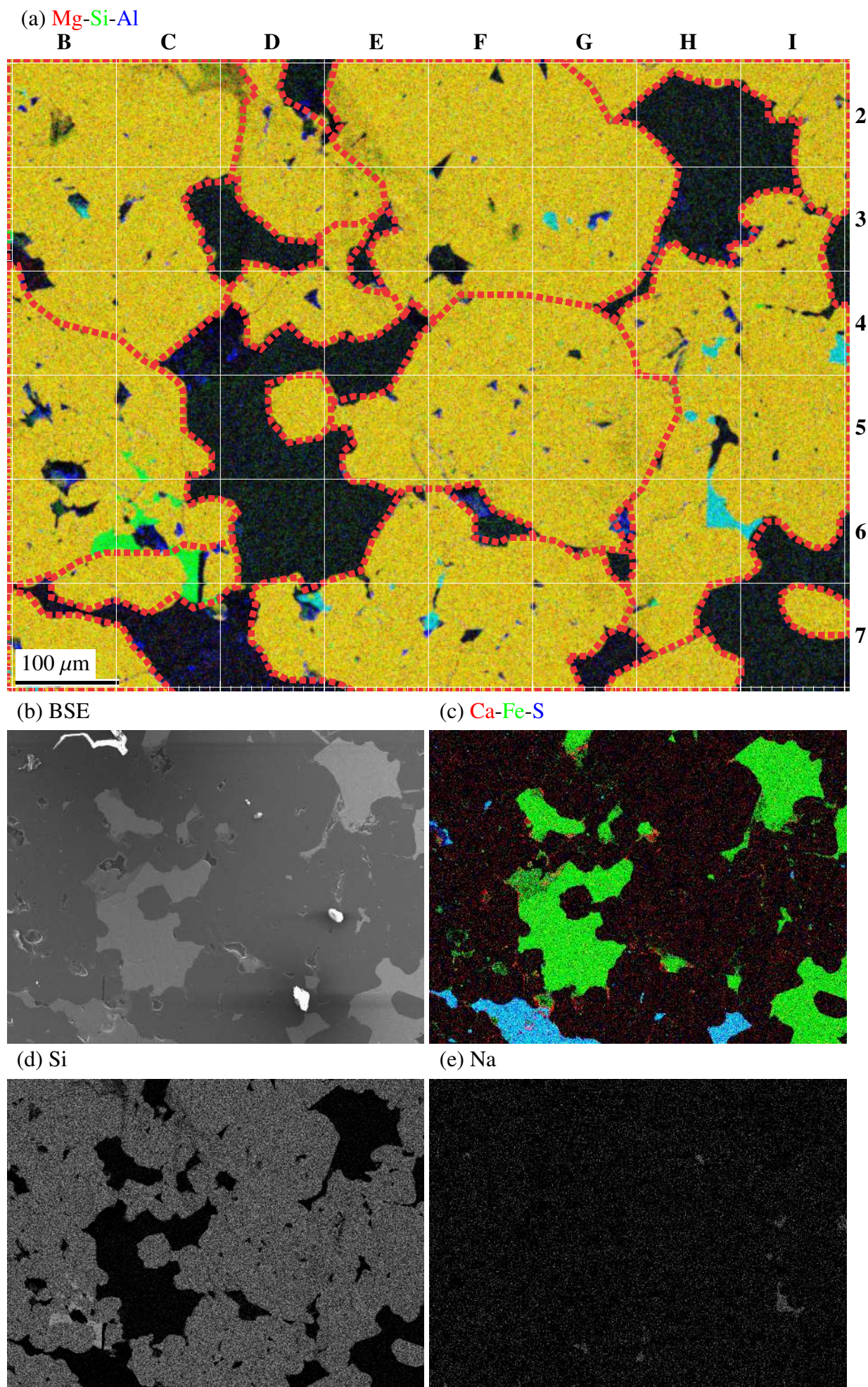


Figure 2.124: Site-11 of ALHA81021 (EL6). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.114.

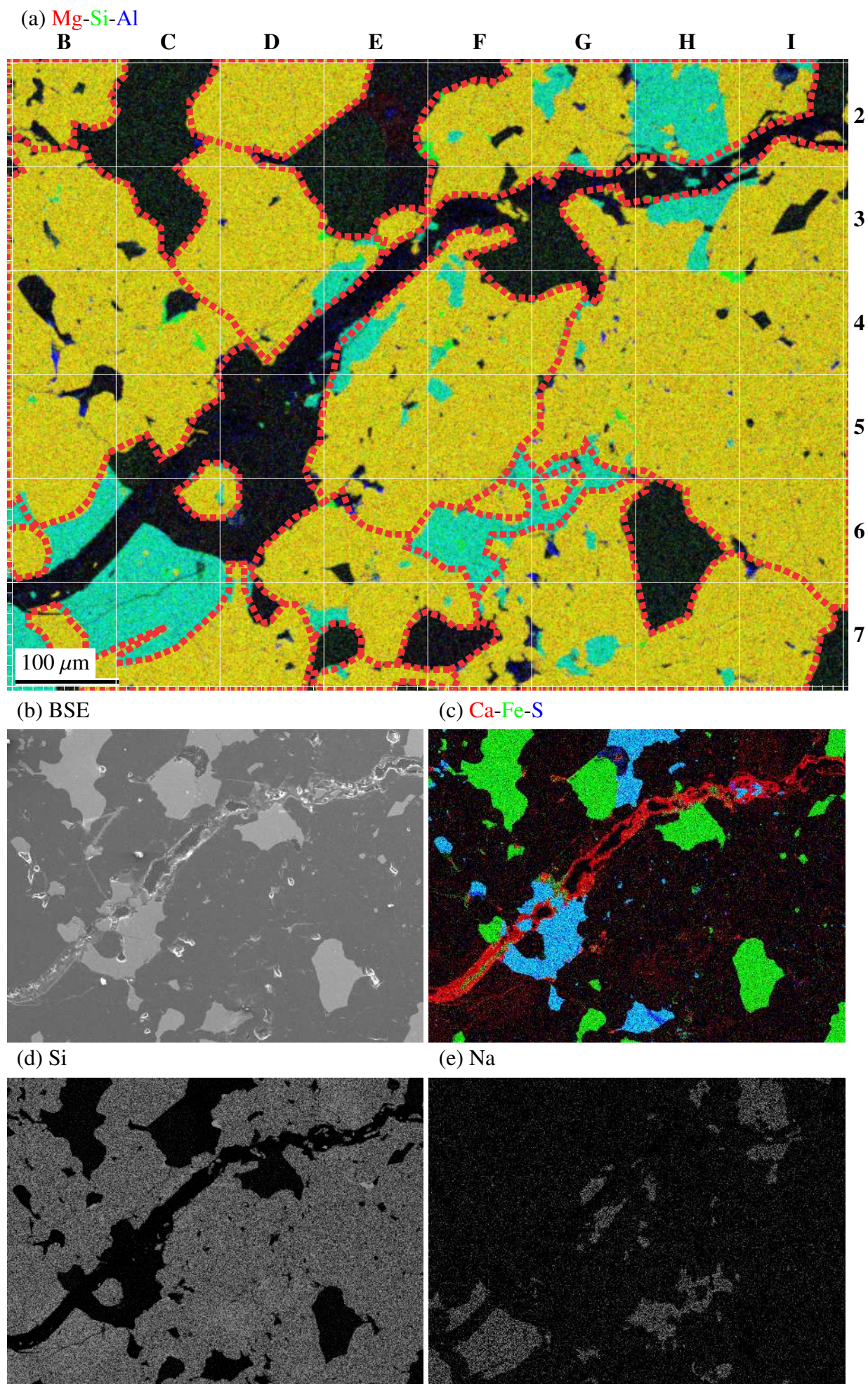


Figure 2.125: Site-12 of ALHA81021 (EL6). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.114.

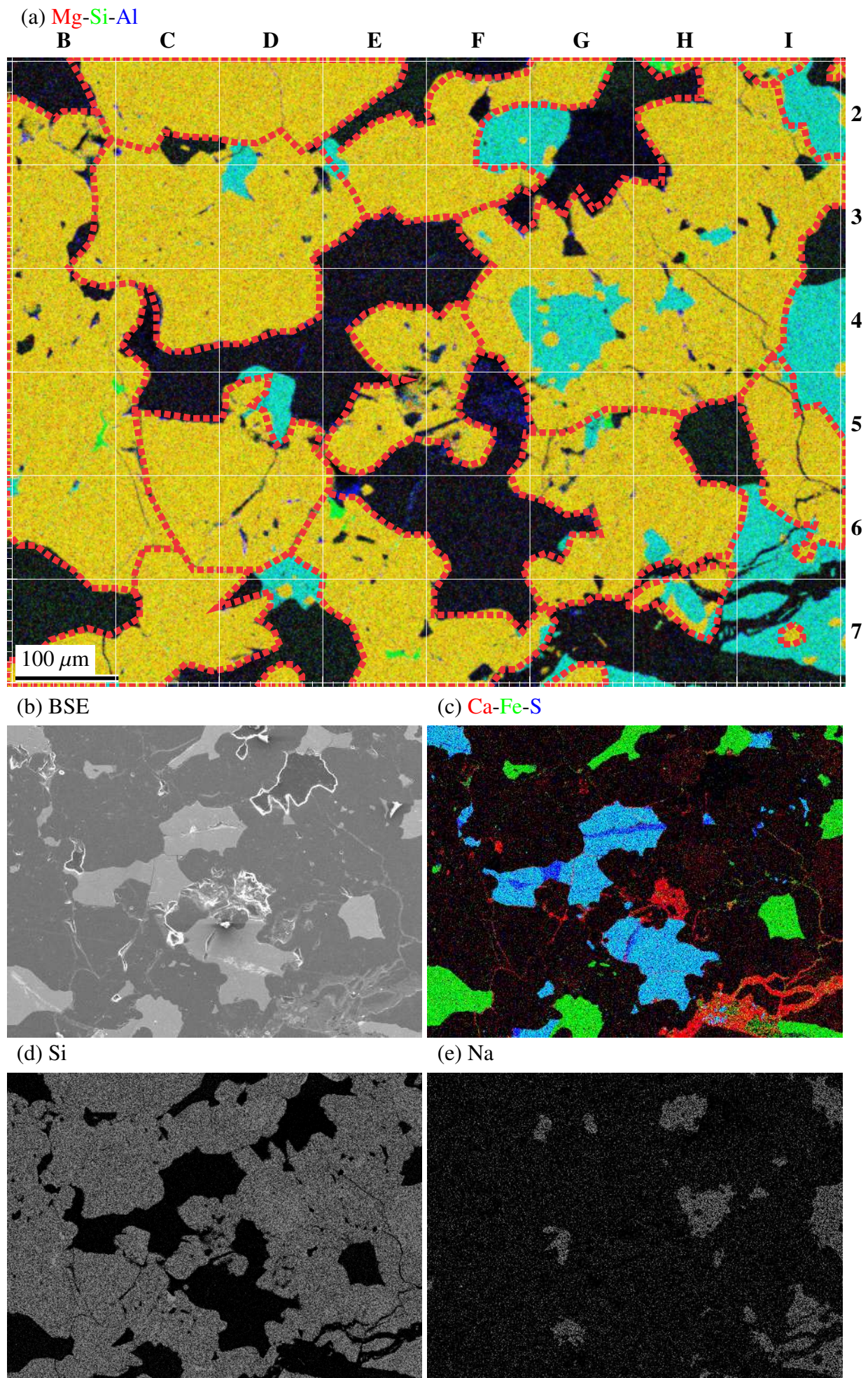


Figure 2.126: Site-13 of ALHA81021 (EL6). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.114.

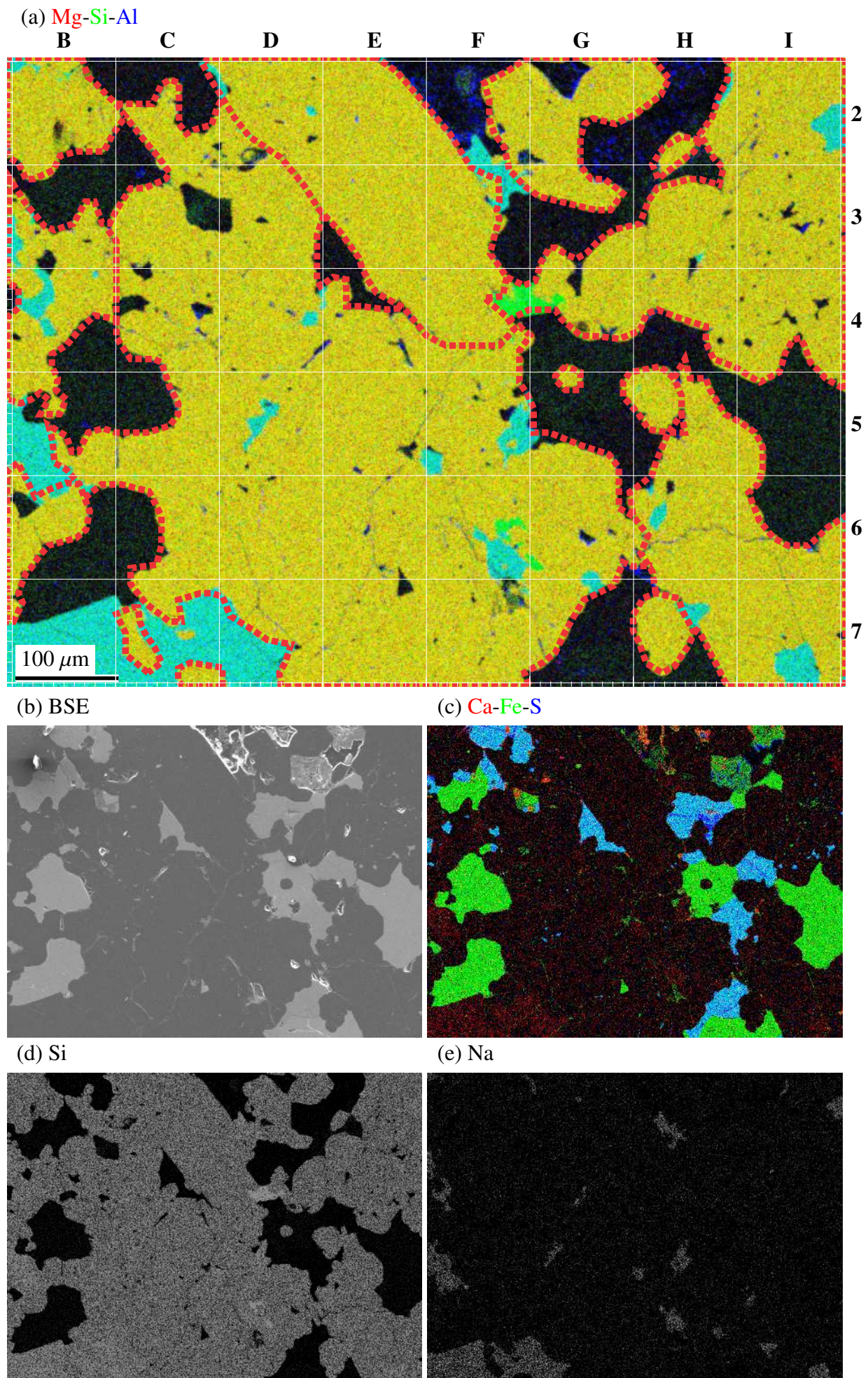


Figure 2.127: Site-14 of ALHA81021 (EL6). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.114.

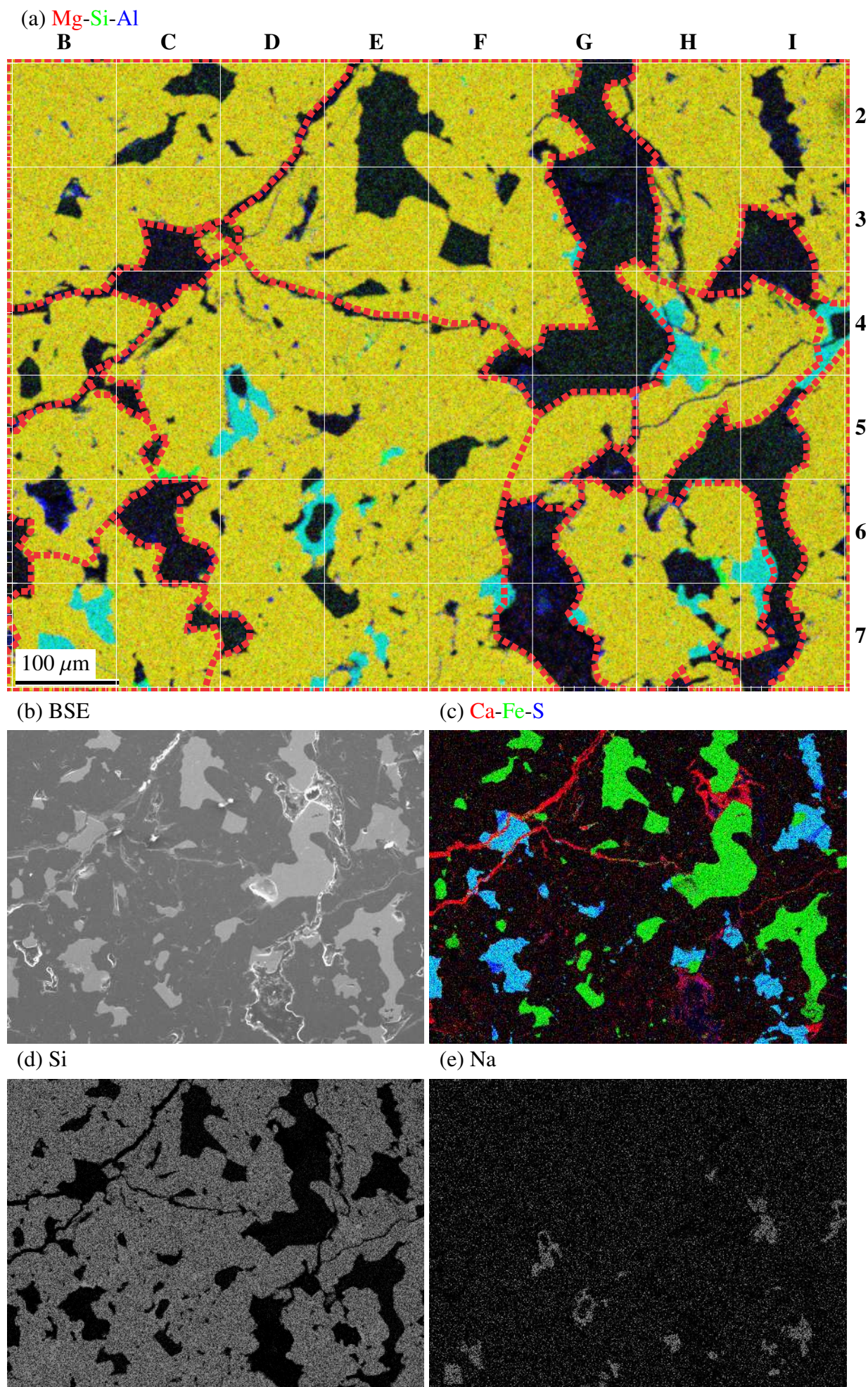


Figure 2.128: Site-15 of ALHA81021 (EL6). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.114.

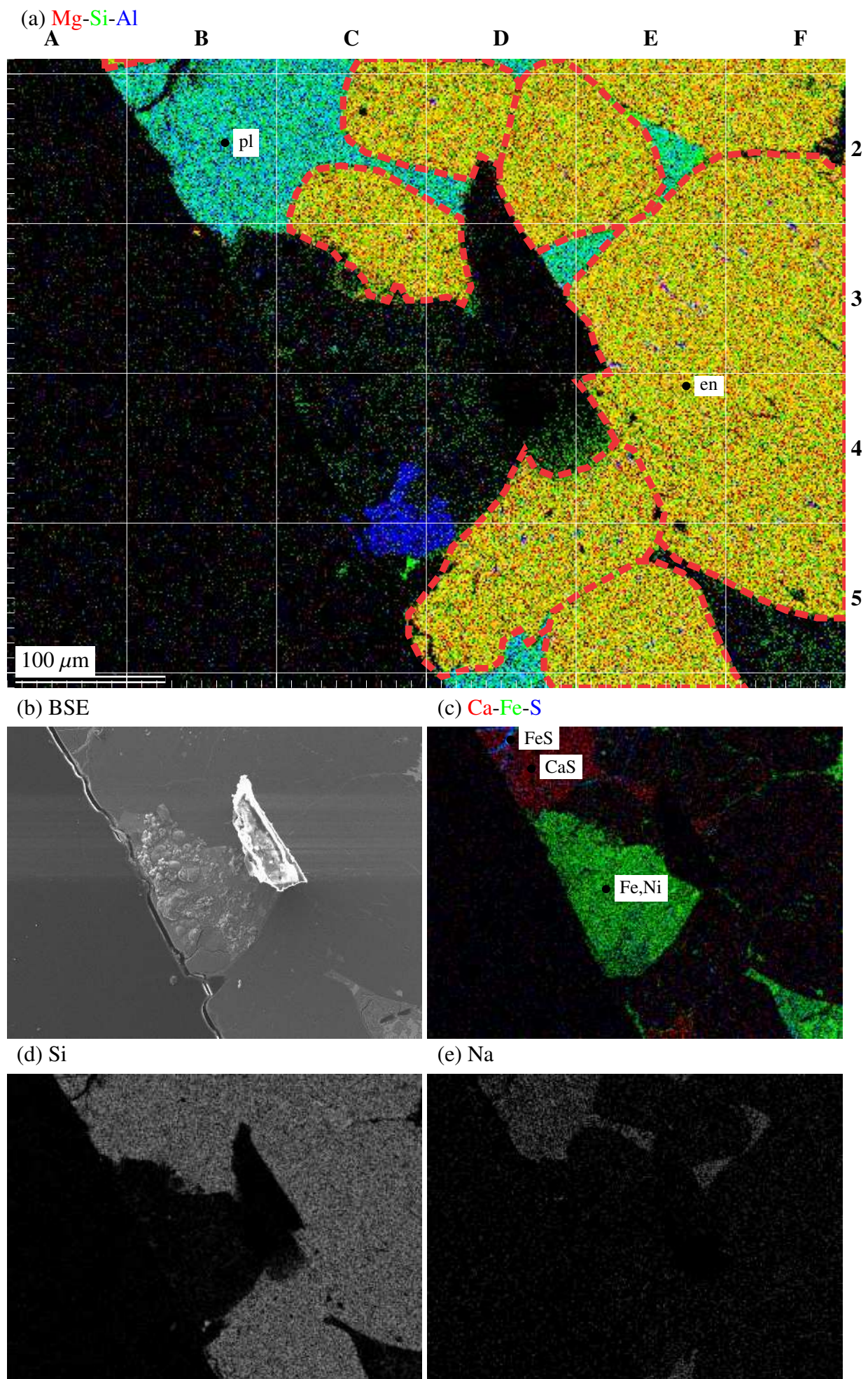


Figure 2.129: Site-1 of Zaklodzie (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown.

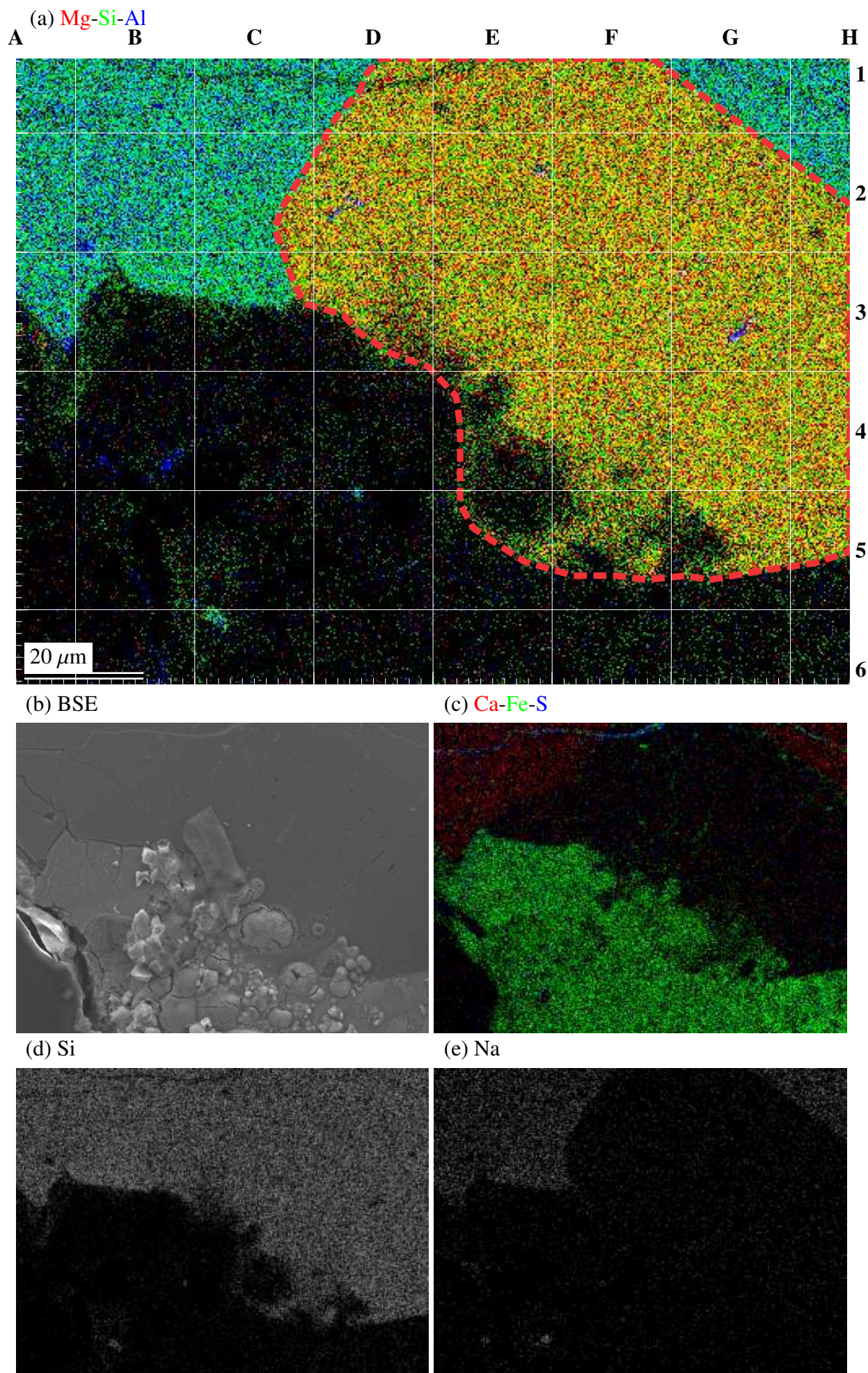


Figure 2.130: Site-2 of Zaklodzie (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.129.

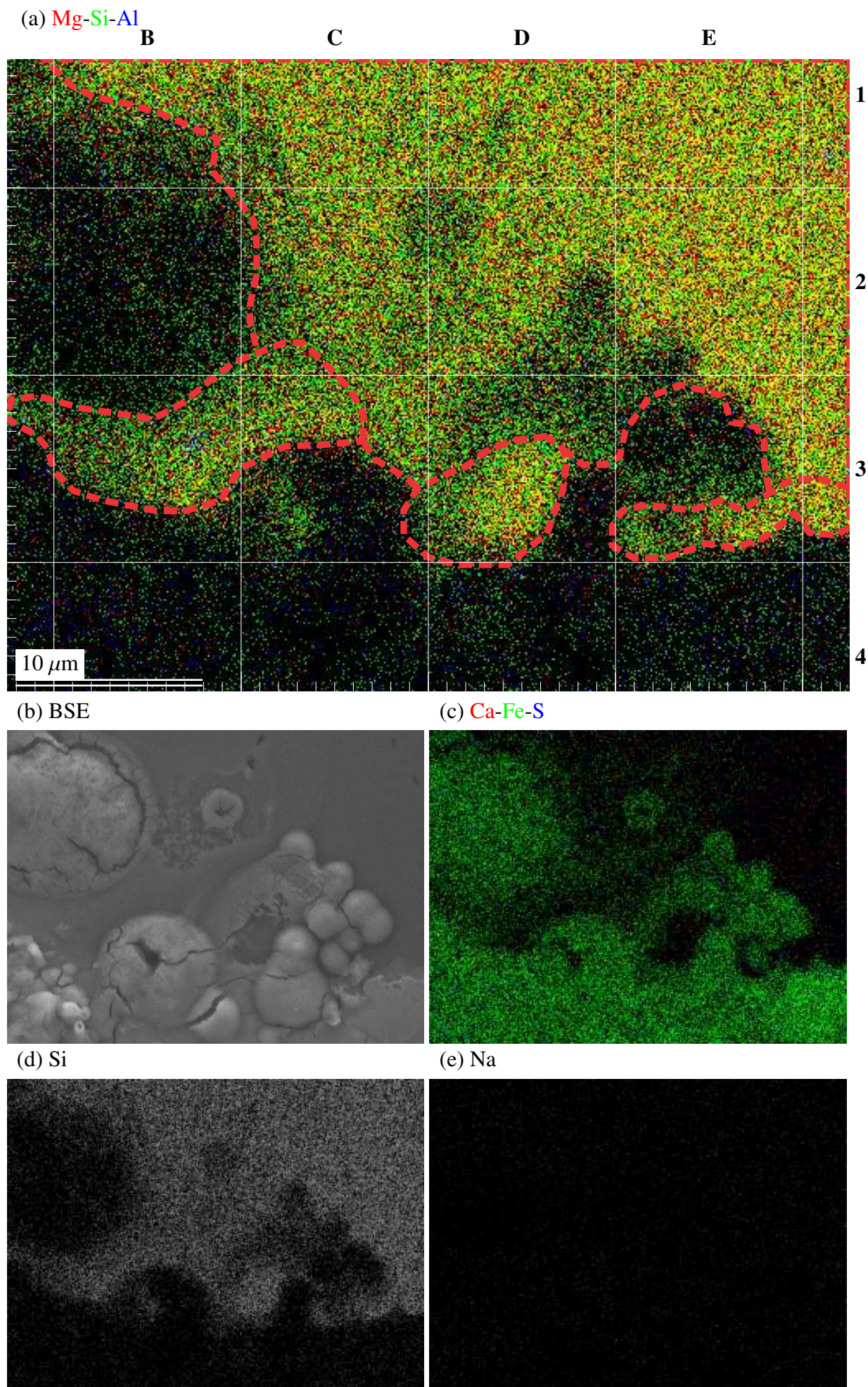


Figure 2.131: Site-3 of Zaklodzie (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.129.

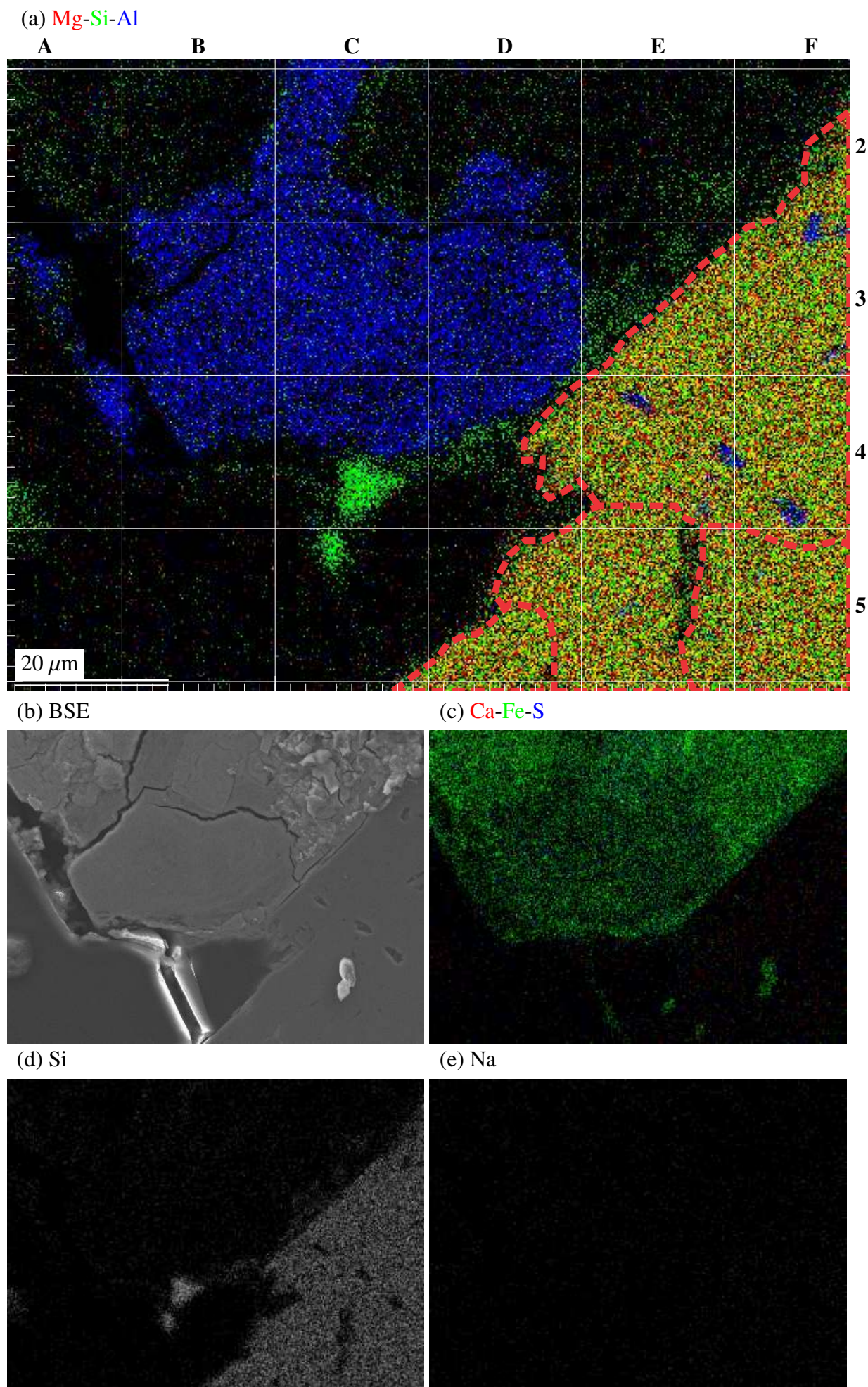


Figure 2.132: Site-4 of Zaklodzie (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.129.

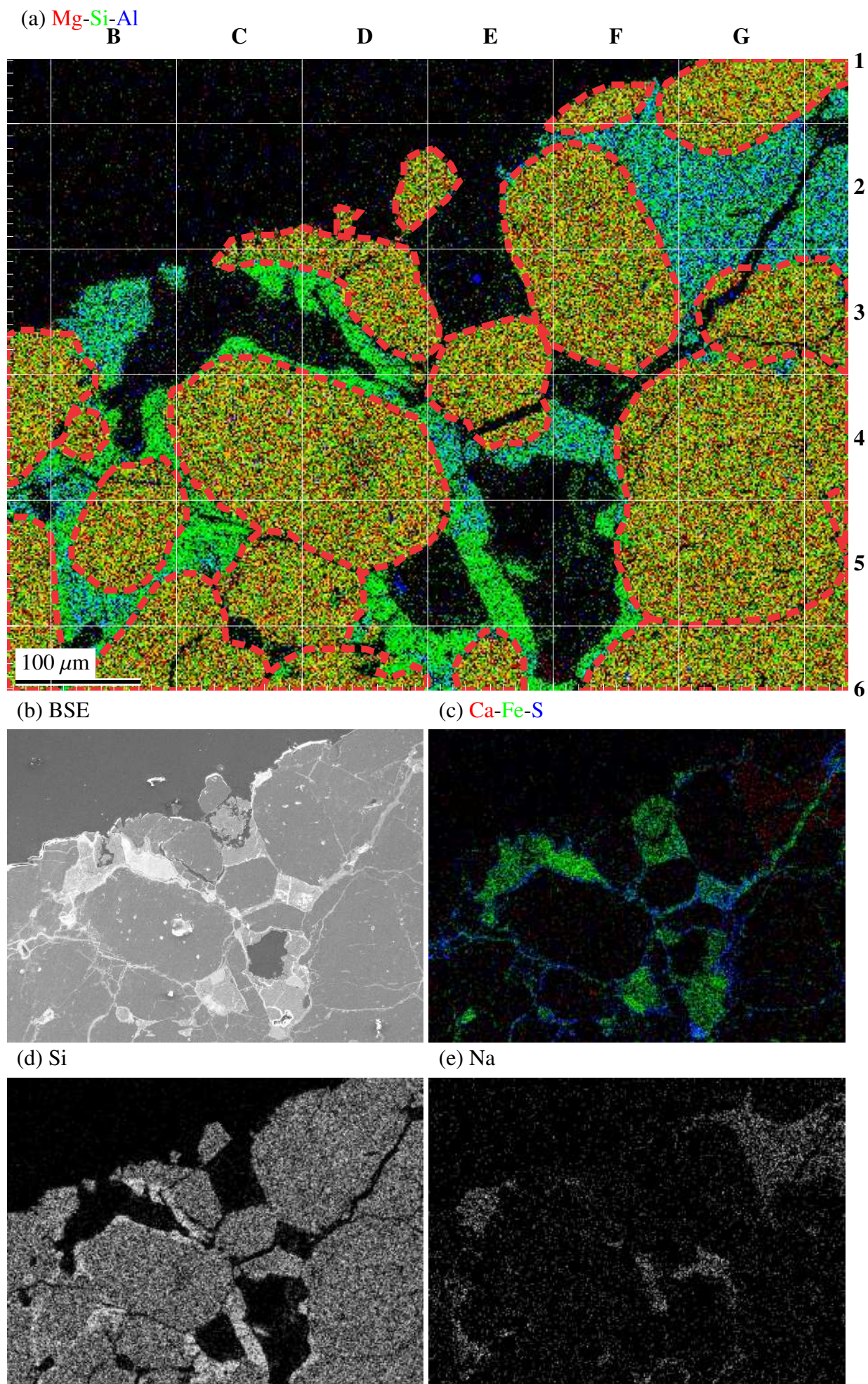


Figure 2.133: Site-5 of Zaklodzie (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.129.

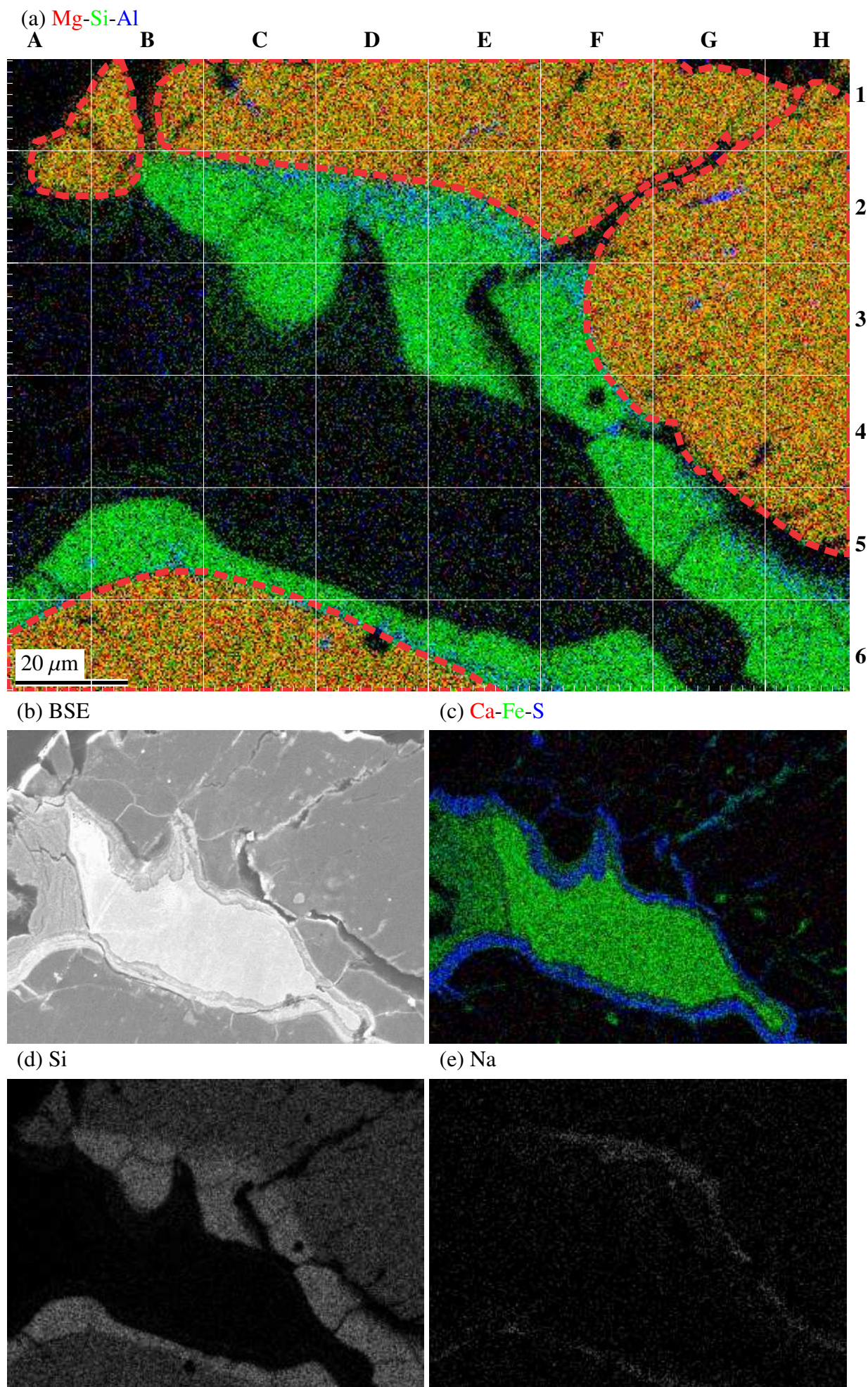


Figure 2.134: Site-6 of Zaklodzie (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.129.

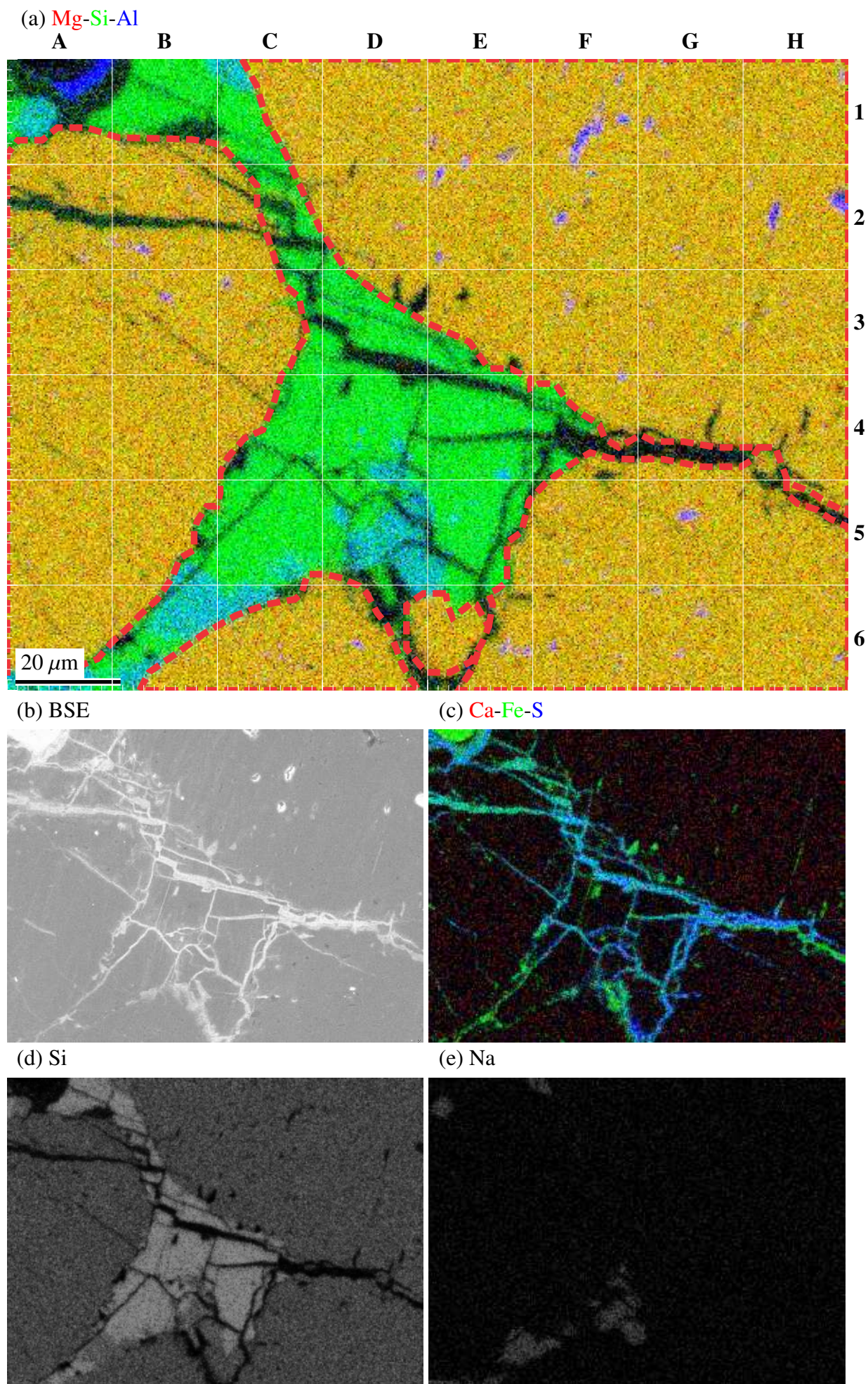


Figure 2.135: Site-7 of Zaklodzie (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.129.

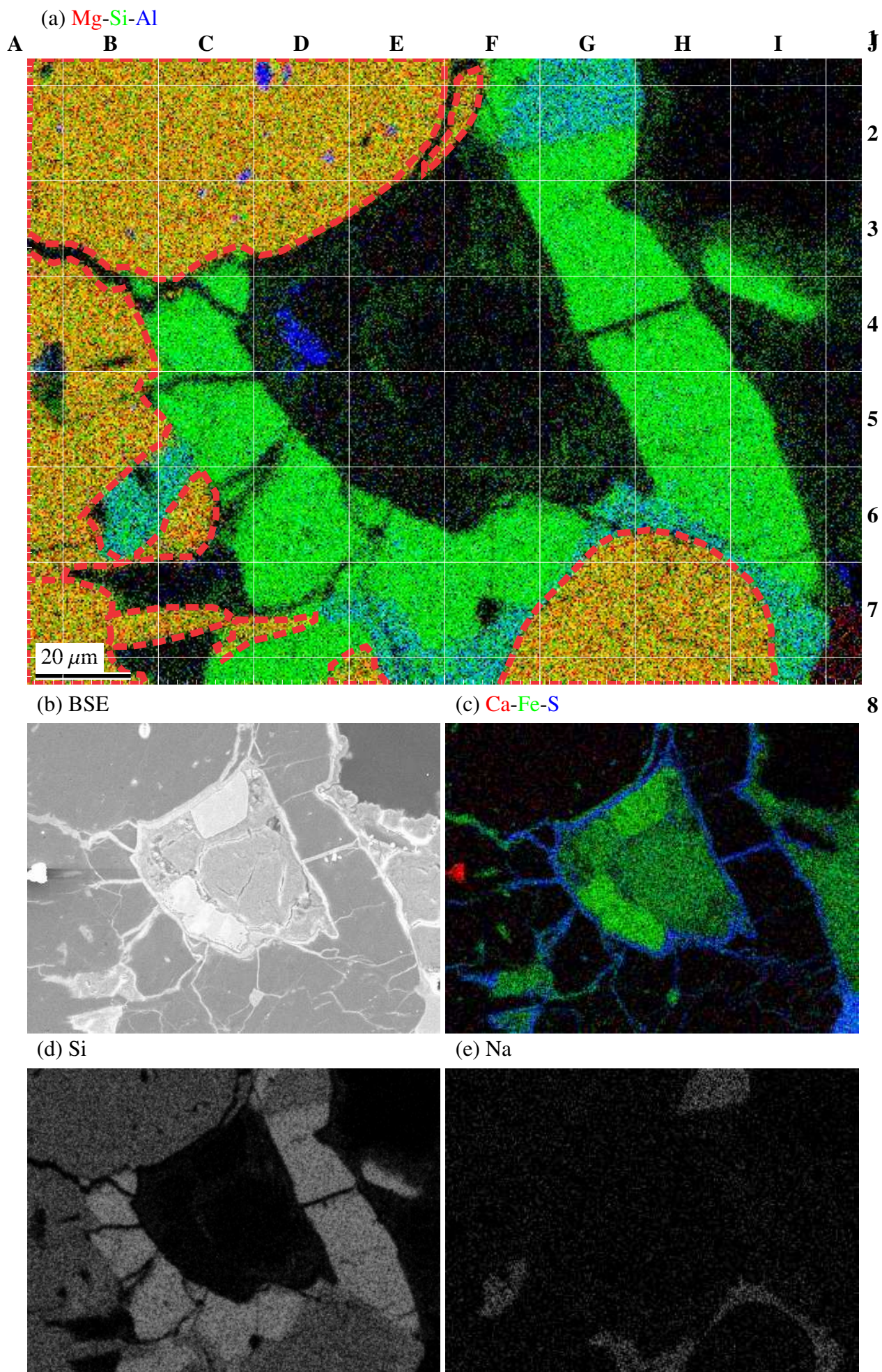


Figure 2.136: Site-8 of Zaklodzie (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.129.

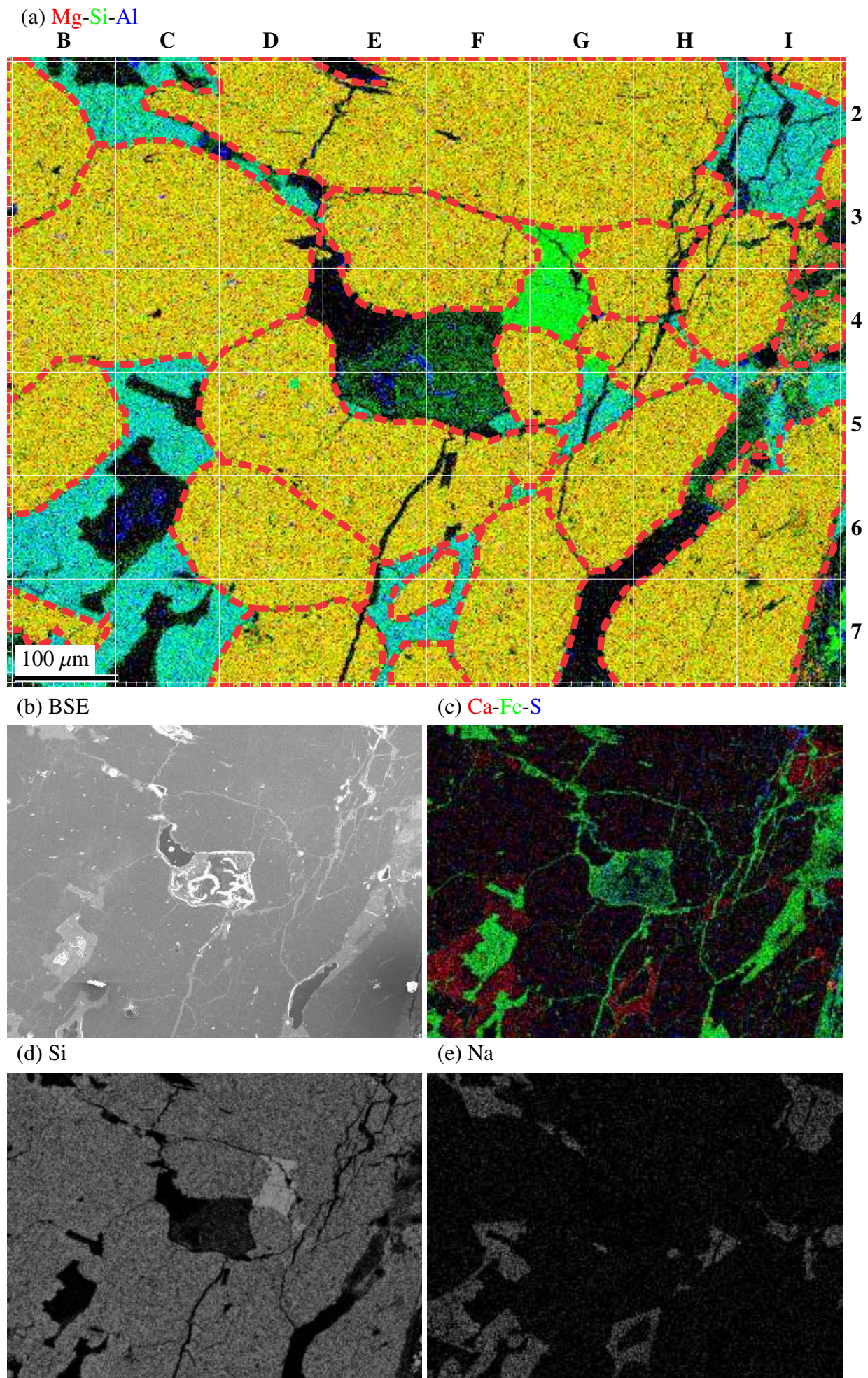


Figure 2.137: Site-9 of Zakłodzie (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.129.

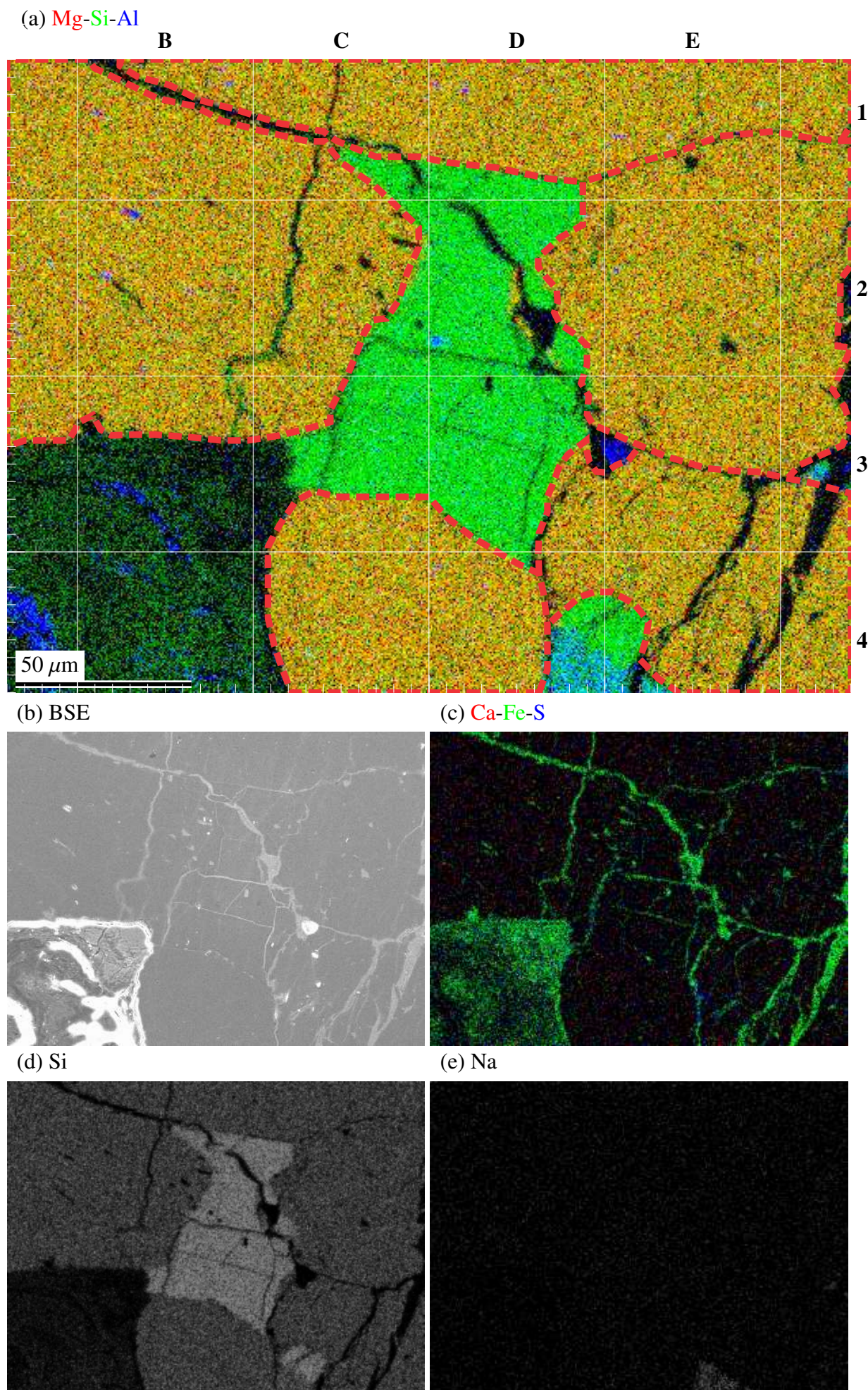


Figure 2.138: Site-10 of Zaklodzie (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.129.

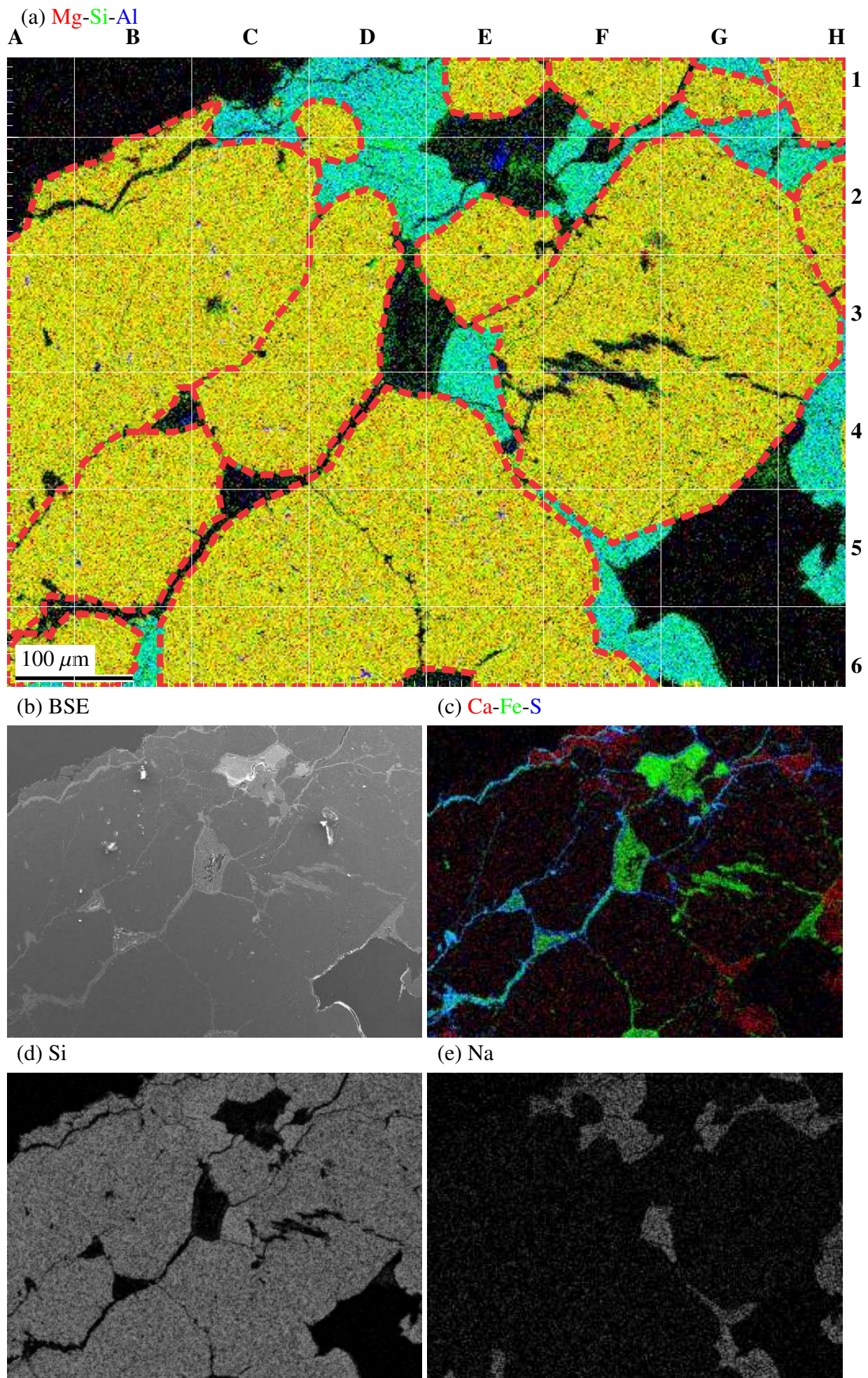


Figure 2.139: Site-11 of Zakłodzie (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.129.

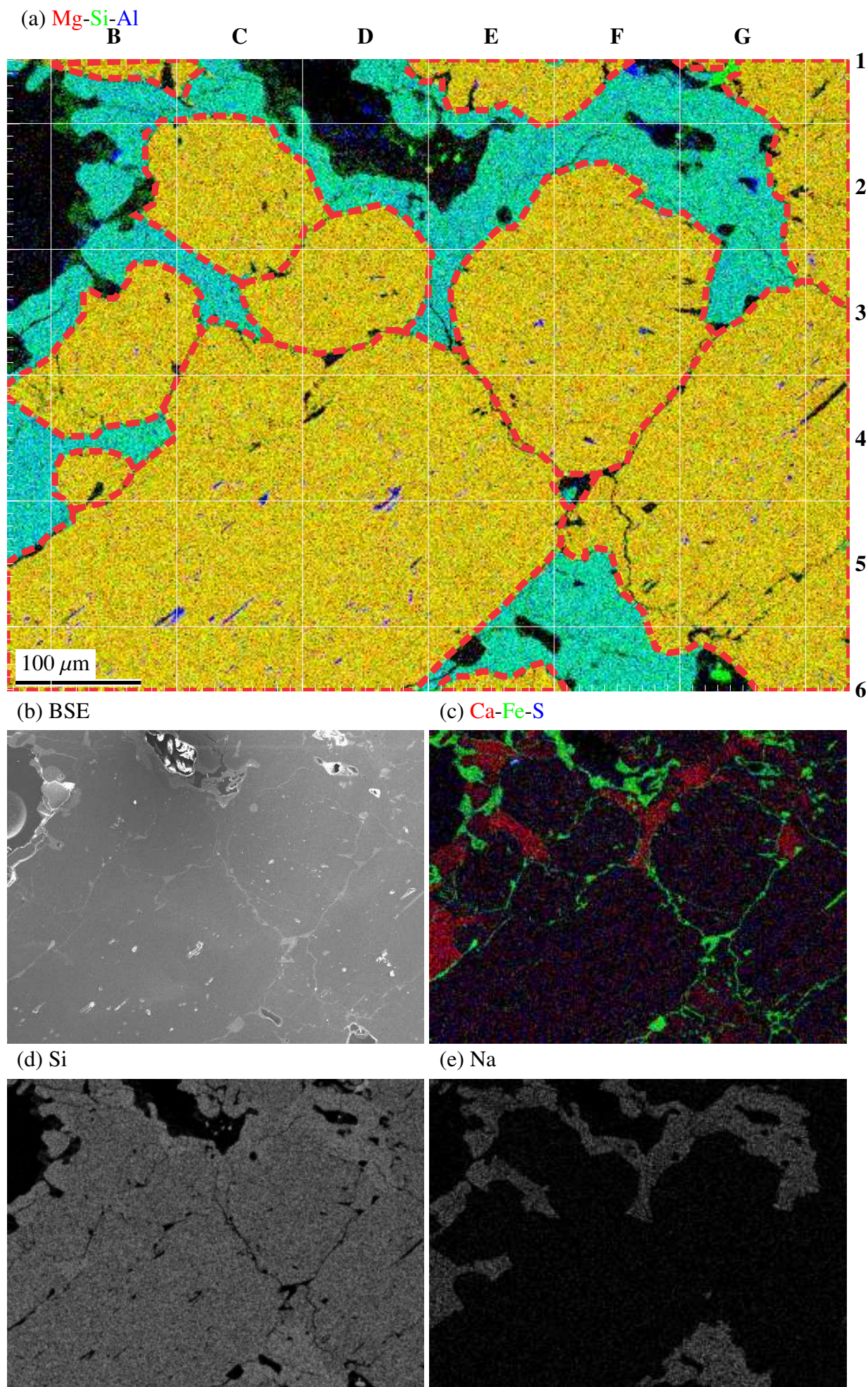


Figure 2.140: Site-12 of Zaklodzie (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.129.

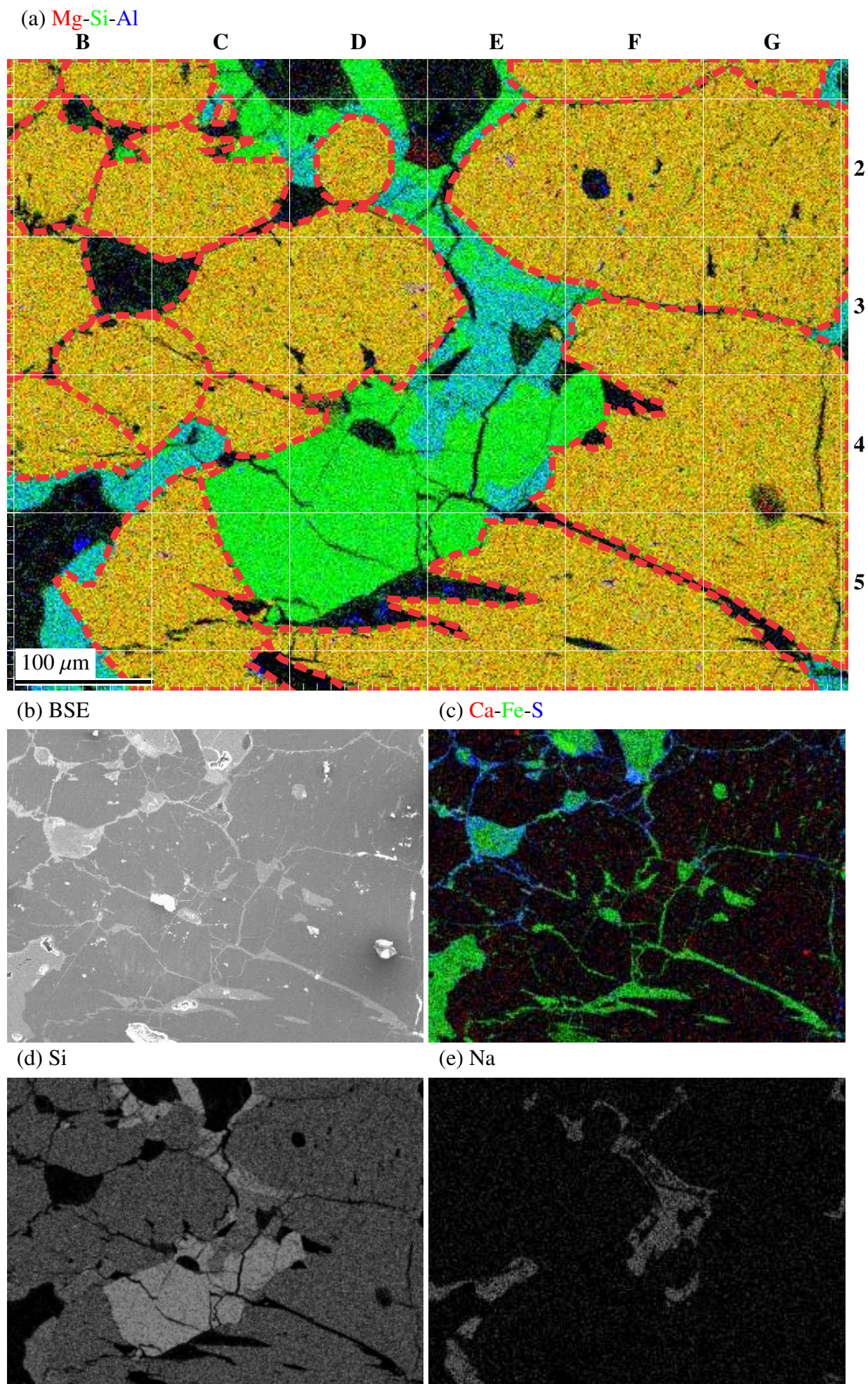


Figure 2.141: Site-13 of Zaklodzie (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.129.

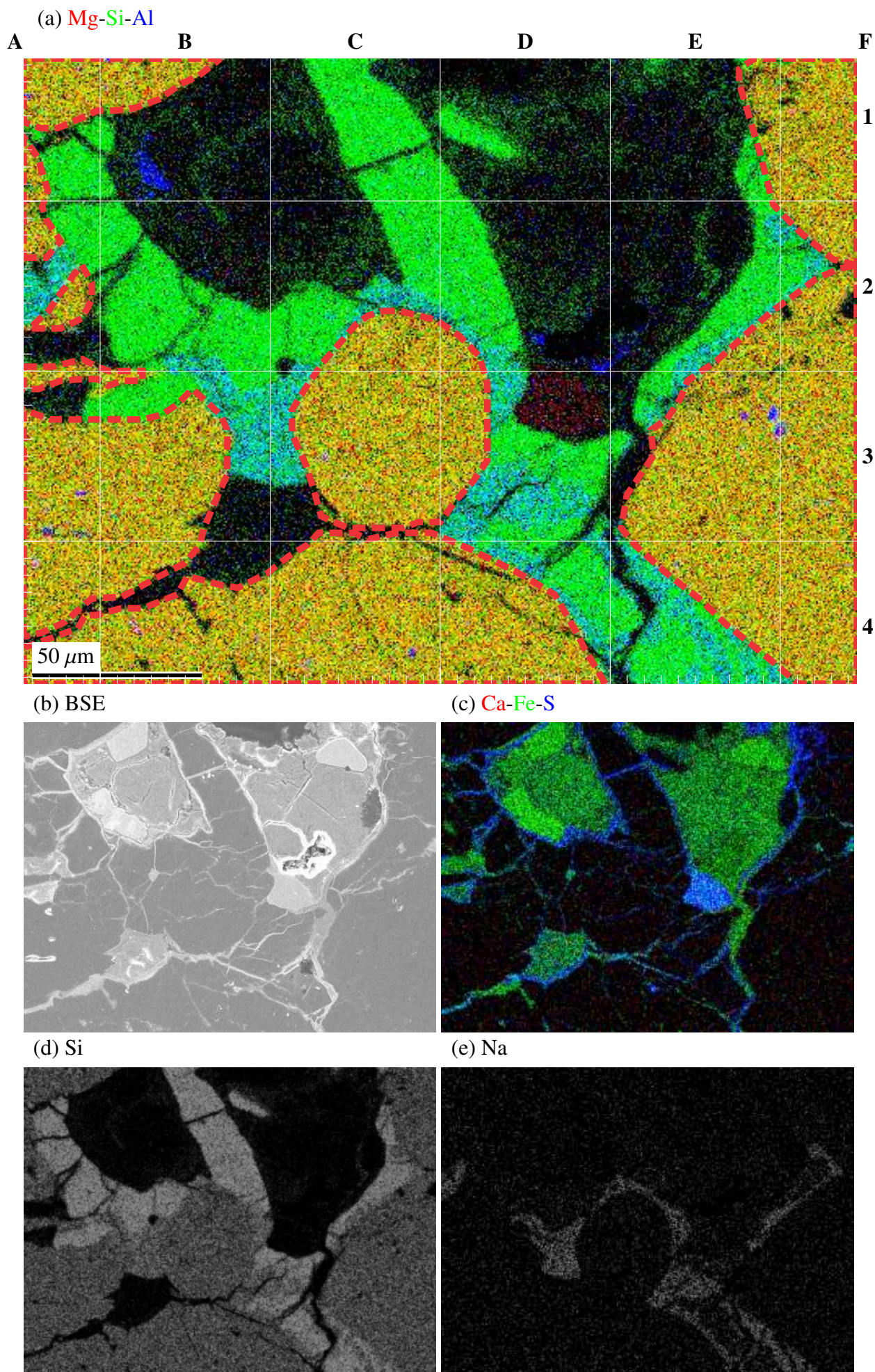


Figure 2.142: Site-14 of Zaklodzie (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.129.

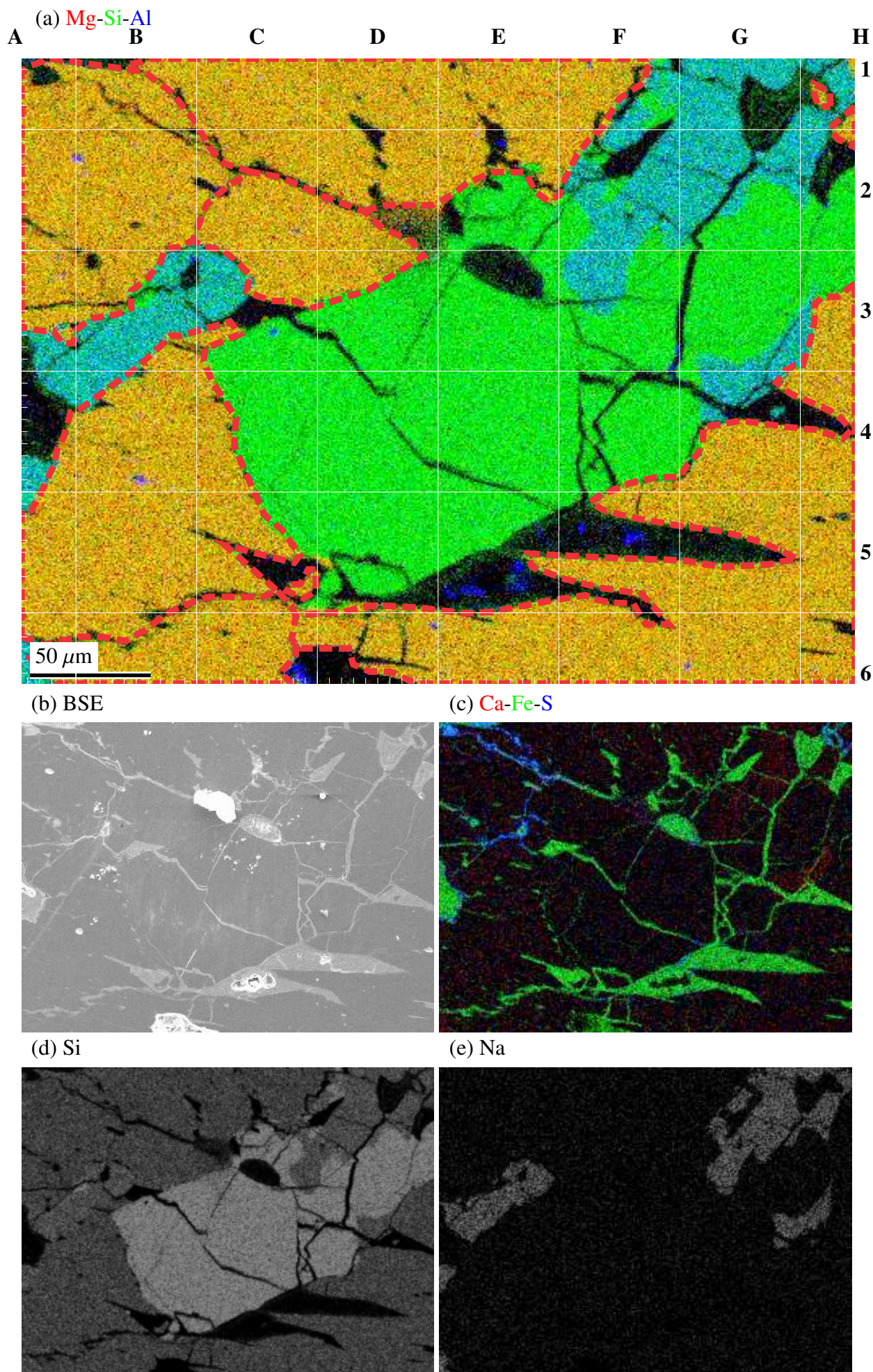


Figure 2.143: Site-15 of Zaklodzie (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.129.

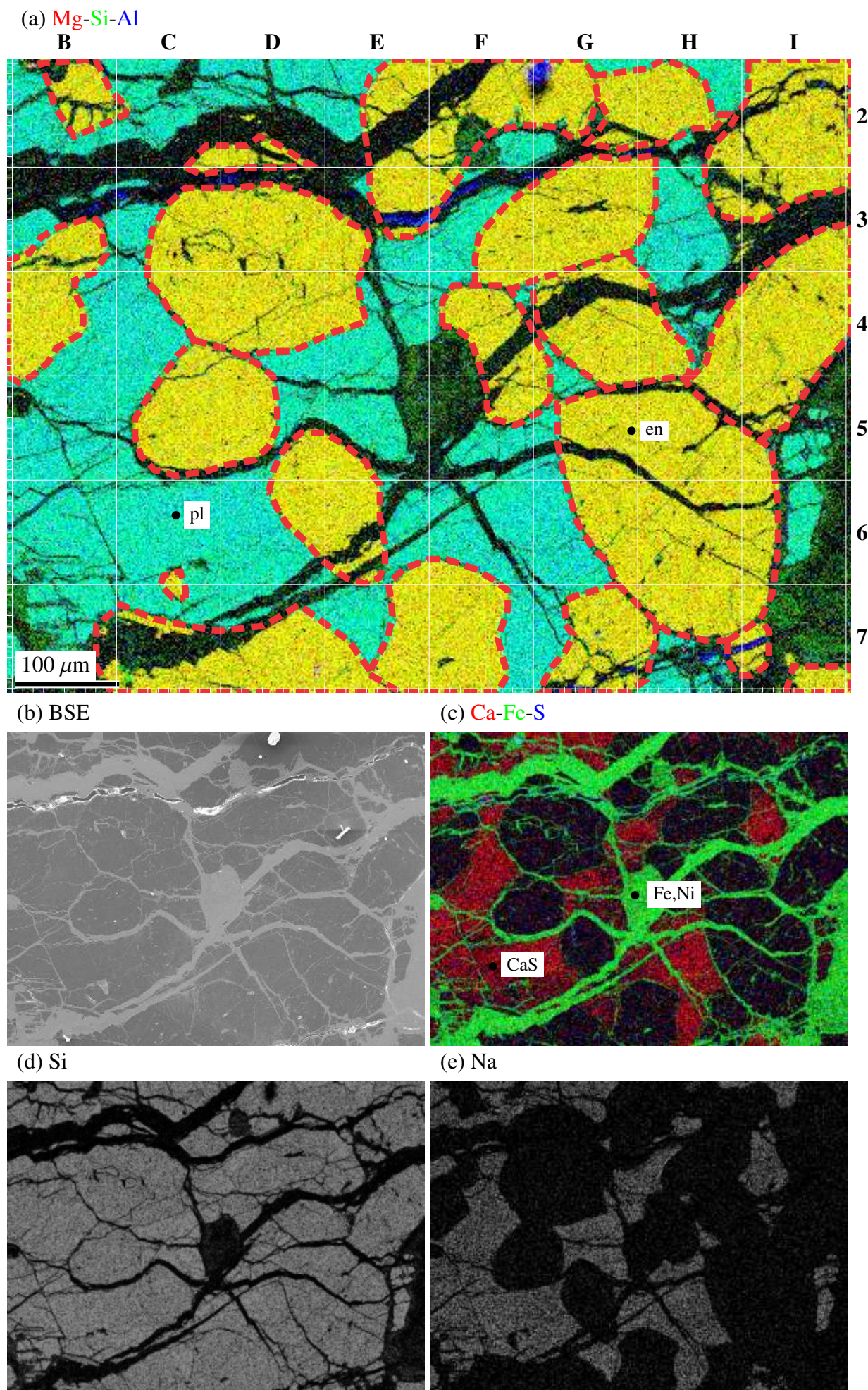


Figure 2.144: Site-1 of NWA4301 (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown.

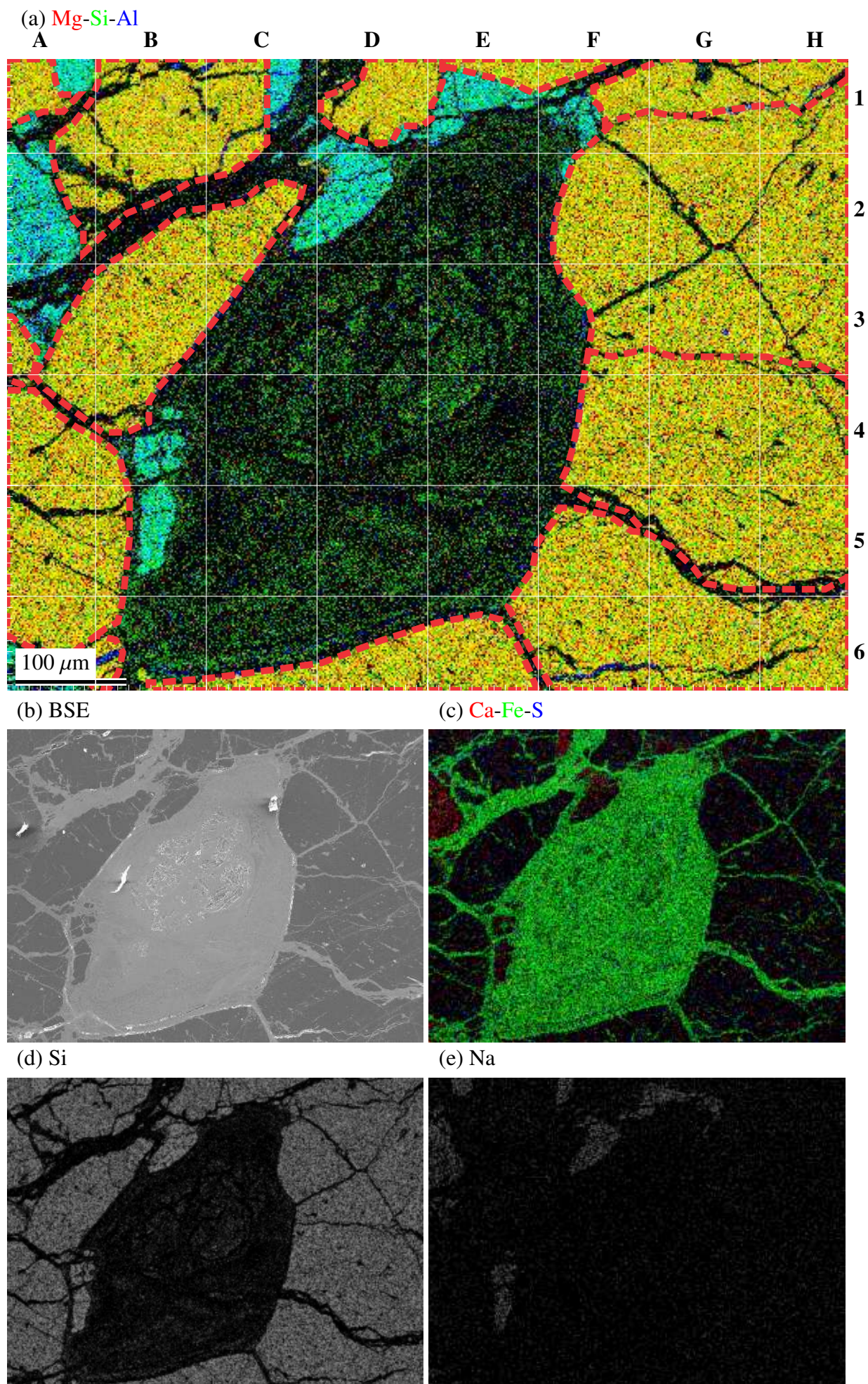


Figure 2.145: Site-2 of NWA4301 (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.144.

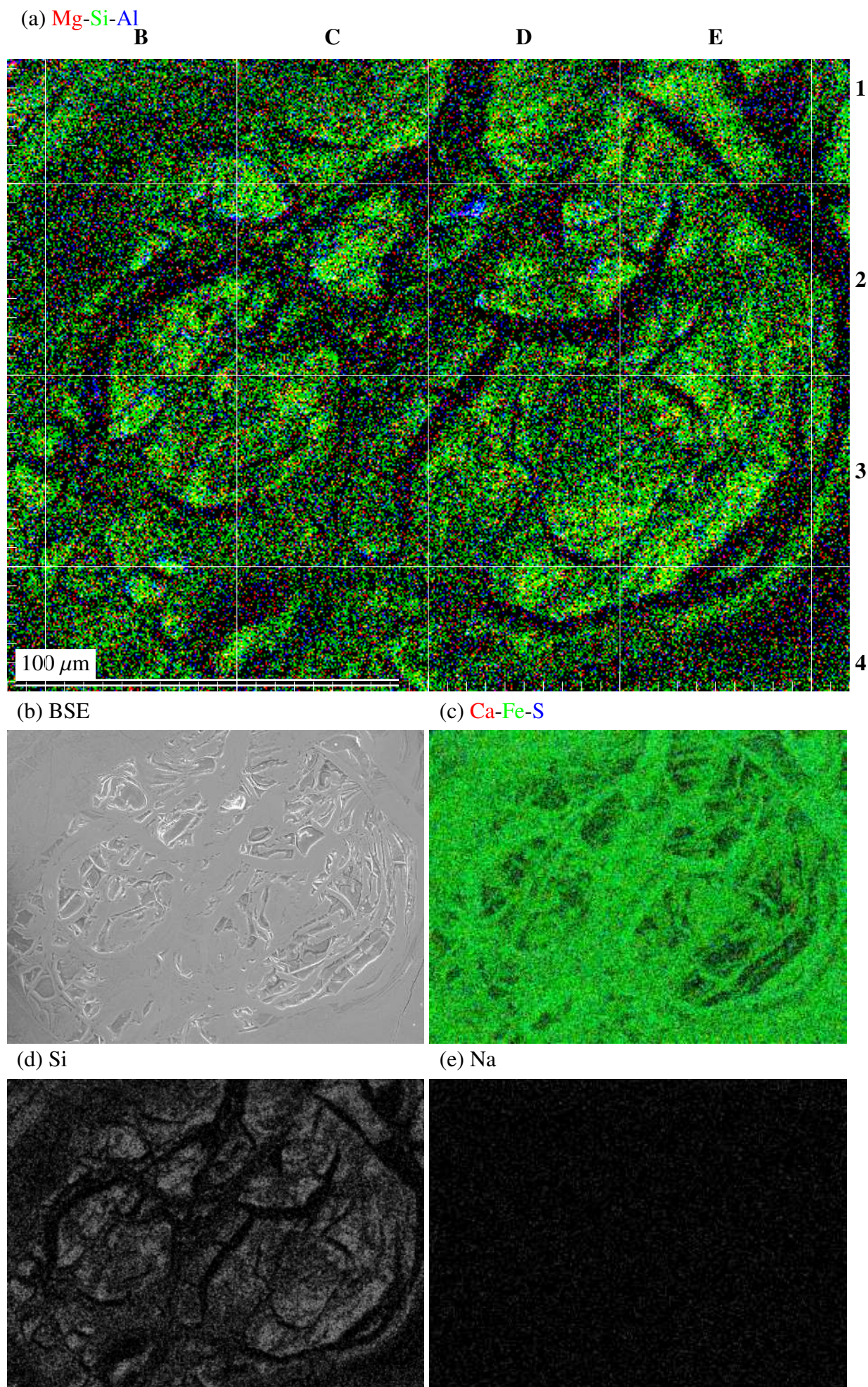


Figure 2.146: Site-3 of NWA4301 (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.144.

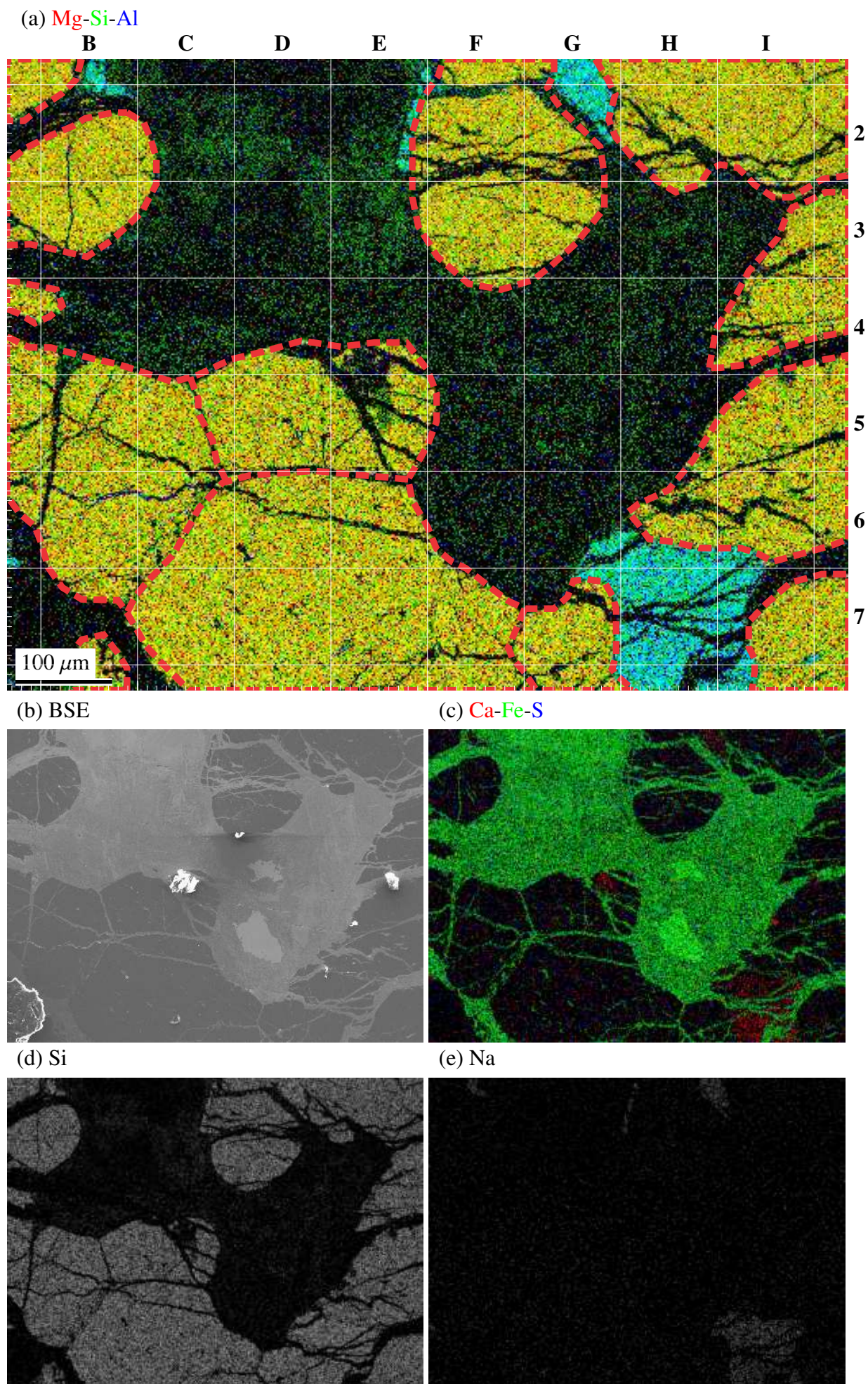


Figure 2.147: Site-4 of NWA4301 (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.144.

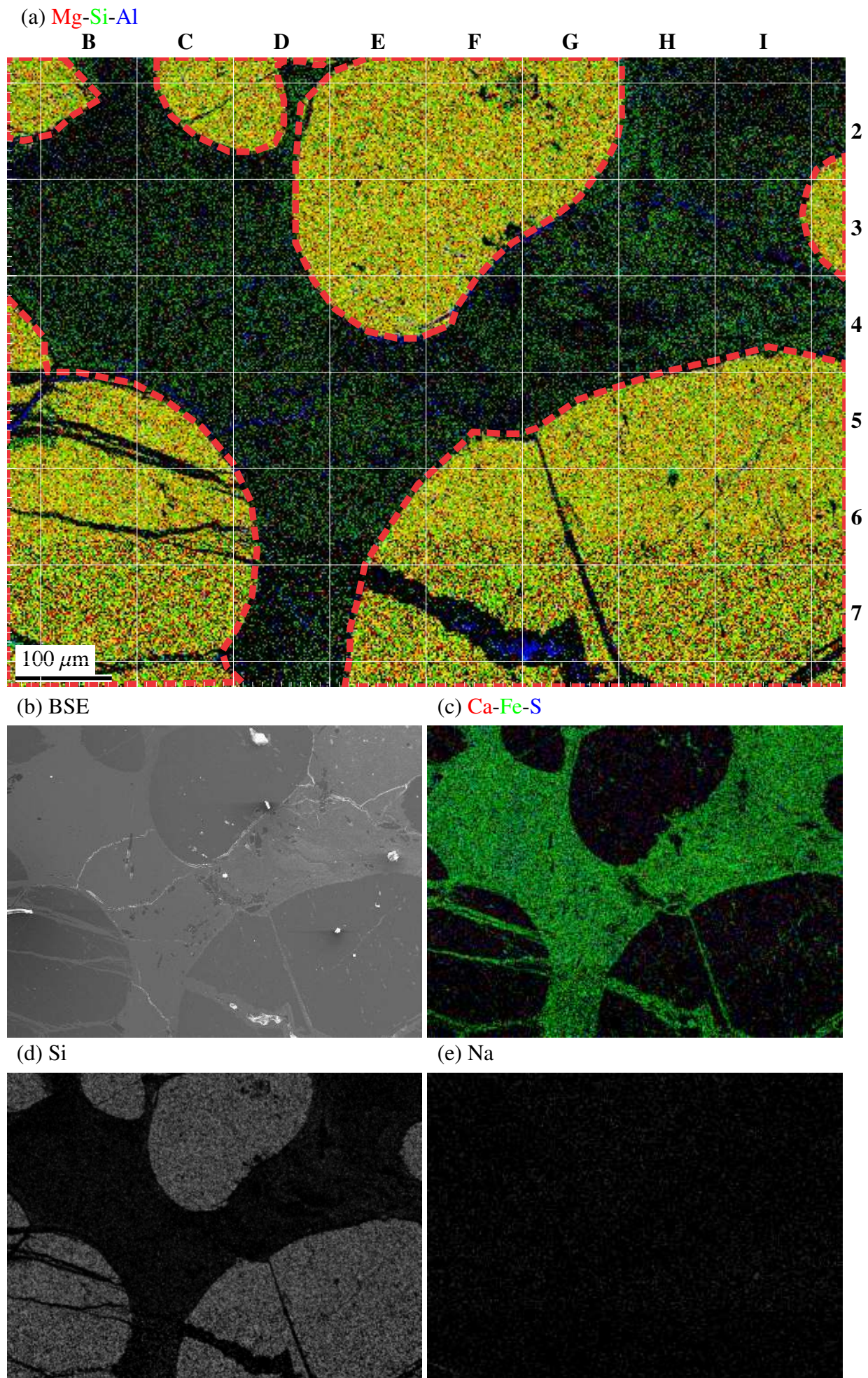


Figure 2.148: Site-5 of NWA4301 (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.144.

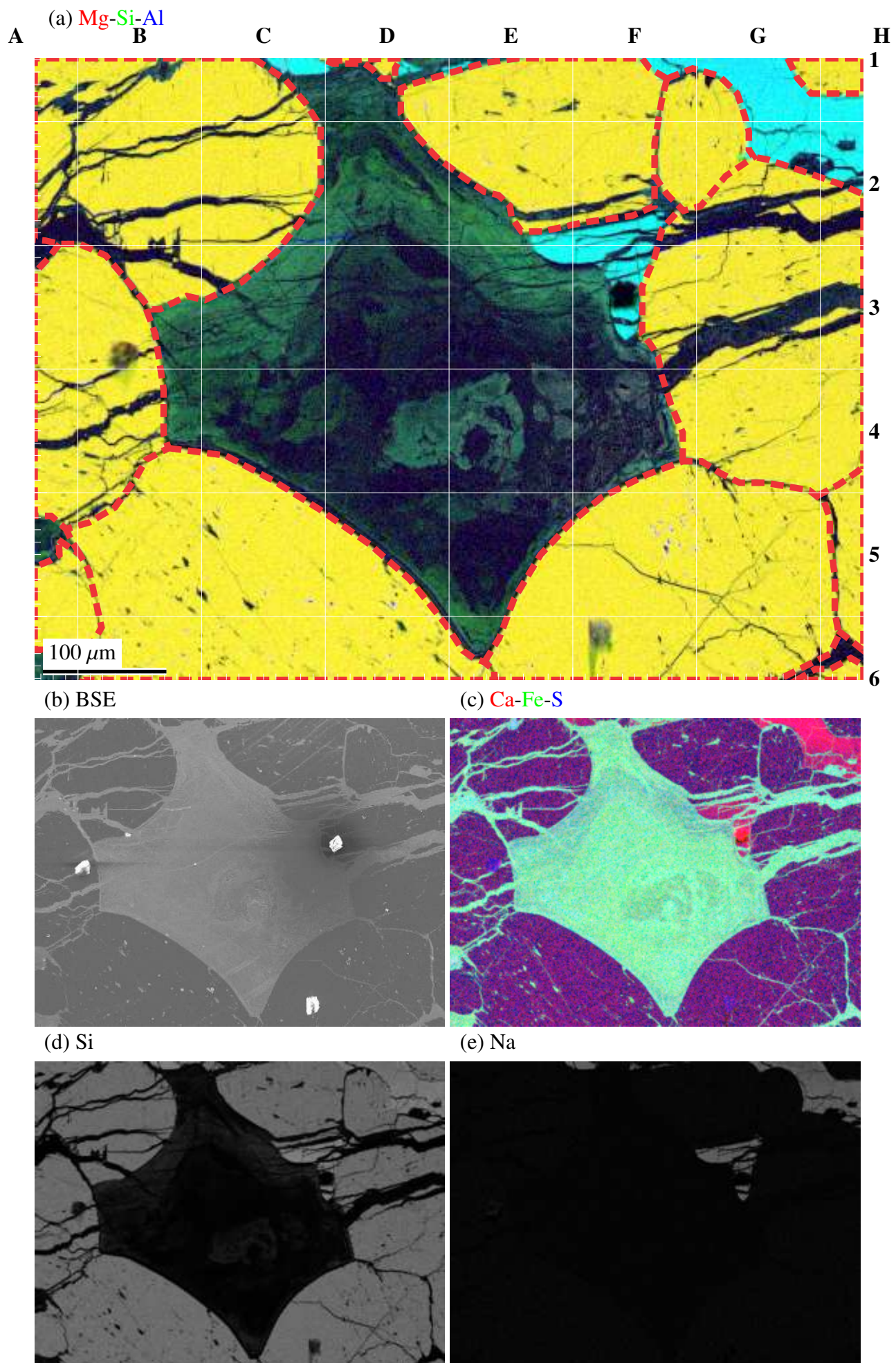


Figure 2.149: Site-6 of NWA4301 (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.144.

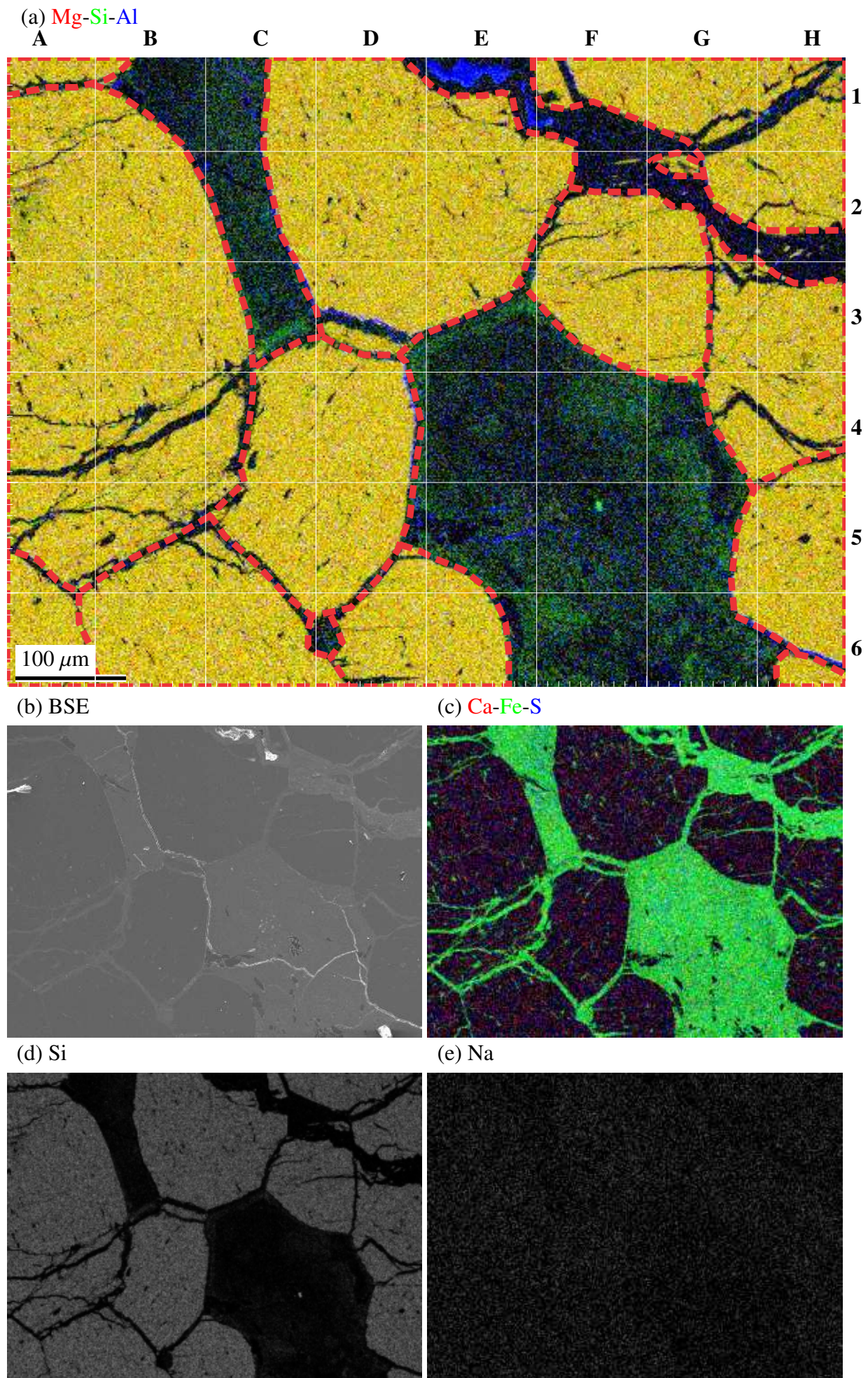


Figure 2.150: Site-7 of NWA4301 (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.144.

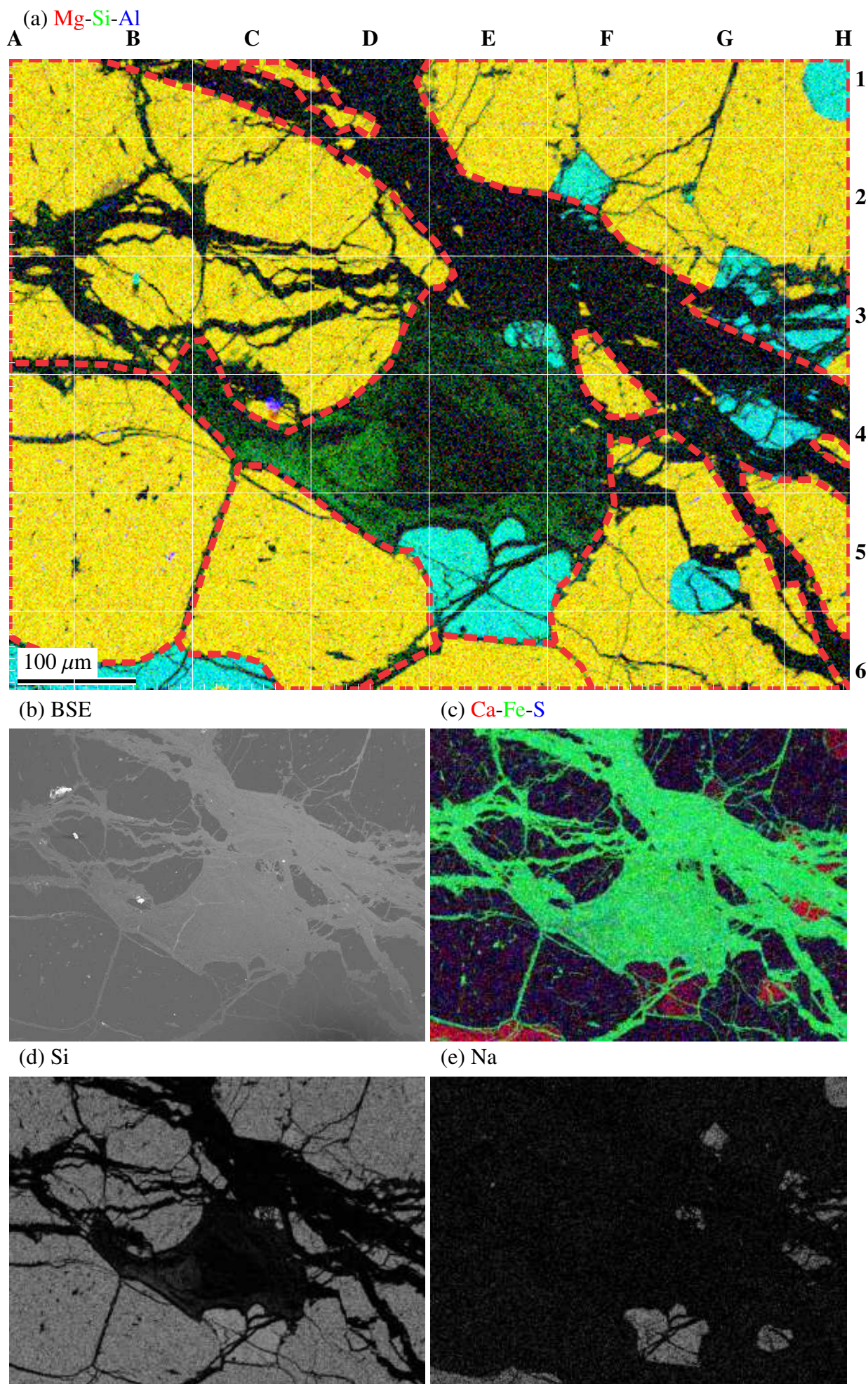


Figure 2.151: Site-8 of NWA4301 (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.144.

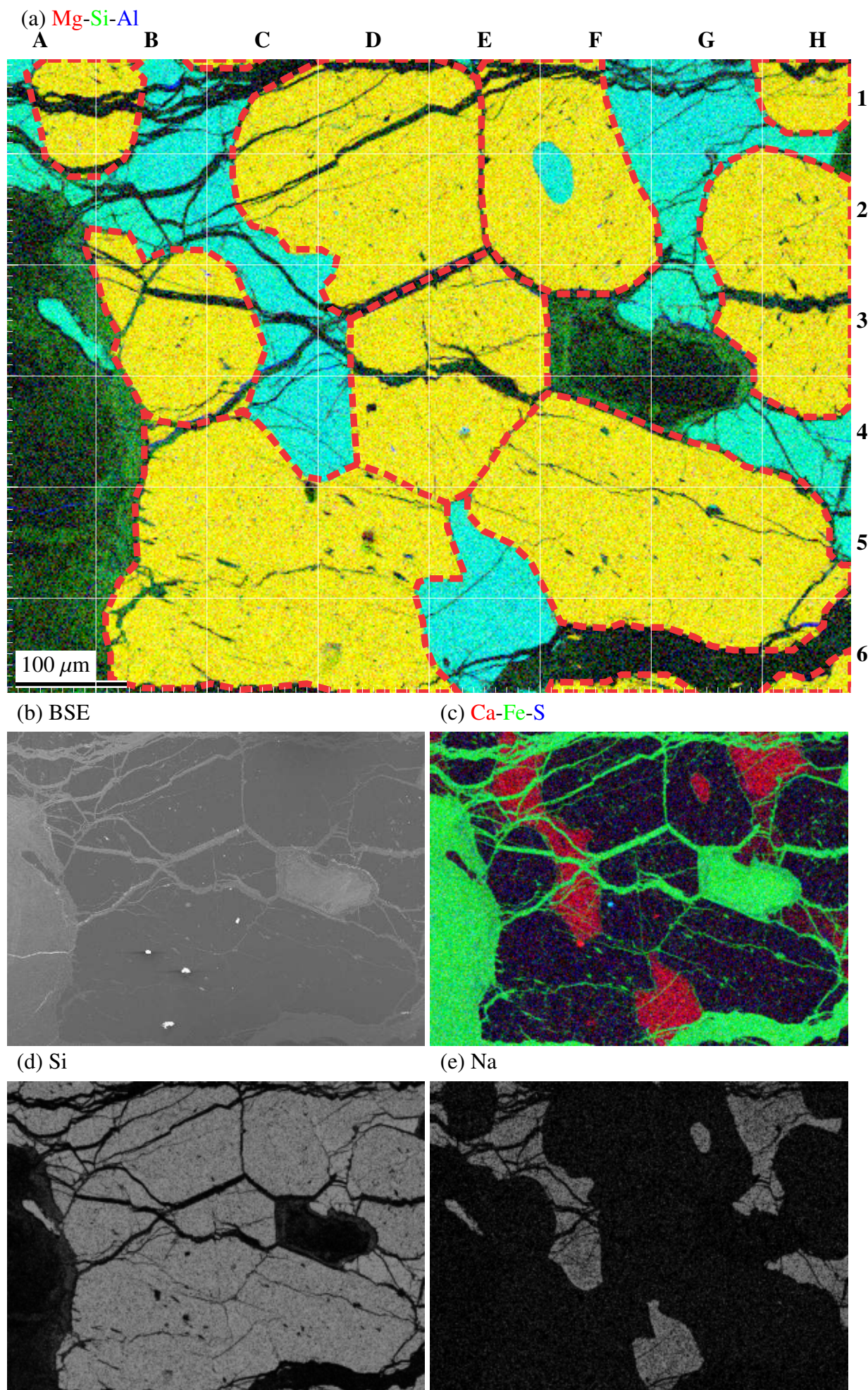


Figure 2.152: Site-9 of NWA4301 (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.144.

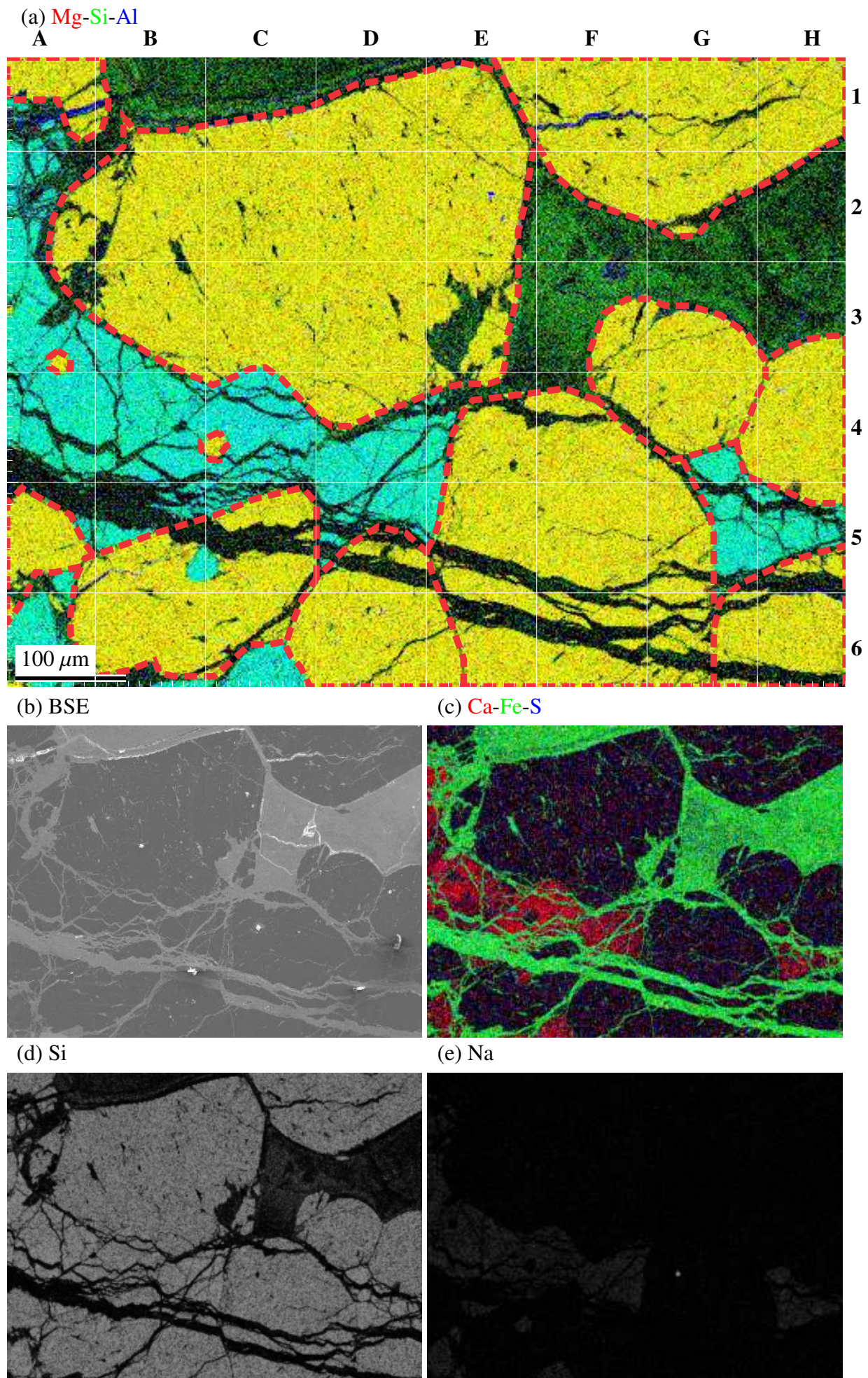


Figure 2.153: Site-10 of NWA4301 (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.144.

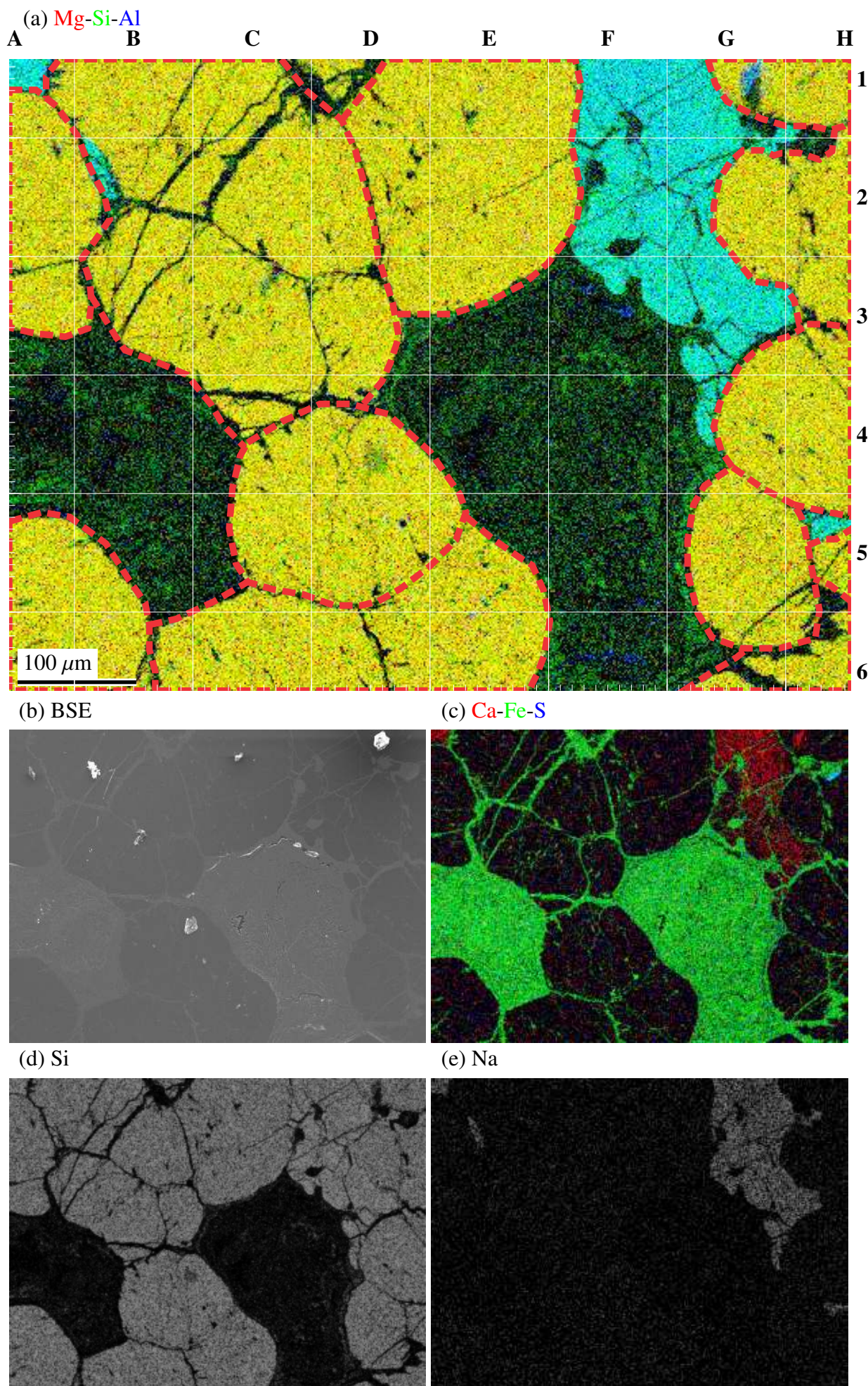


Figure 2.154: Site-11 of NWA4301 (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.144.

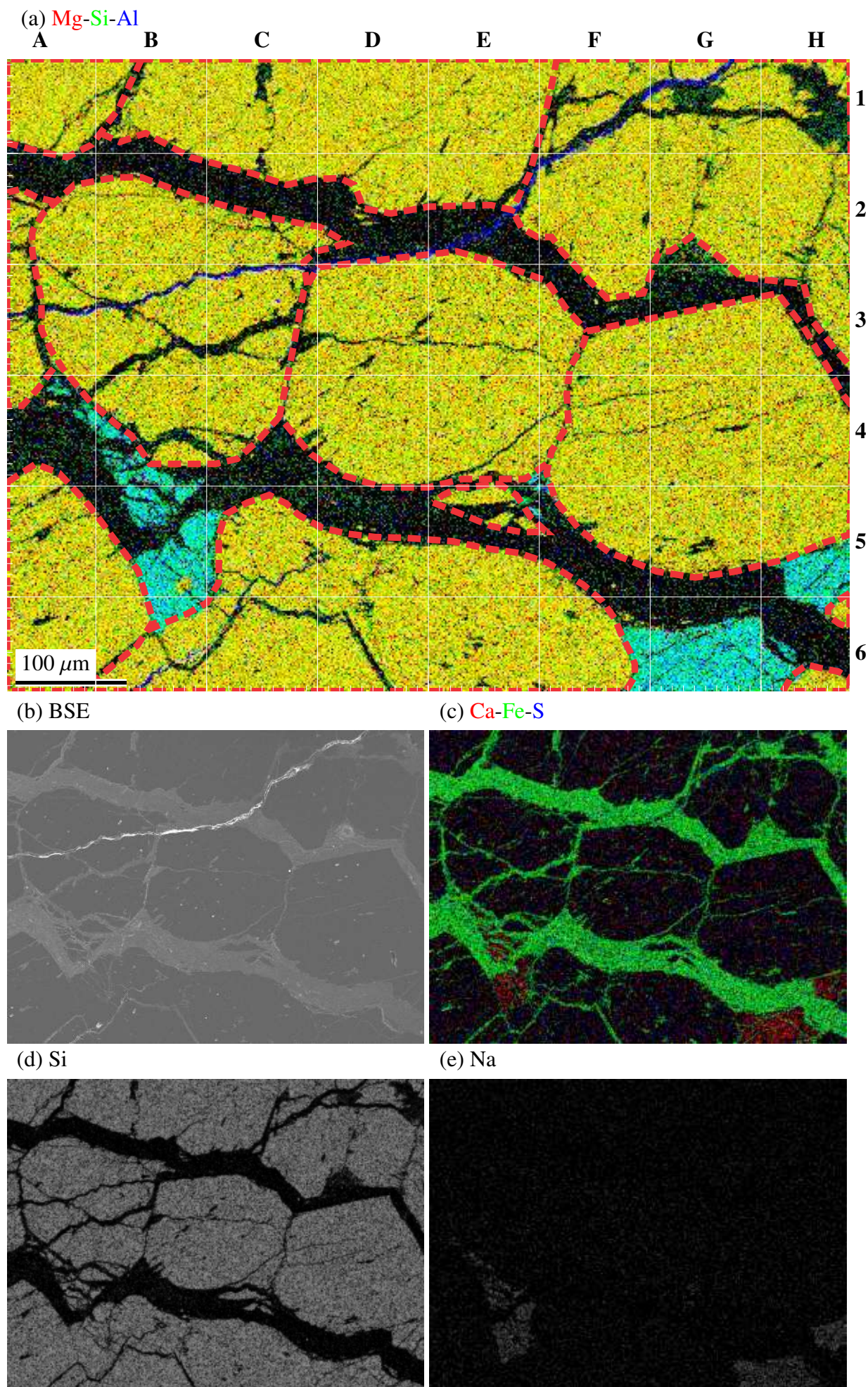


Figure 2.155: Site-12 of NWA4301 (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.144.

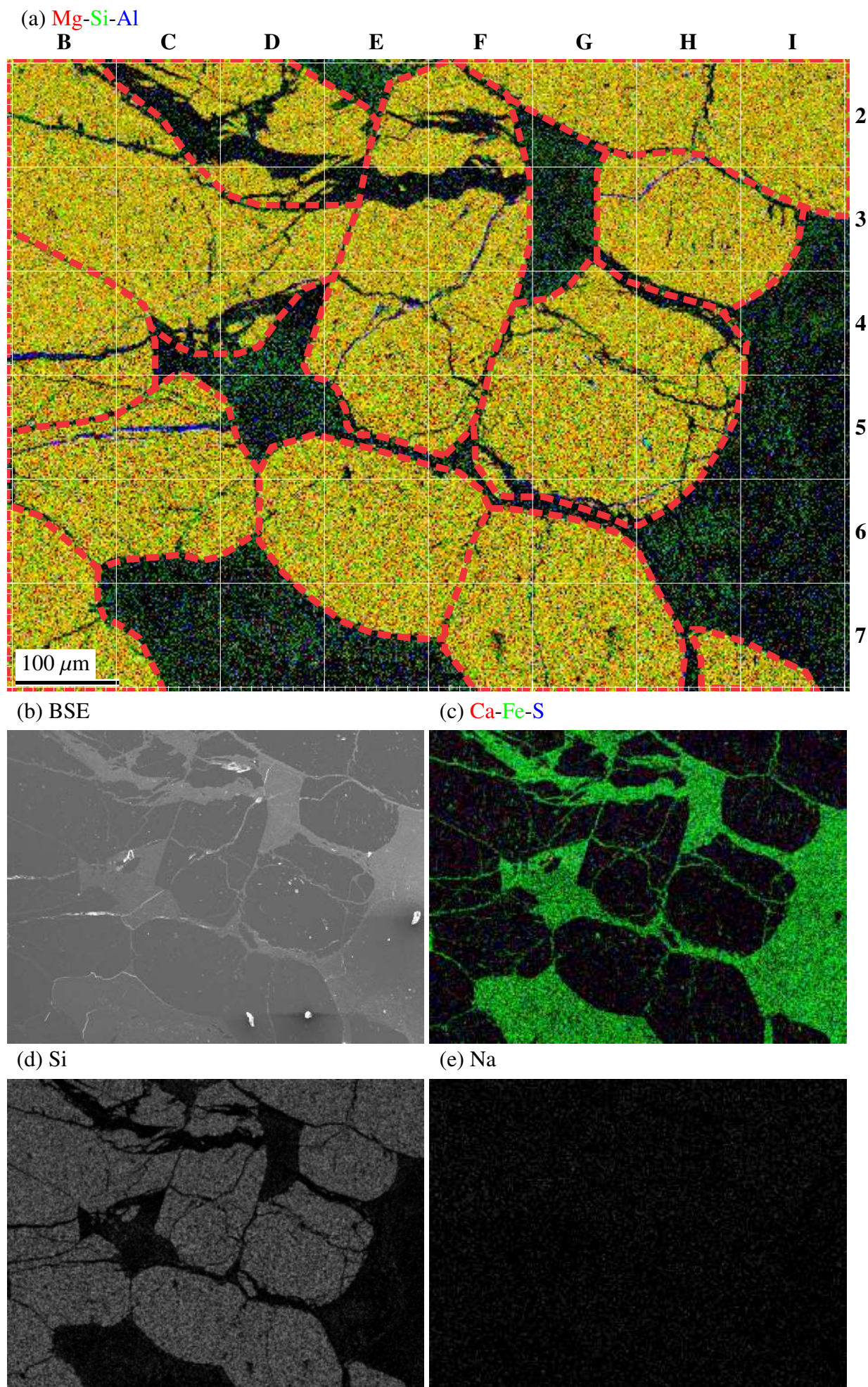


Figure 2.156: Site-13 of NWA4301 (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.144.

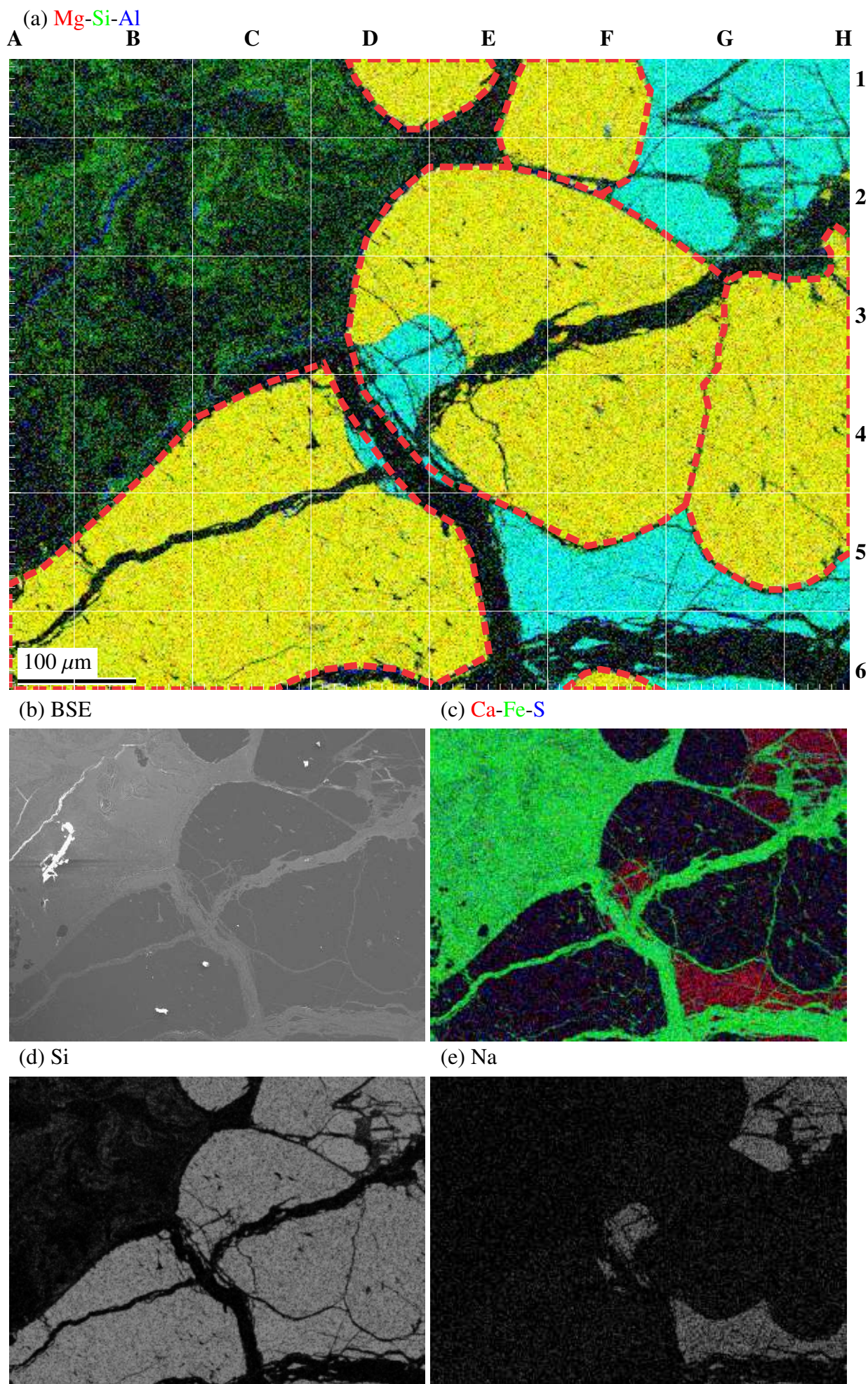


Figure 2.157: Site-14 of NWA4301 (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.144.

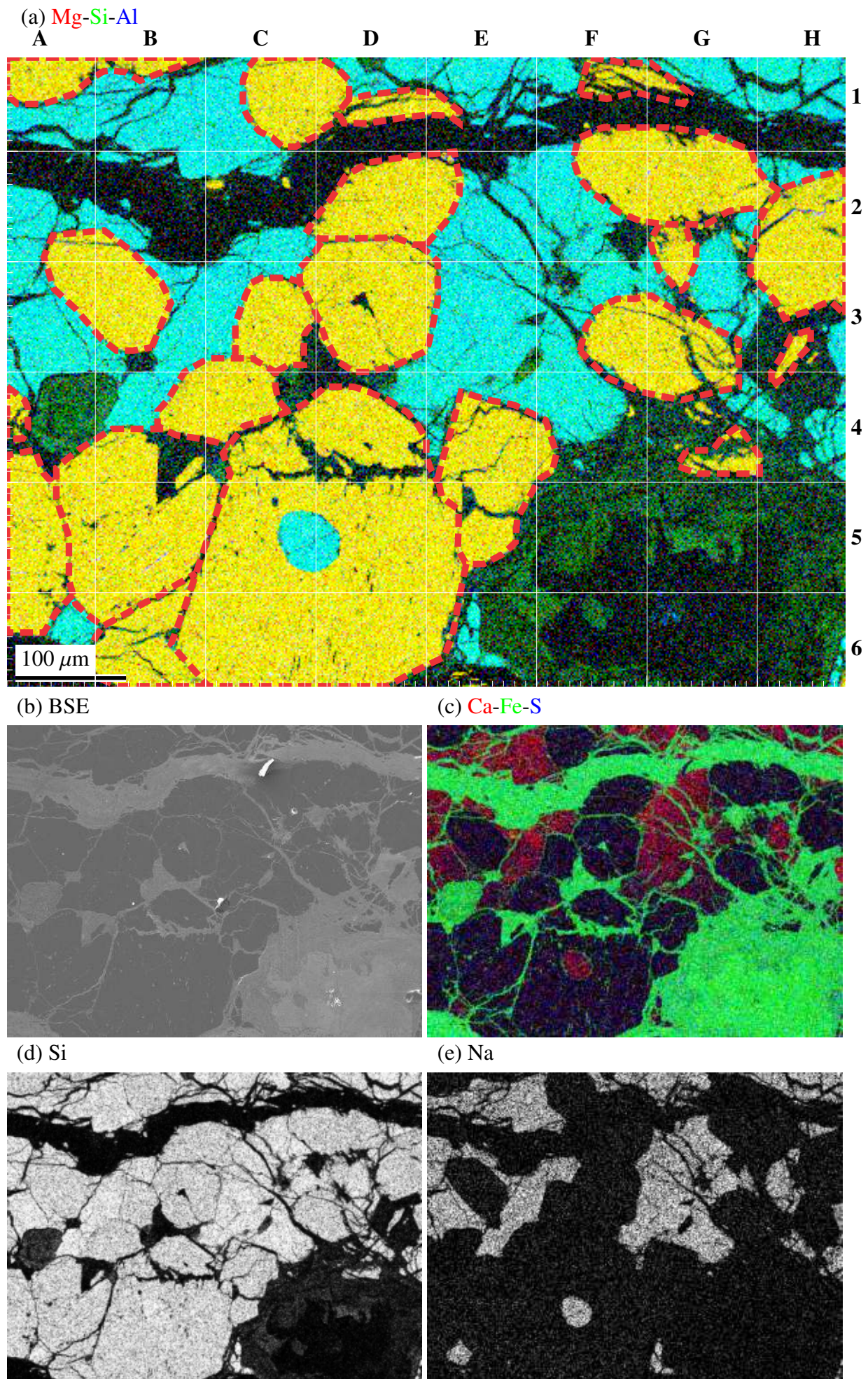


Figure 2.158: Site-15 of NWA4301 (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.144.

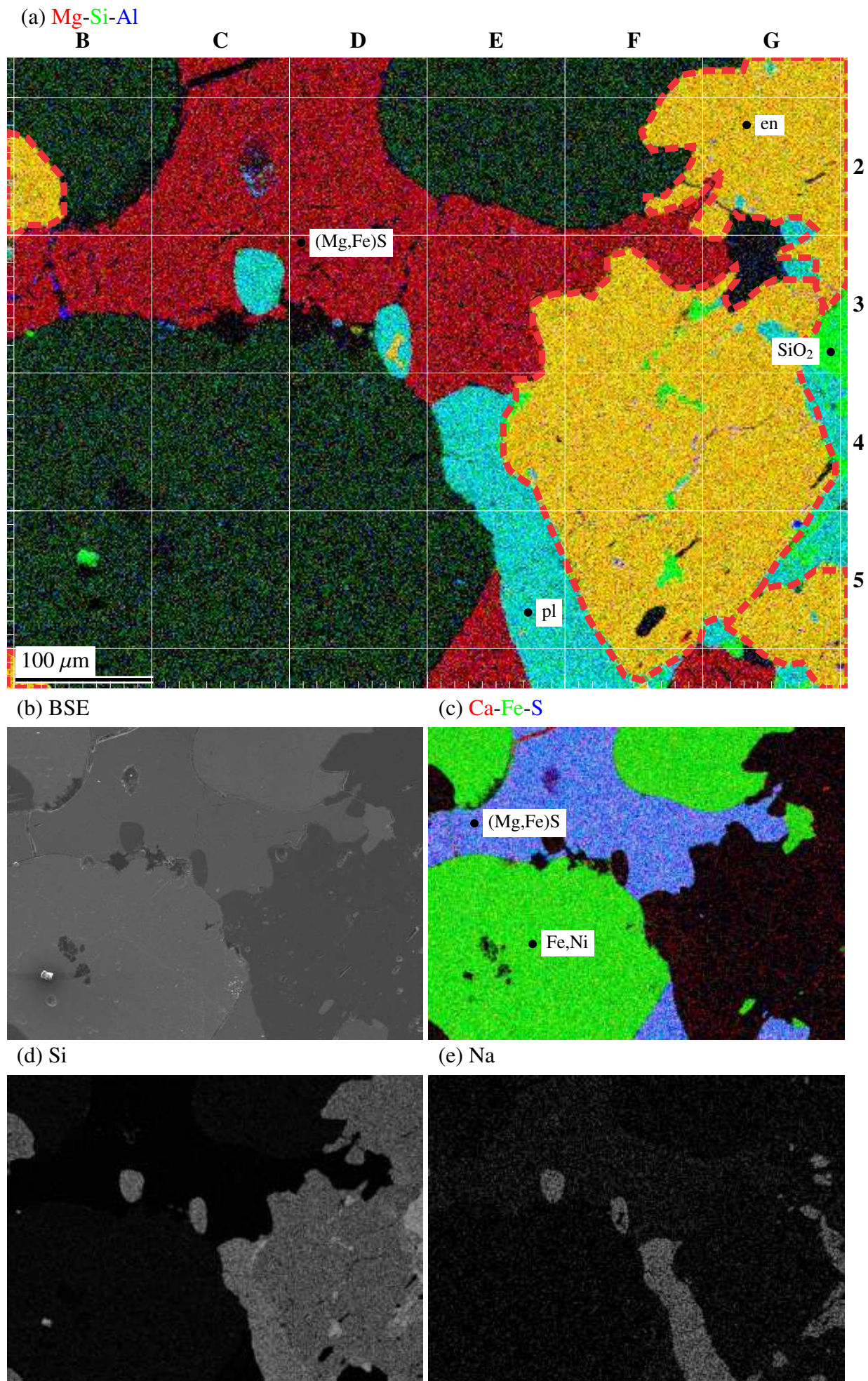


Figure 2.159: Site-1 of NWA8173a (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown.

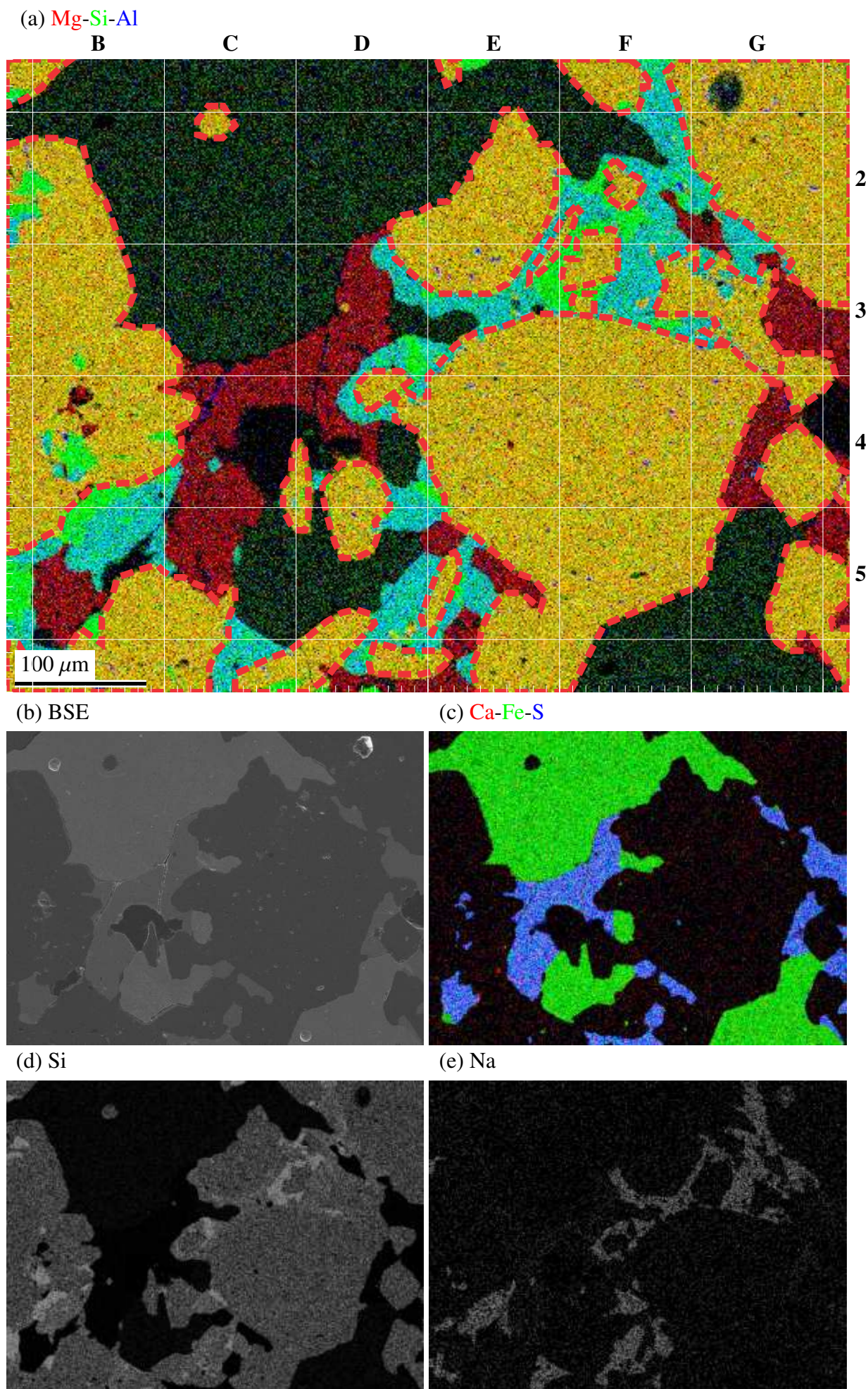


Figure 2.160: Site-2 of NWA8173a (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.159.

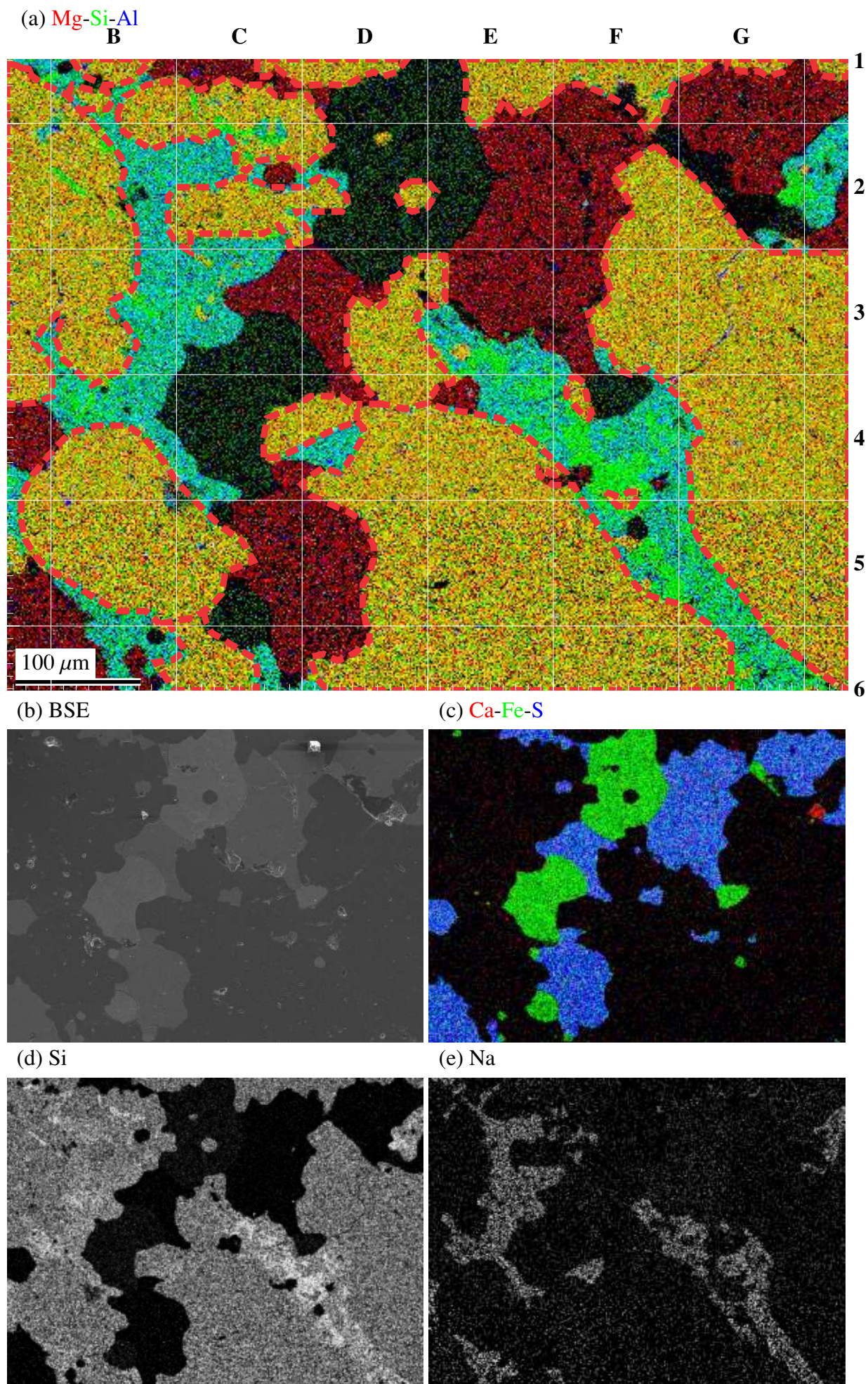
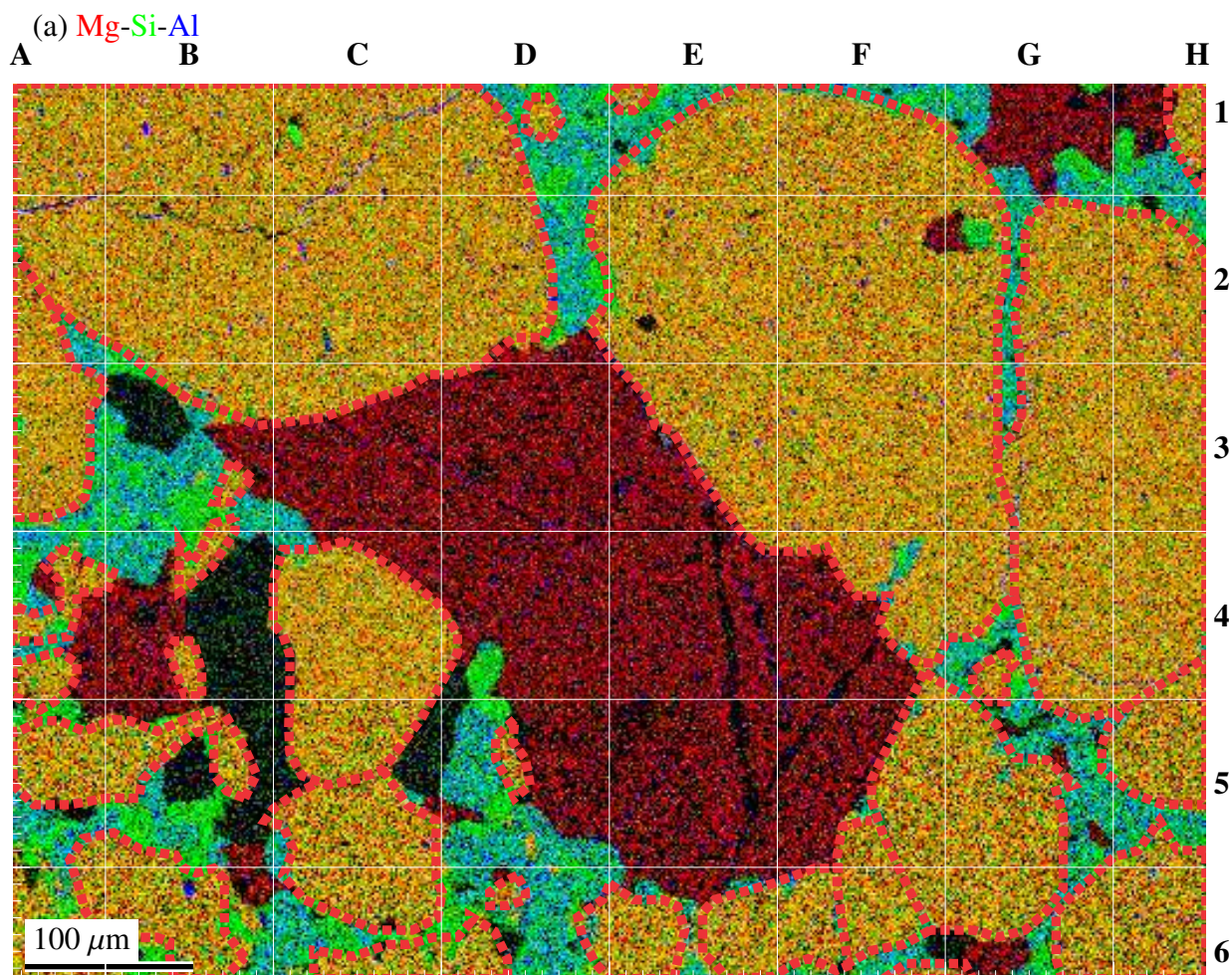
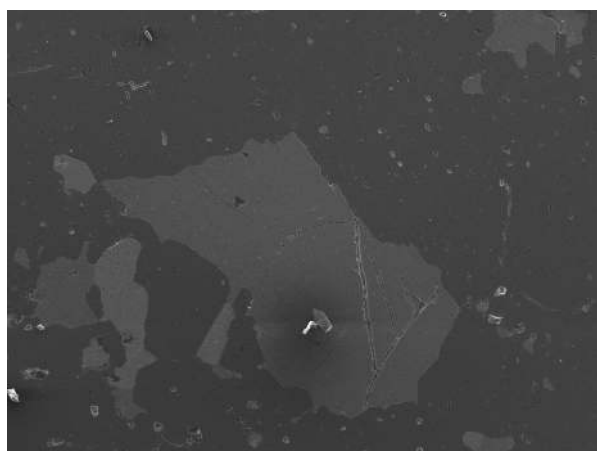


Figure 2.161: Site-3 of NWA8173a (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.159.

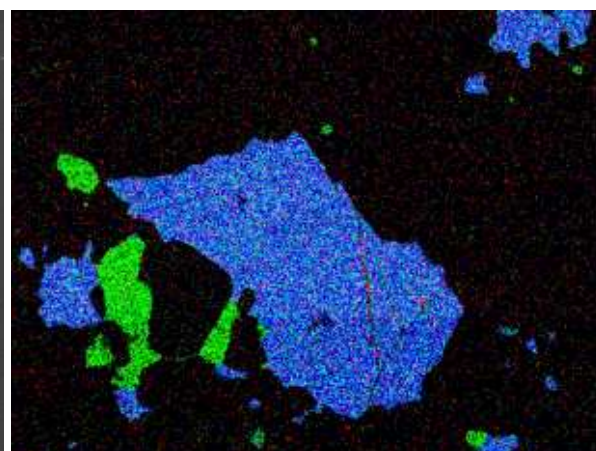


(b) BSE

(c) Ca-Fe-S



(d) Si



(e) Na

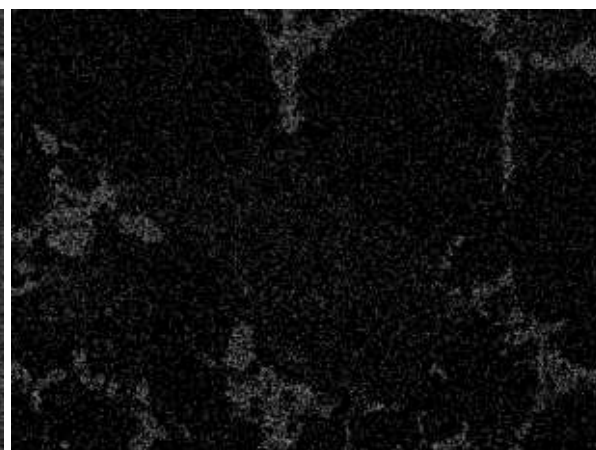
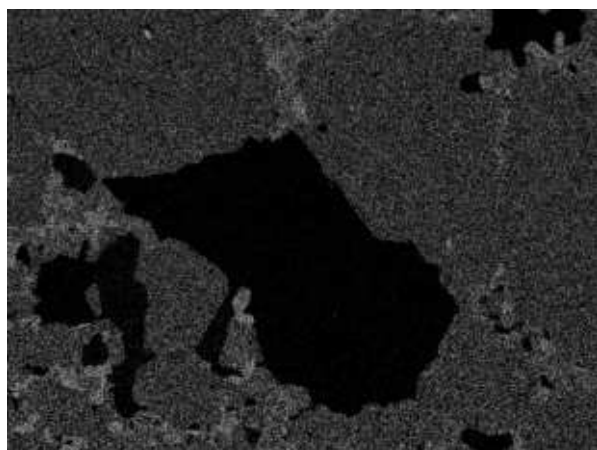


Figure 2.162: Site-4 of NWA8173a (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.159.

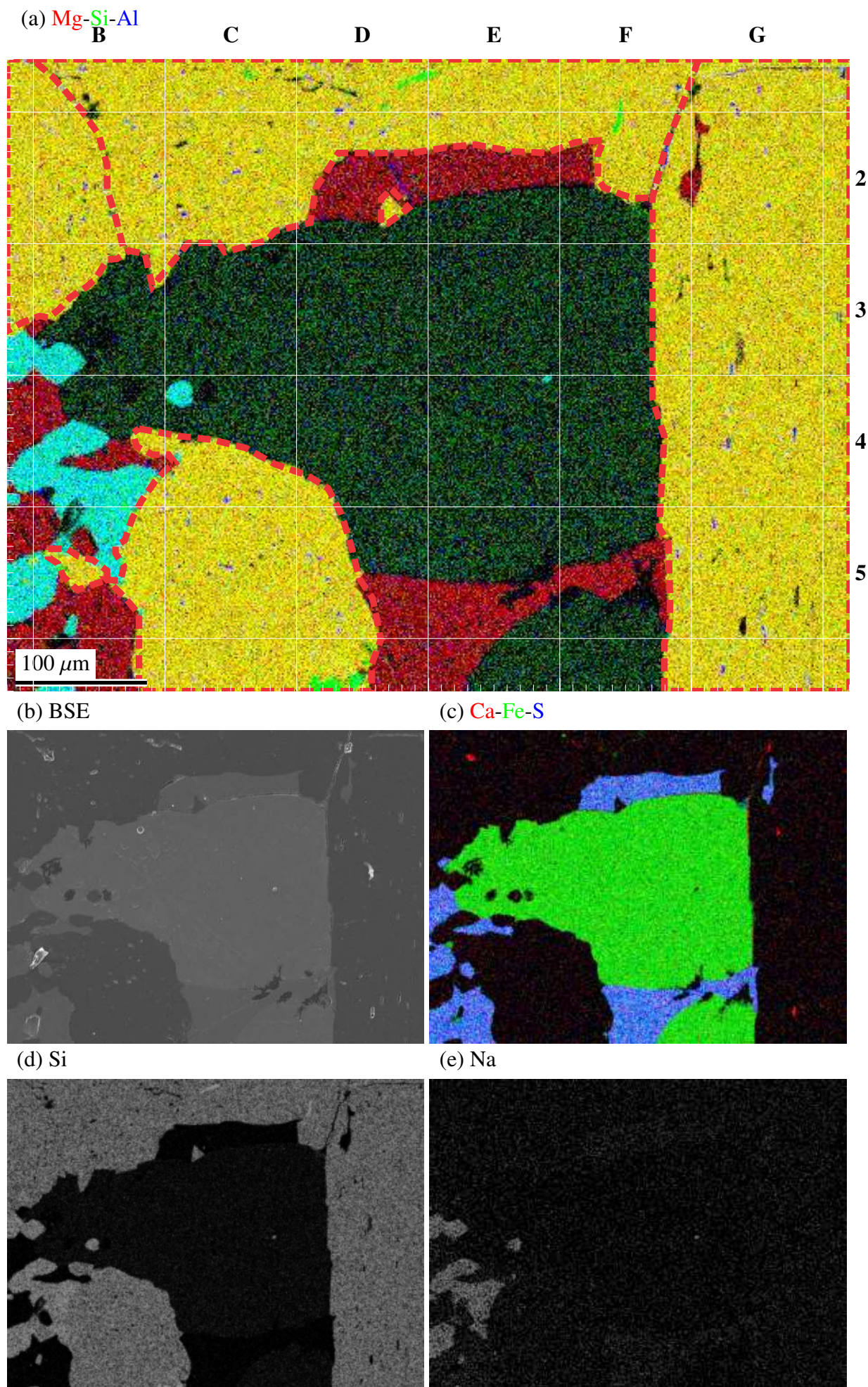


Figure 2.163: Site-5 of NWA8173a (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.159.

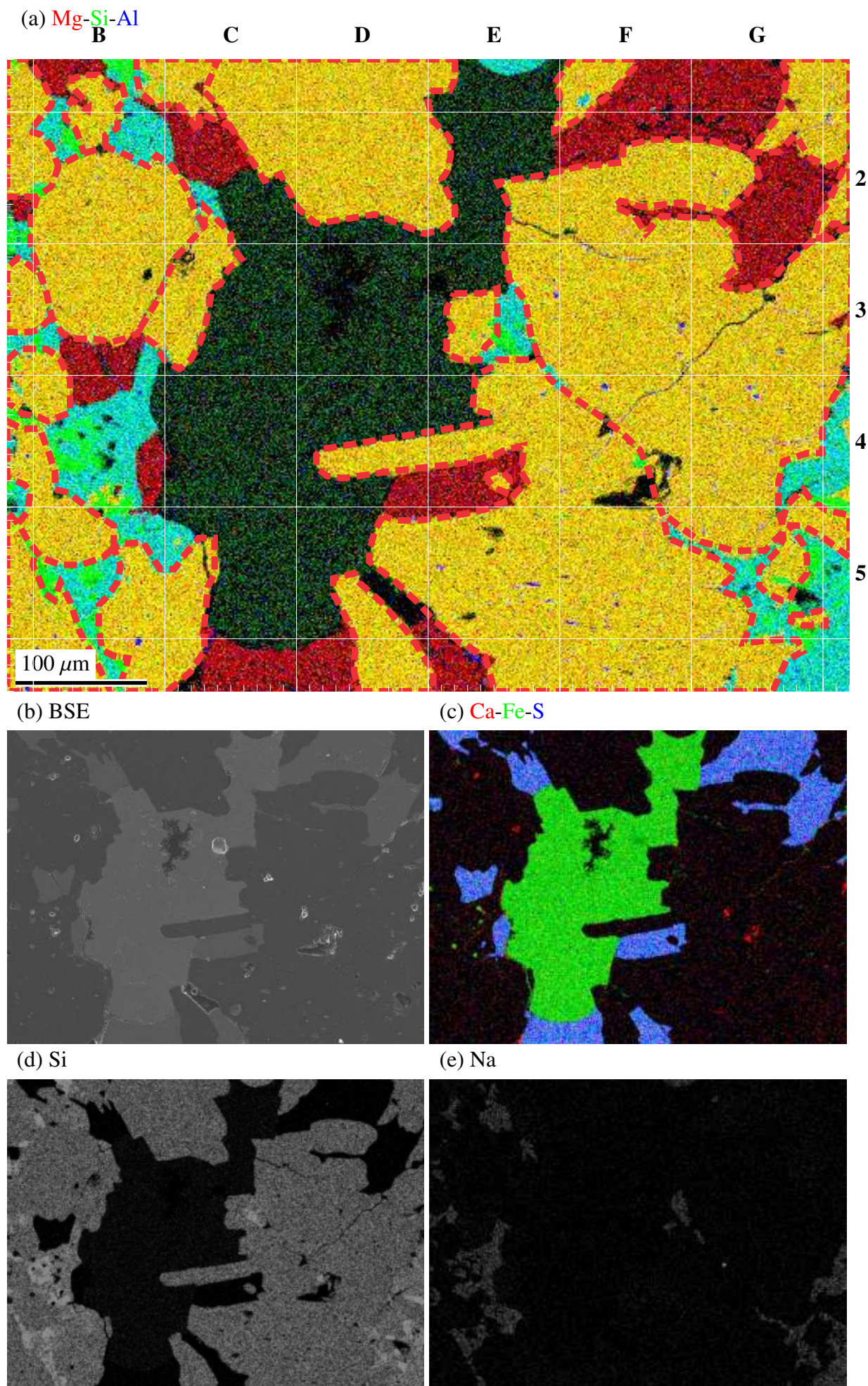


Figure 2.164: Site-6 of NWA8173a (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.159.

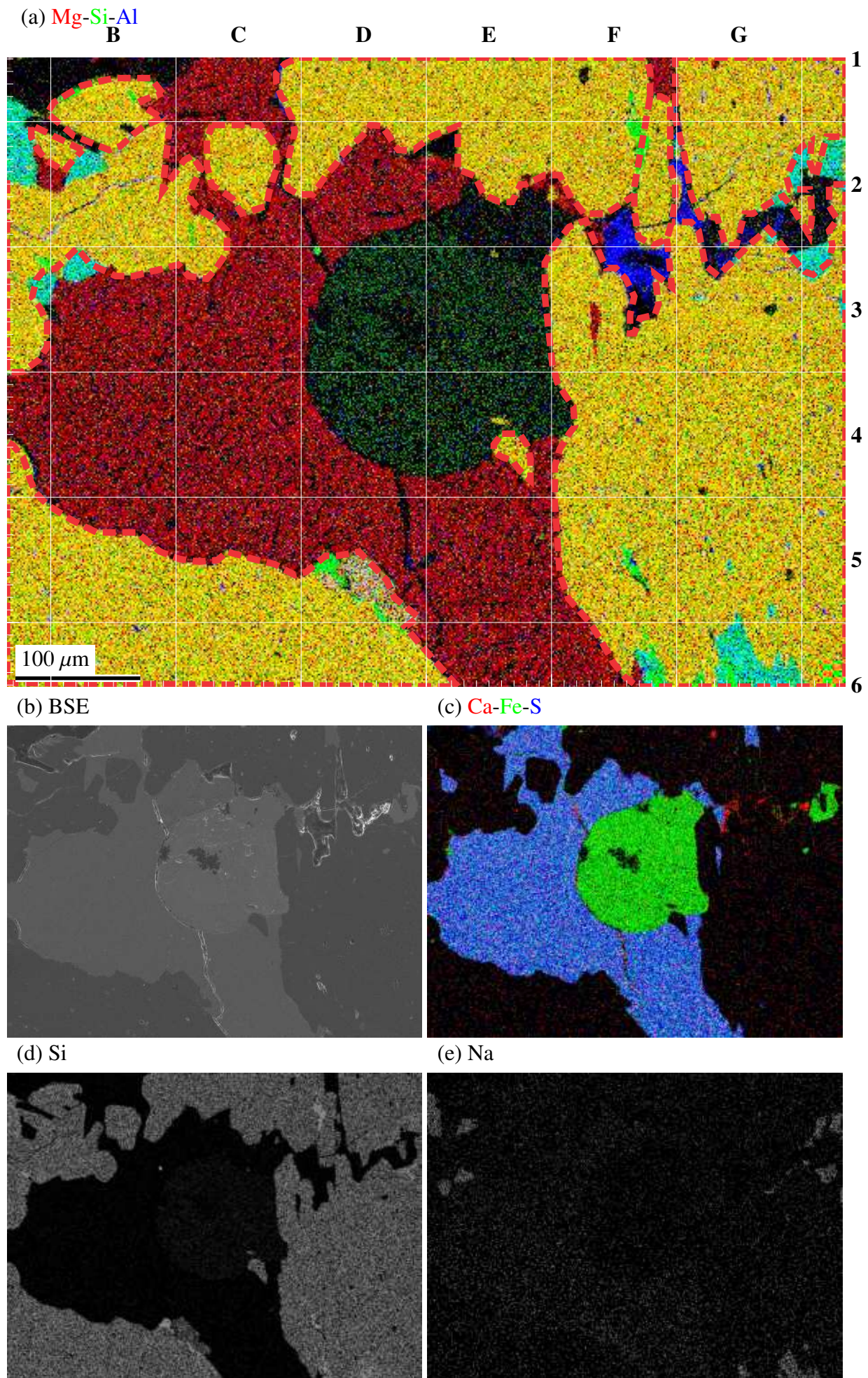


Figure 2.165: Site-7 of NWA8173a (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.159.

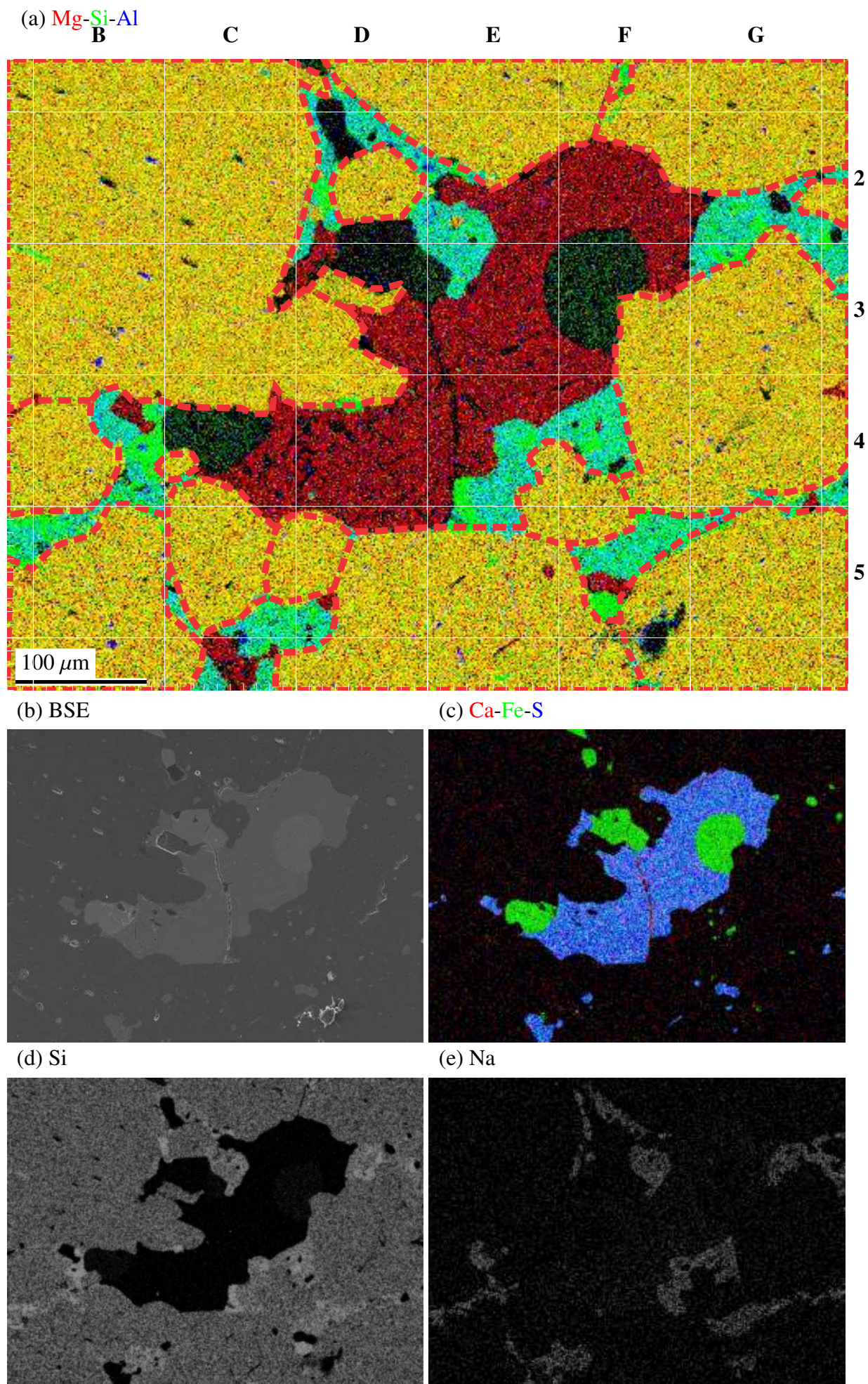


Figure 2.166: Site-8 of NWA8173a (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.159.

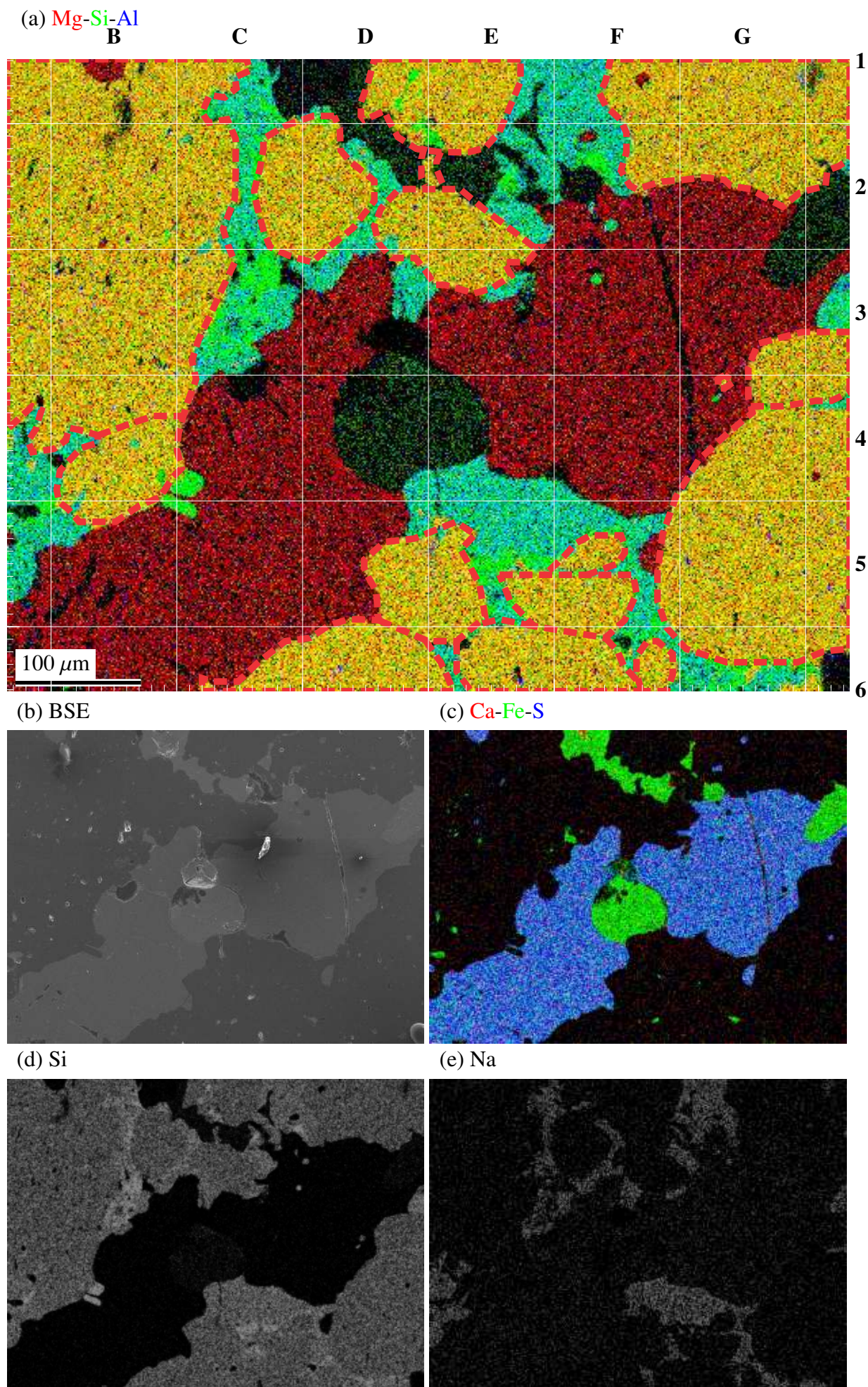


Figure 2.167: Site-9 of NWA8173a (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.159.

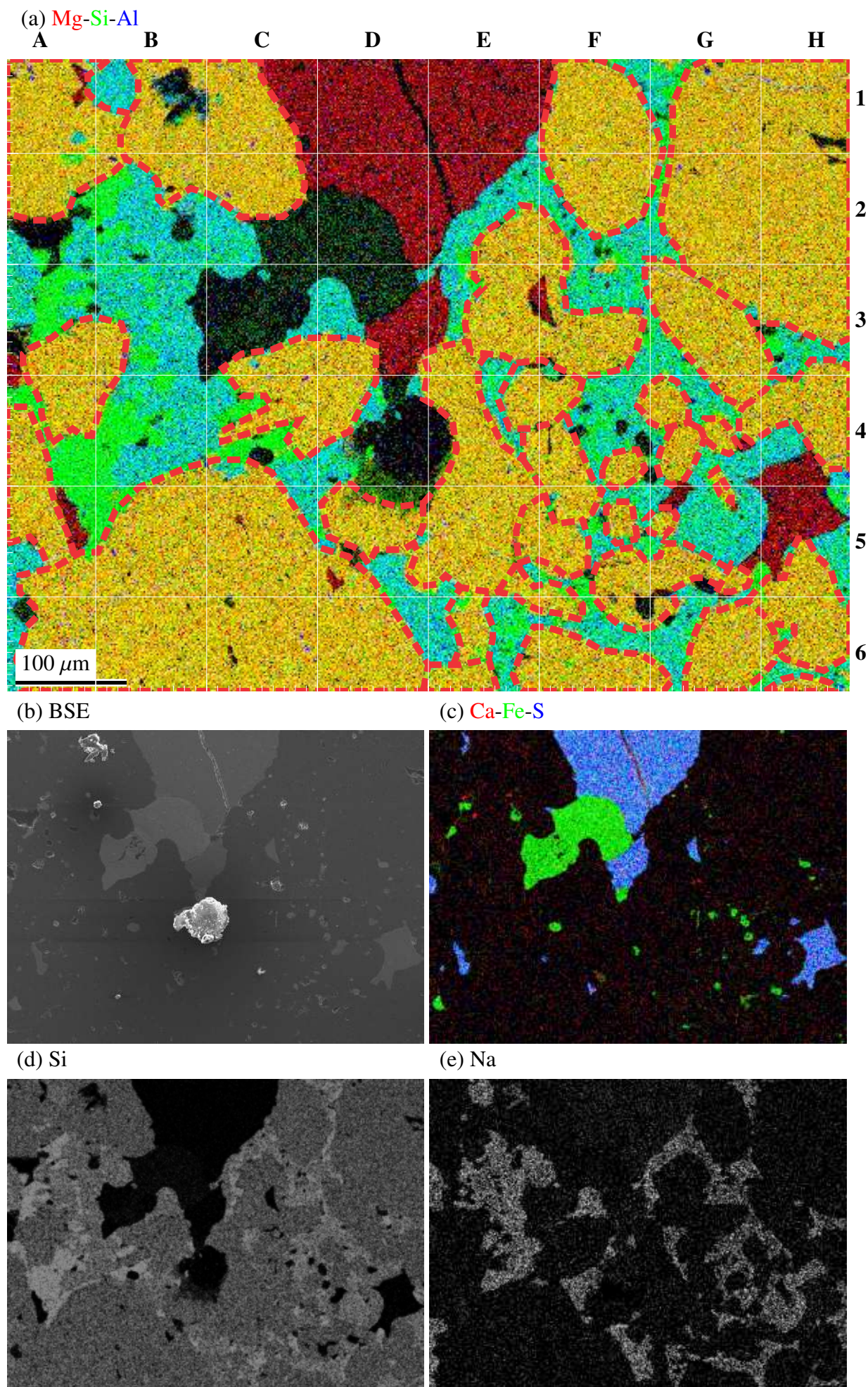


Figure 2.168: Site-10 of NWA8173a (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.159.

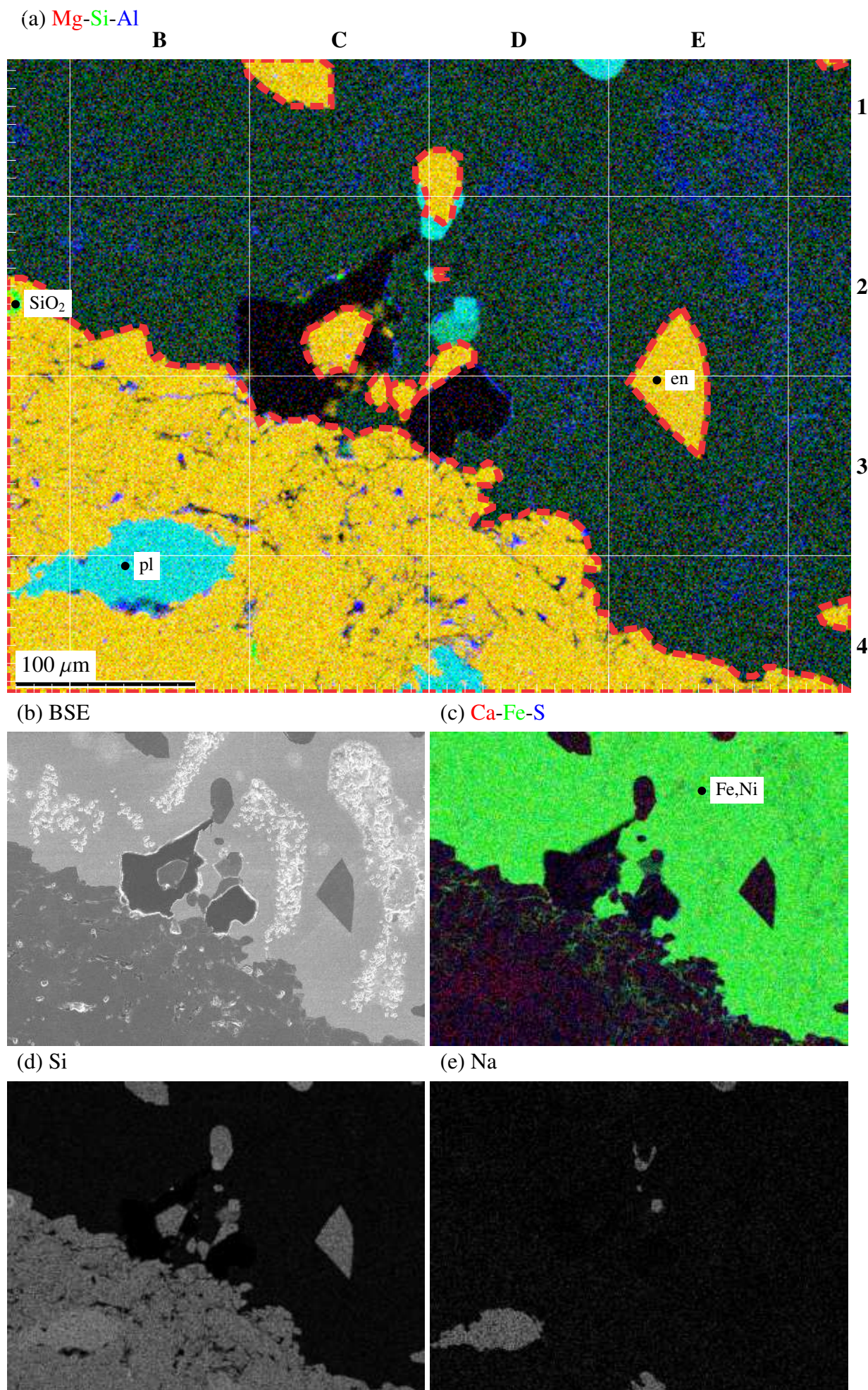


Figure 2.169: Site-1 of NWA8173b (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown.

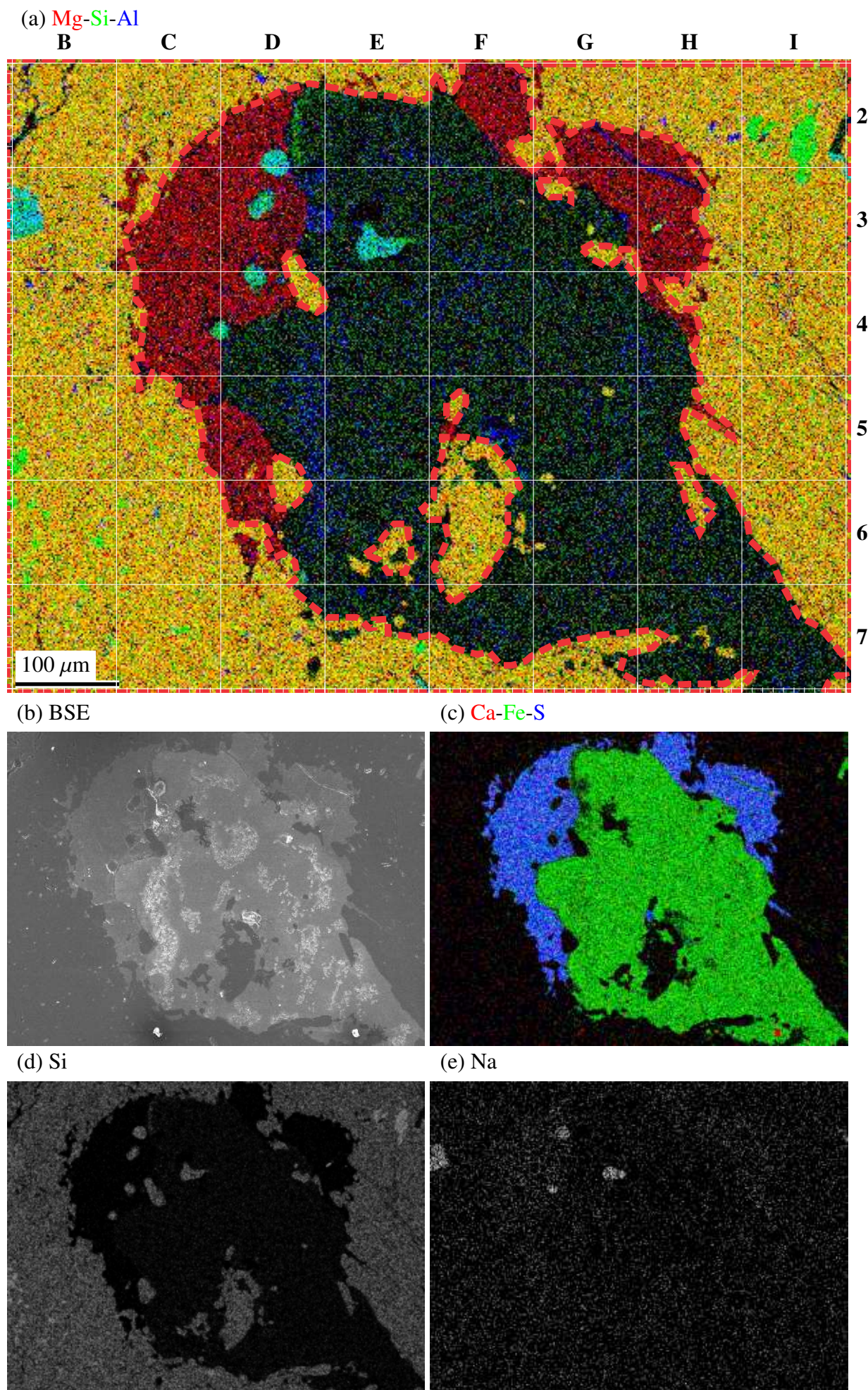


Figure 2.170: Site-2 of NWA8173b (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.169.

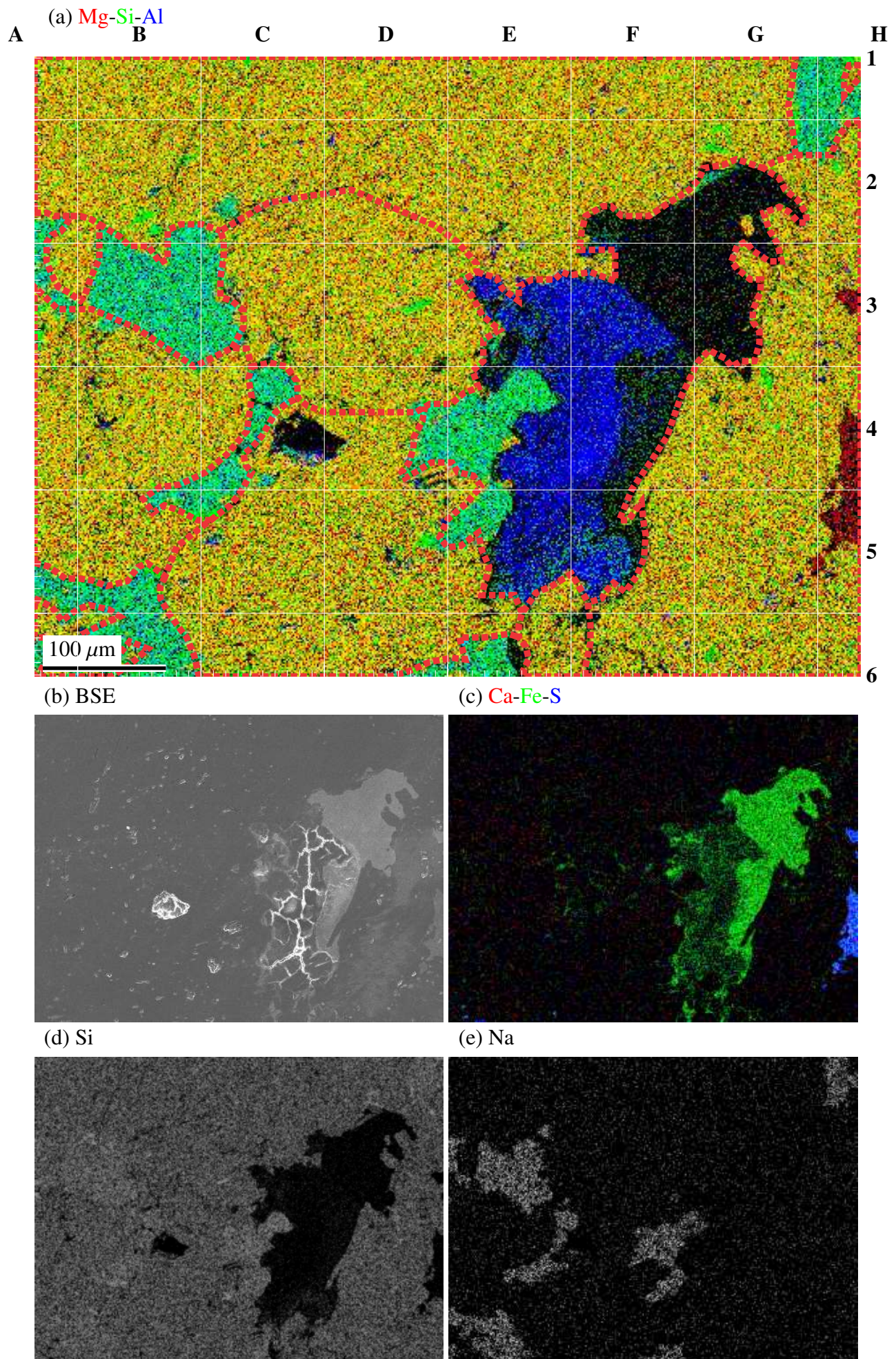


Figure 2.171: Site-3 of NWA8173b (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.169.

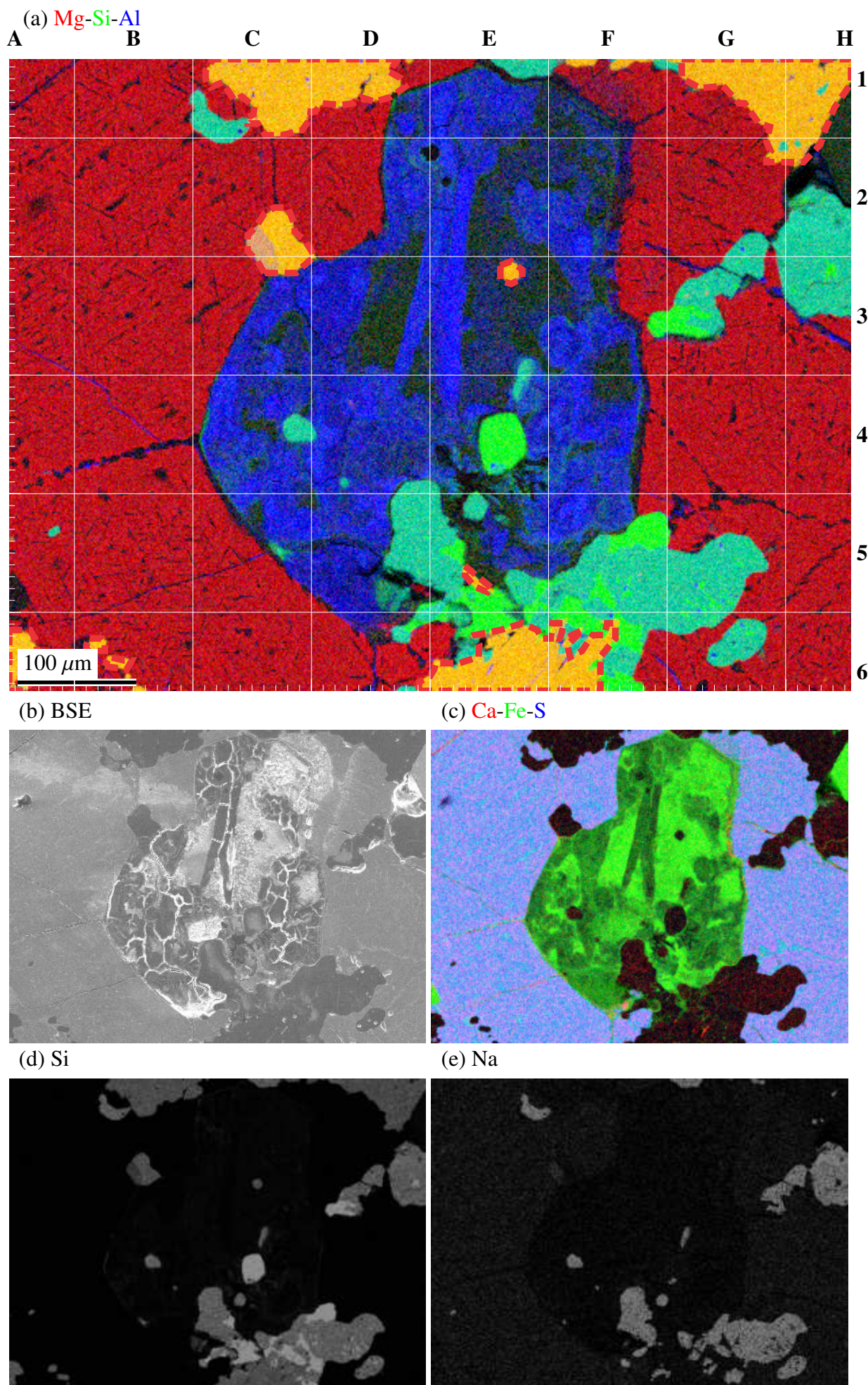


Figure 2.172: Site-4 of NWA8173b (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.169.

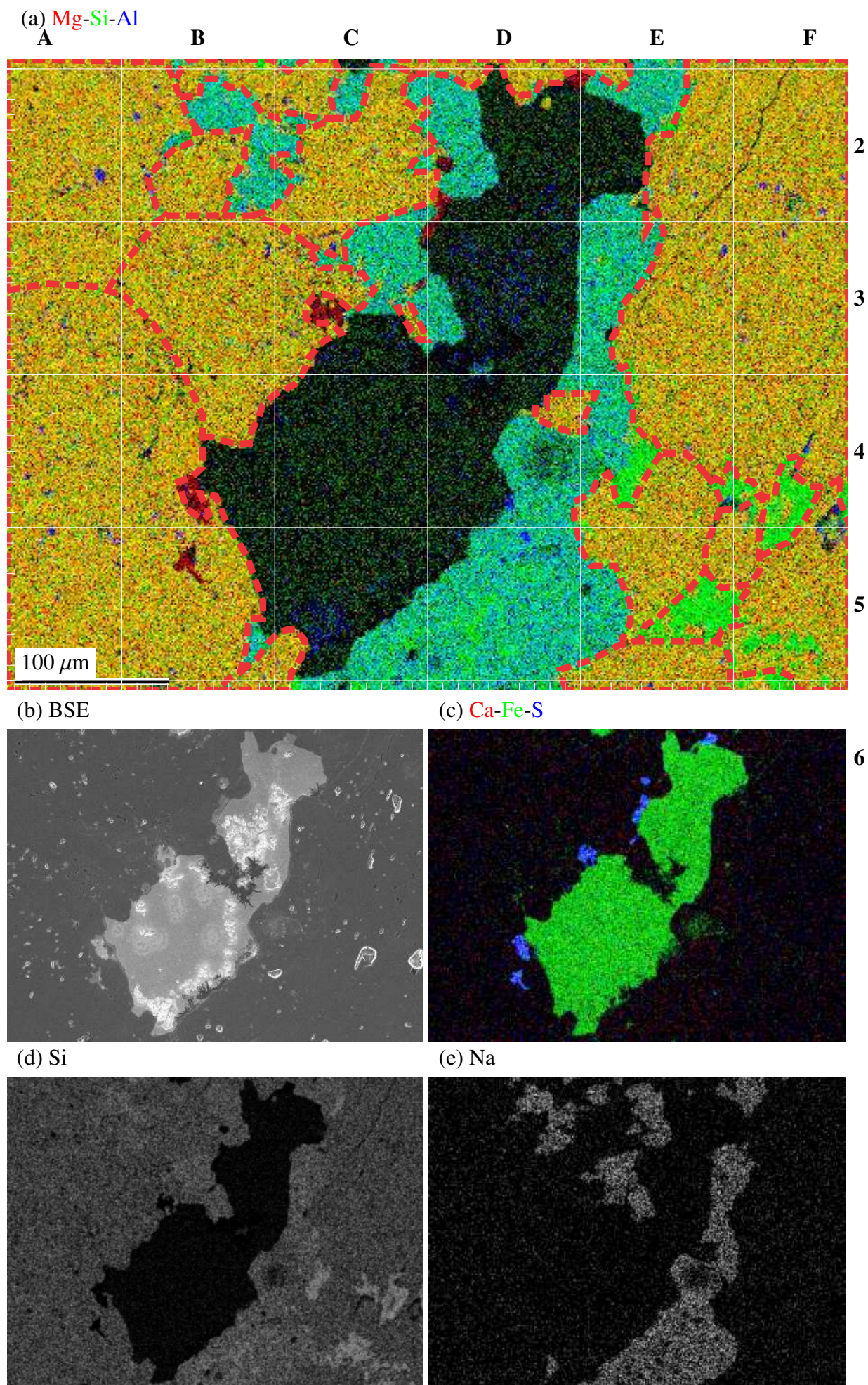


Figure 2.173: Site-5 of NWA8173b (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.169.

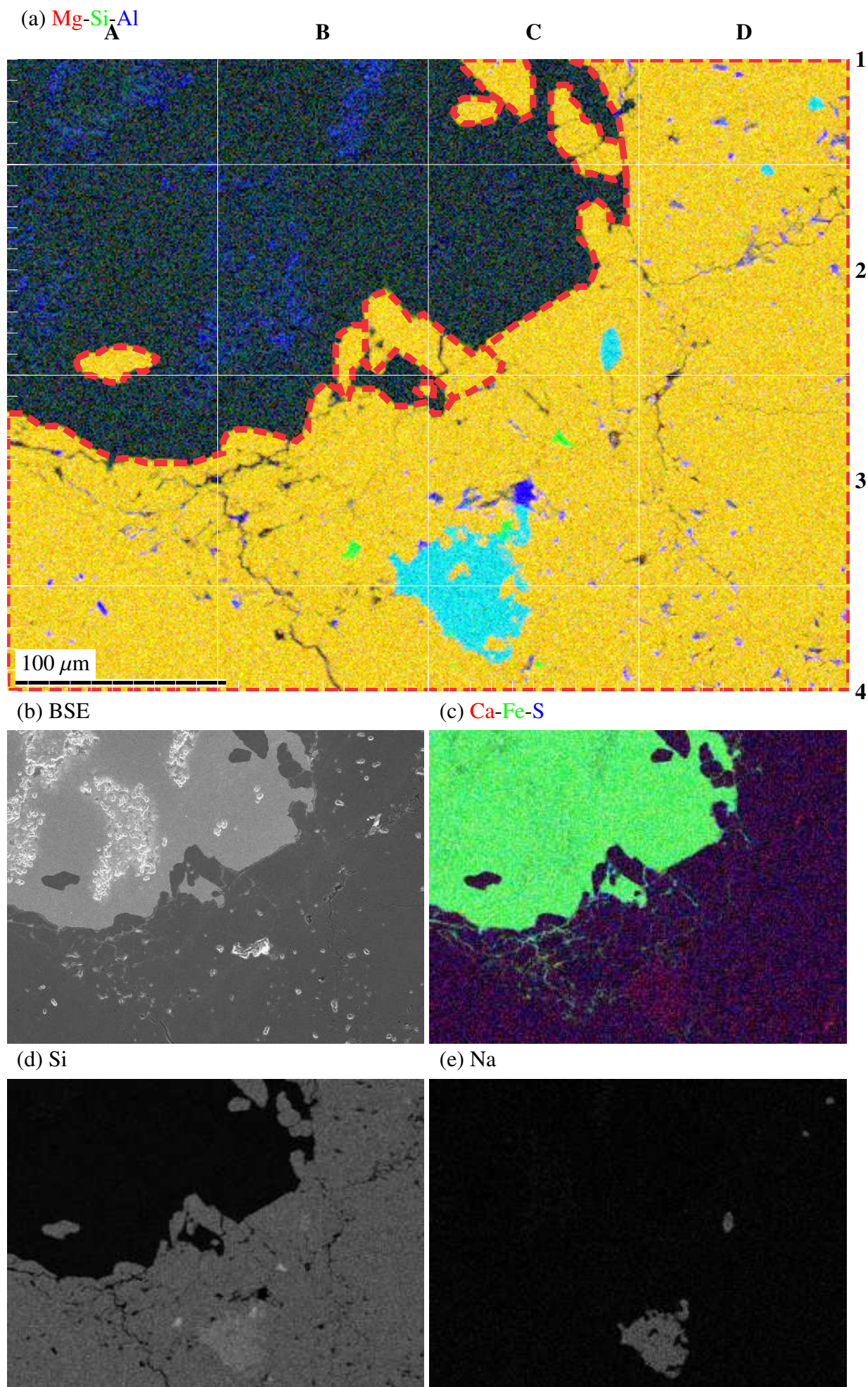


Figure 2.174: Site-6 of NWA8173b (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.169.

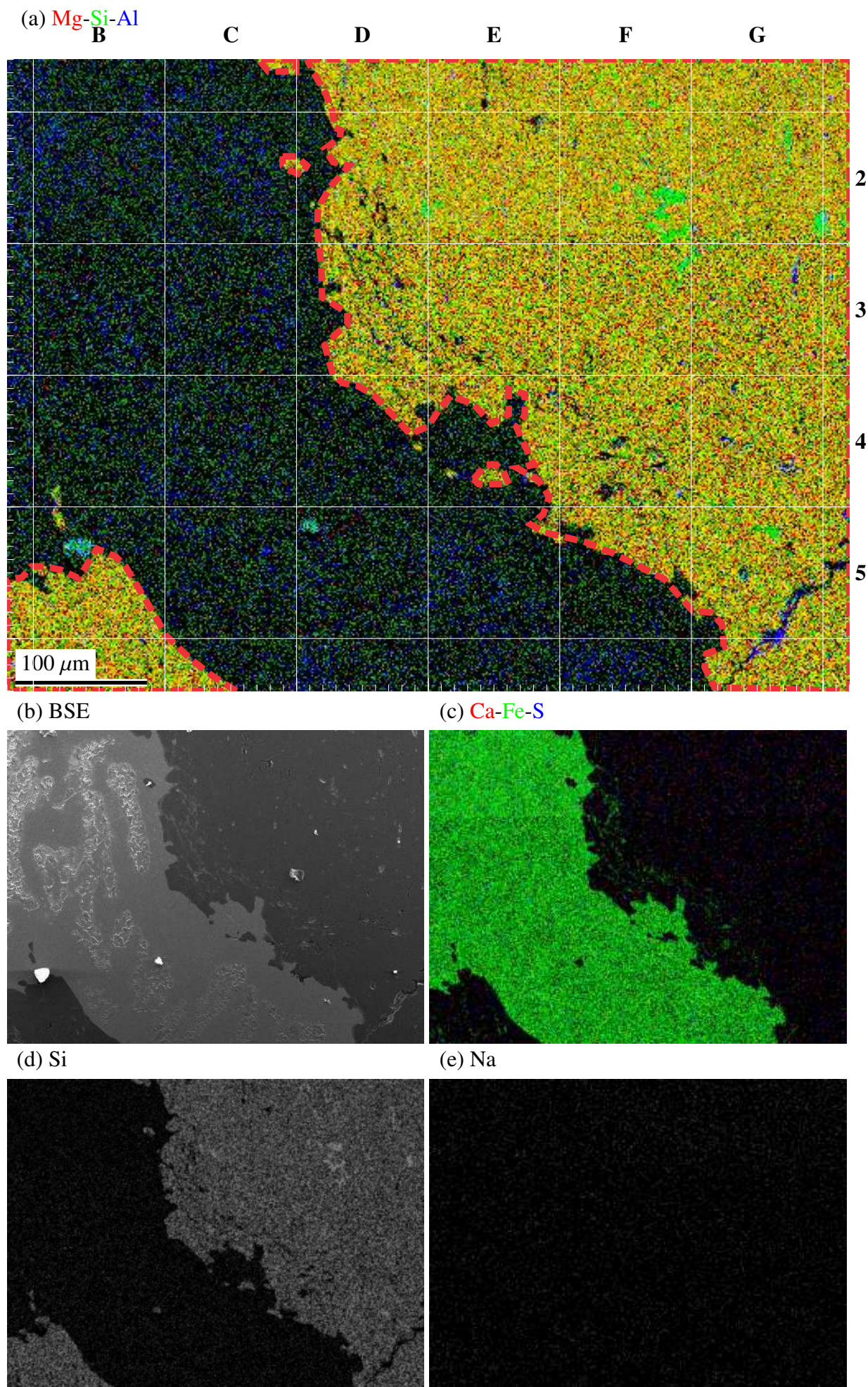


Figure 2.175: Site-7 of NWA8173b (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.169.

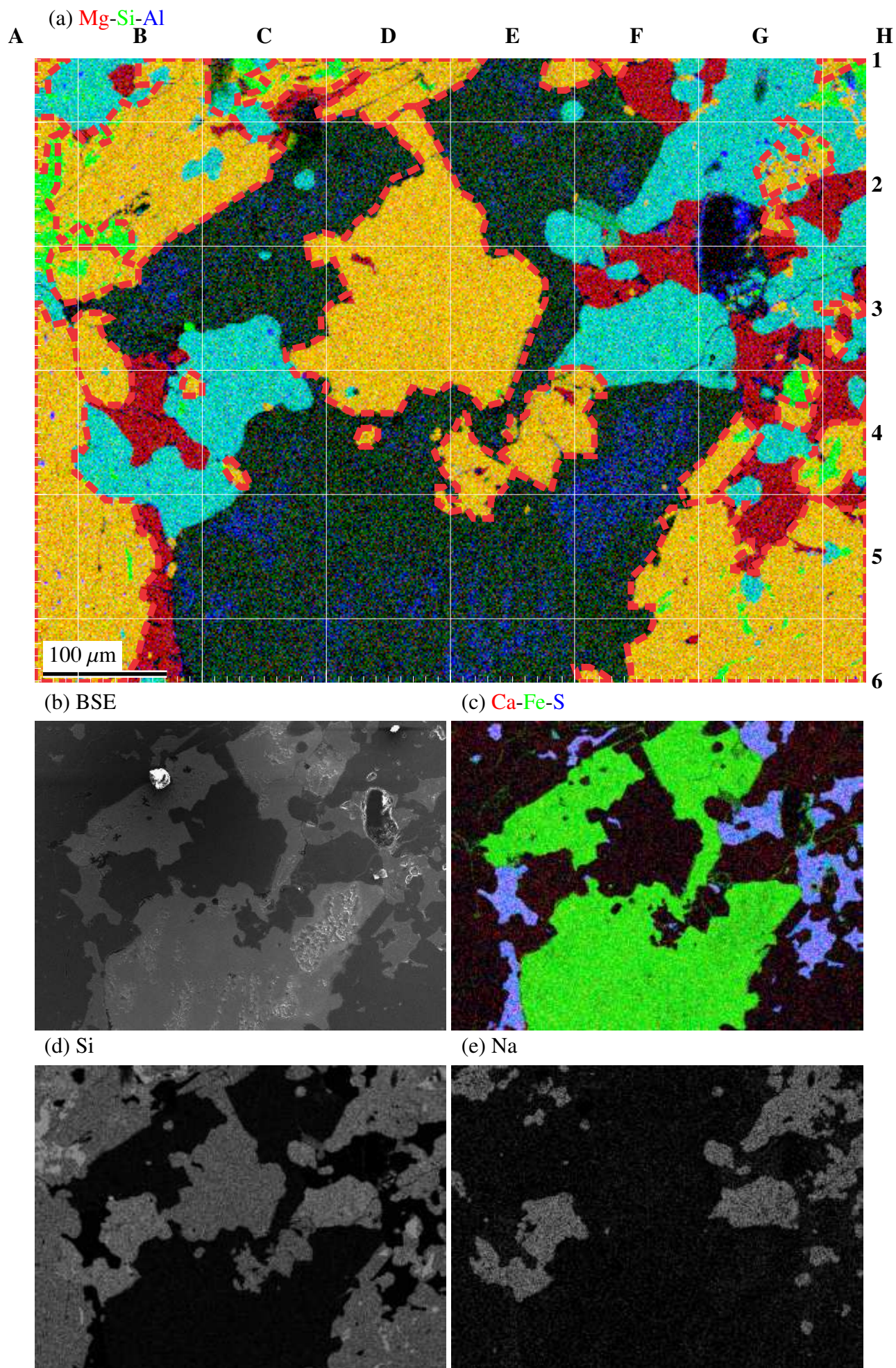


Figure 2.176: Site-8 of NWA8173b (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.169.

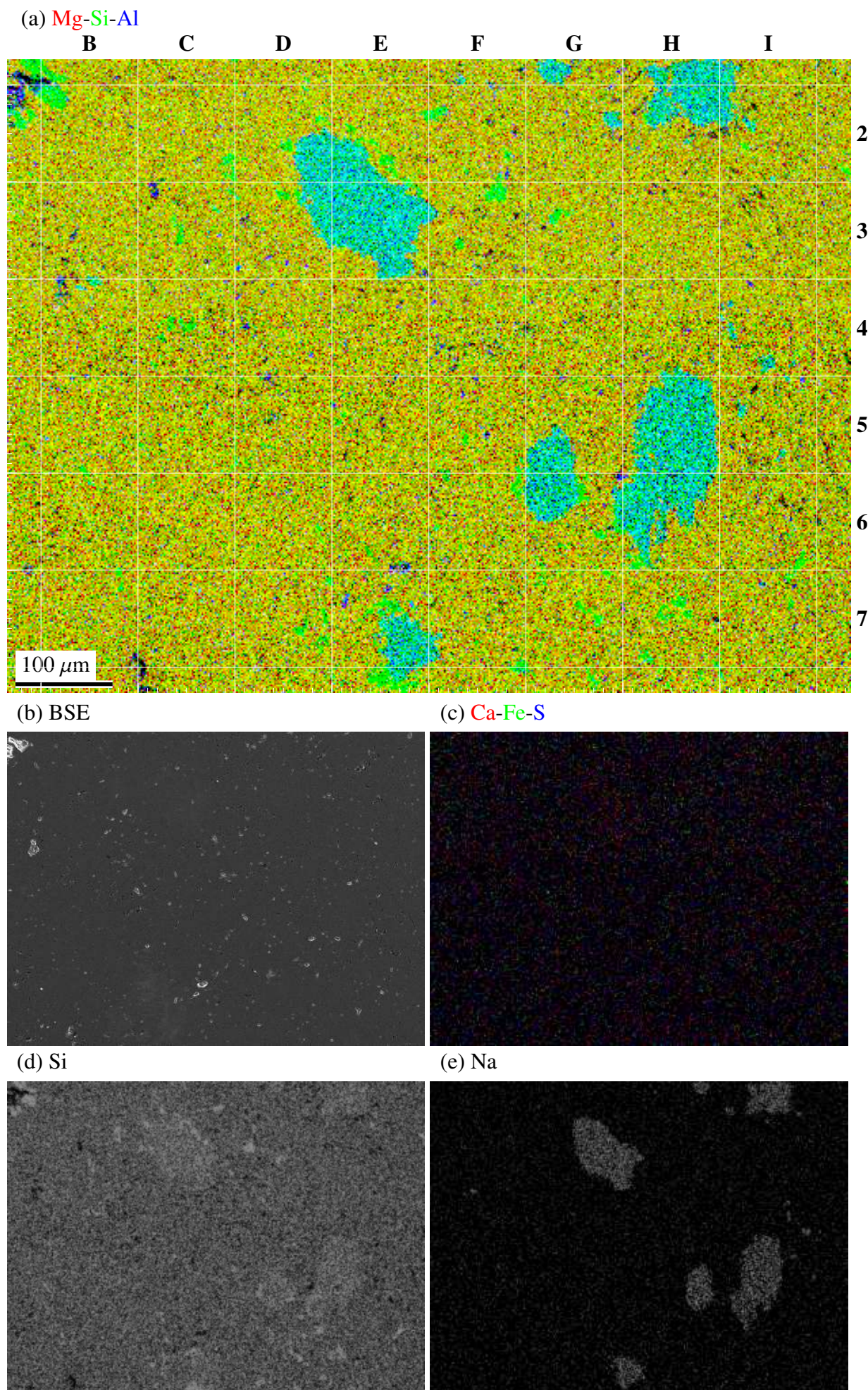
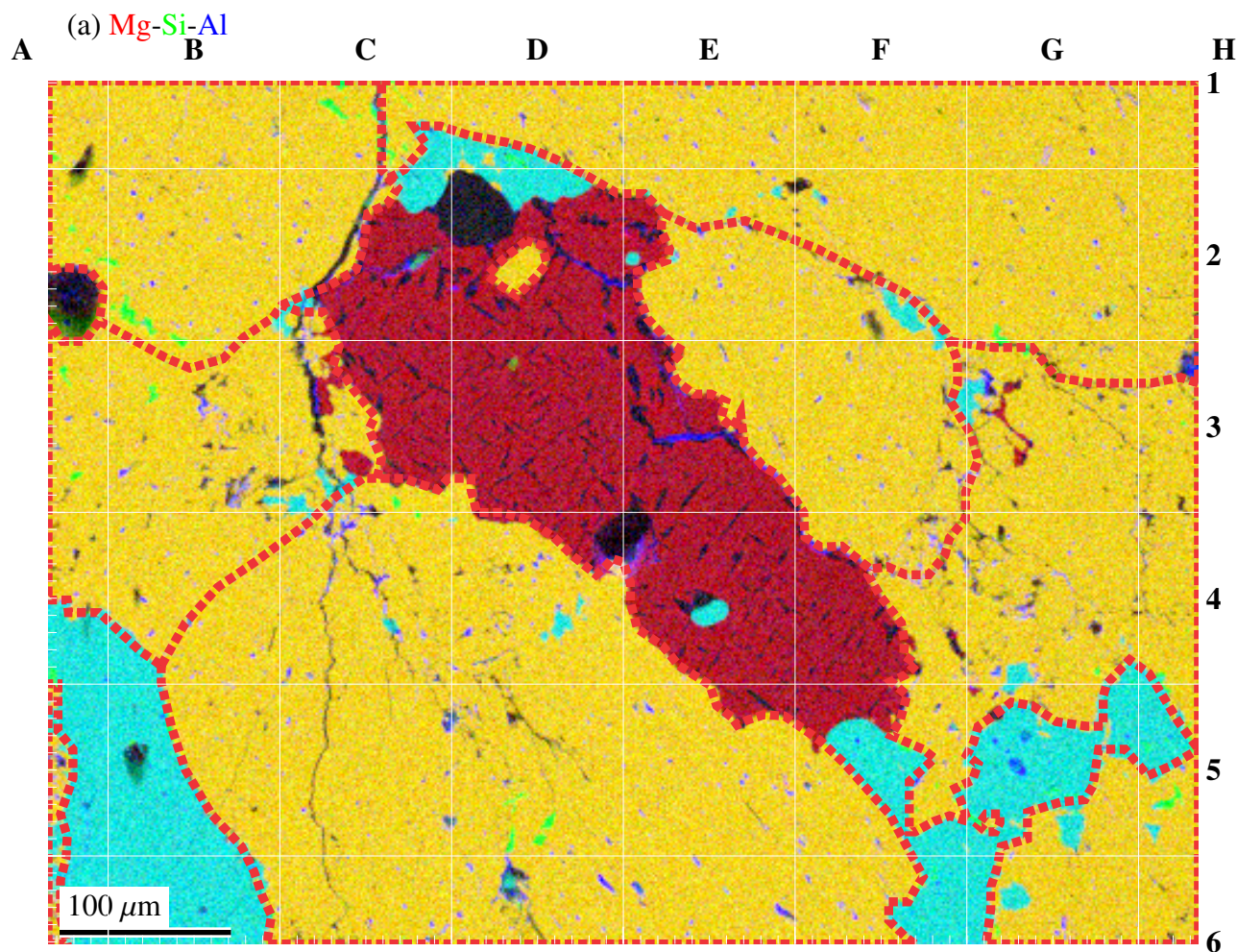
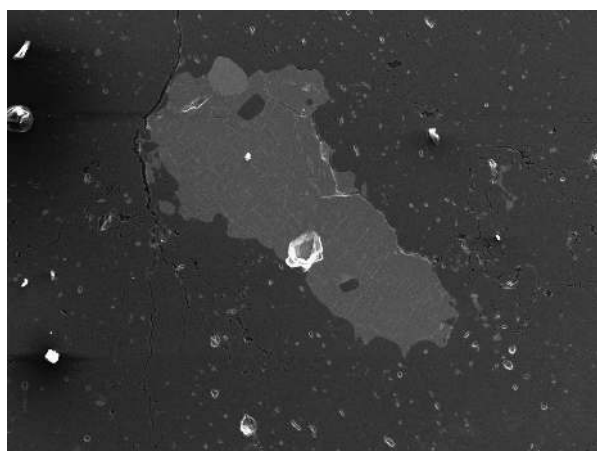


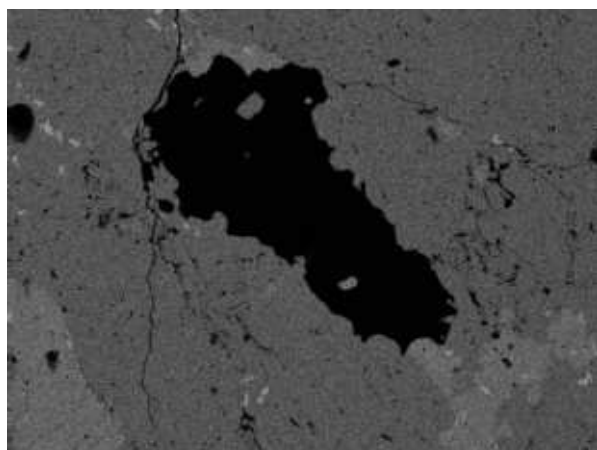
Figure 2.177: Site-9 of NWA8173b (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.169.



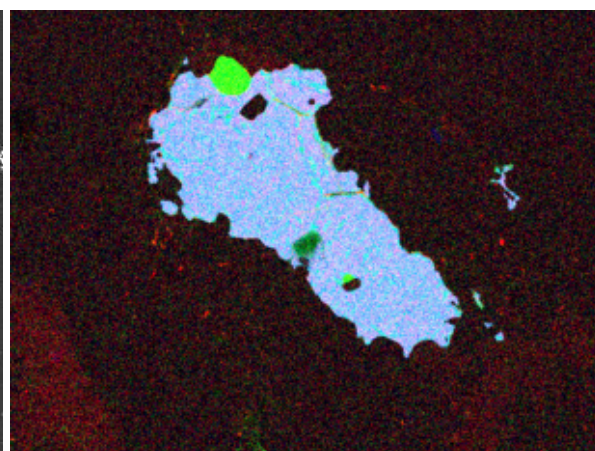
(b) BSE



(d) Si



(c) Ca-Fe-S



(e) Na

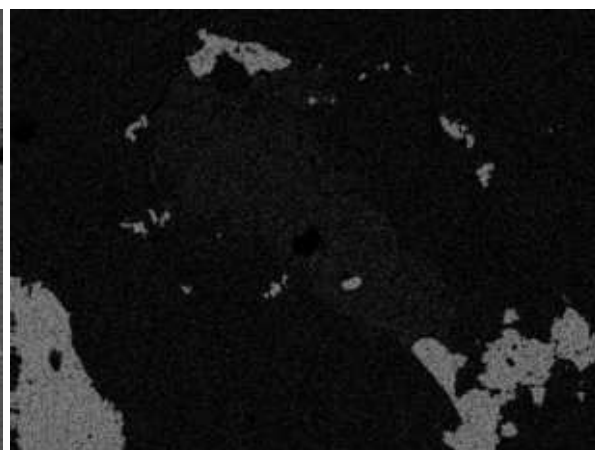


Figure 2.178: Site-10 of NWA8173b (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.169.

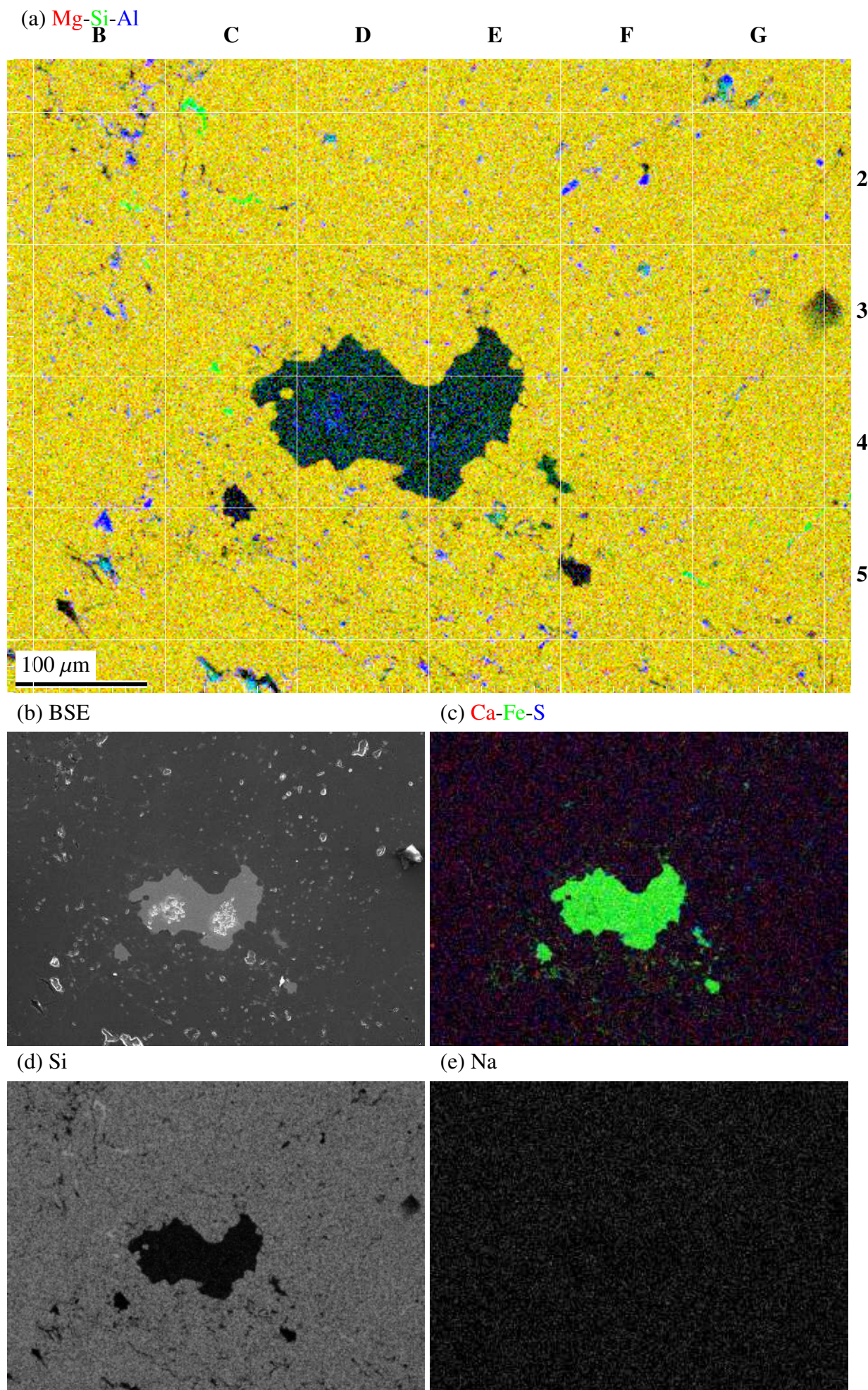


Figure 2.179: Site-11 of NWA8173b (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.169.

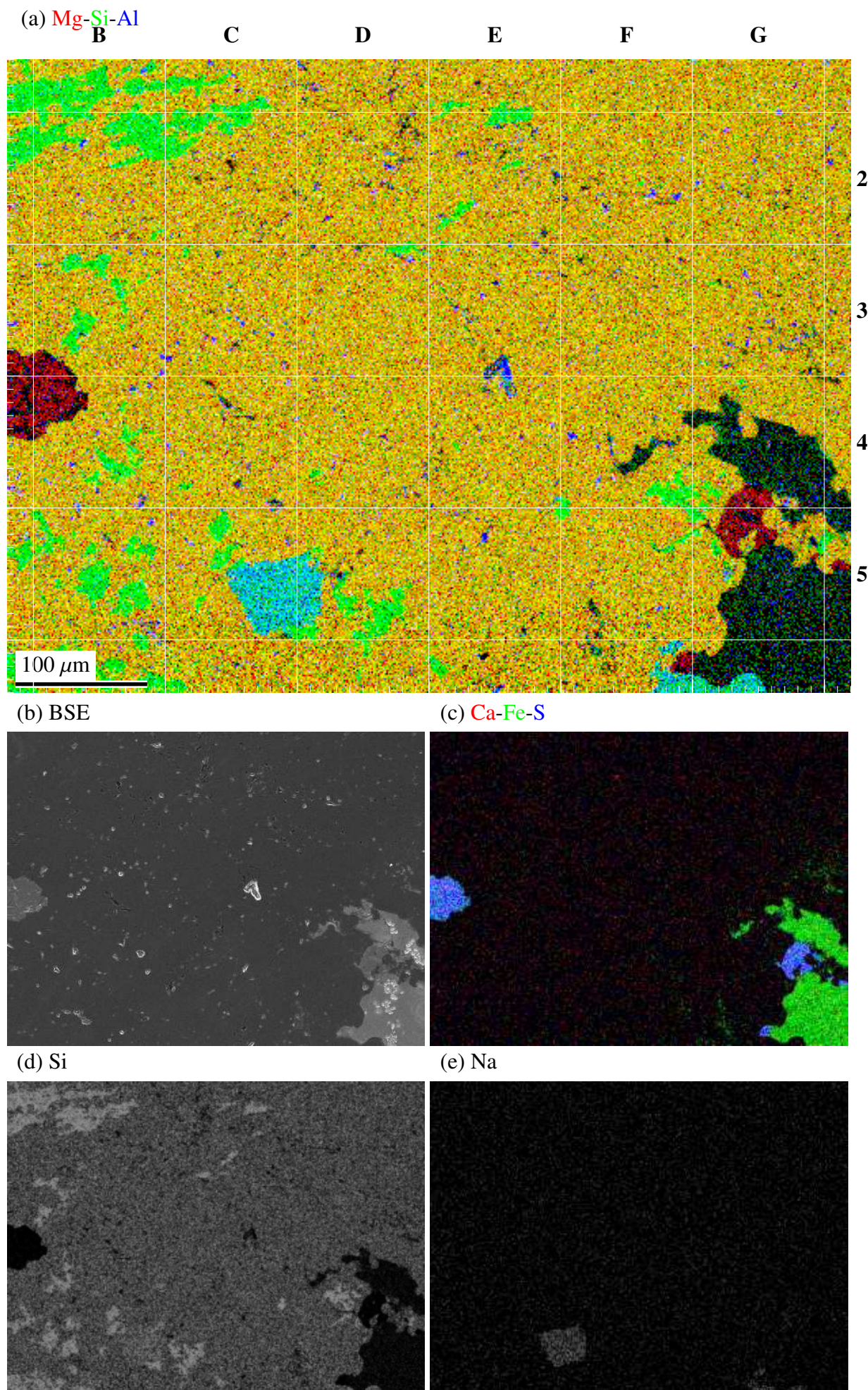


Figure 2.180: Site-12 of NWA8173b (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.169.

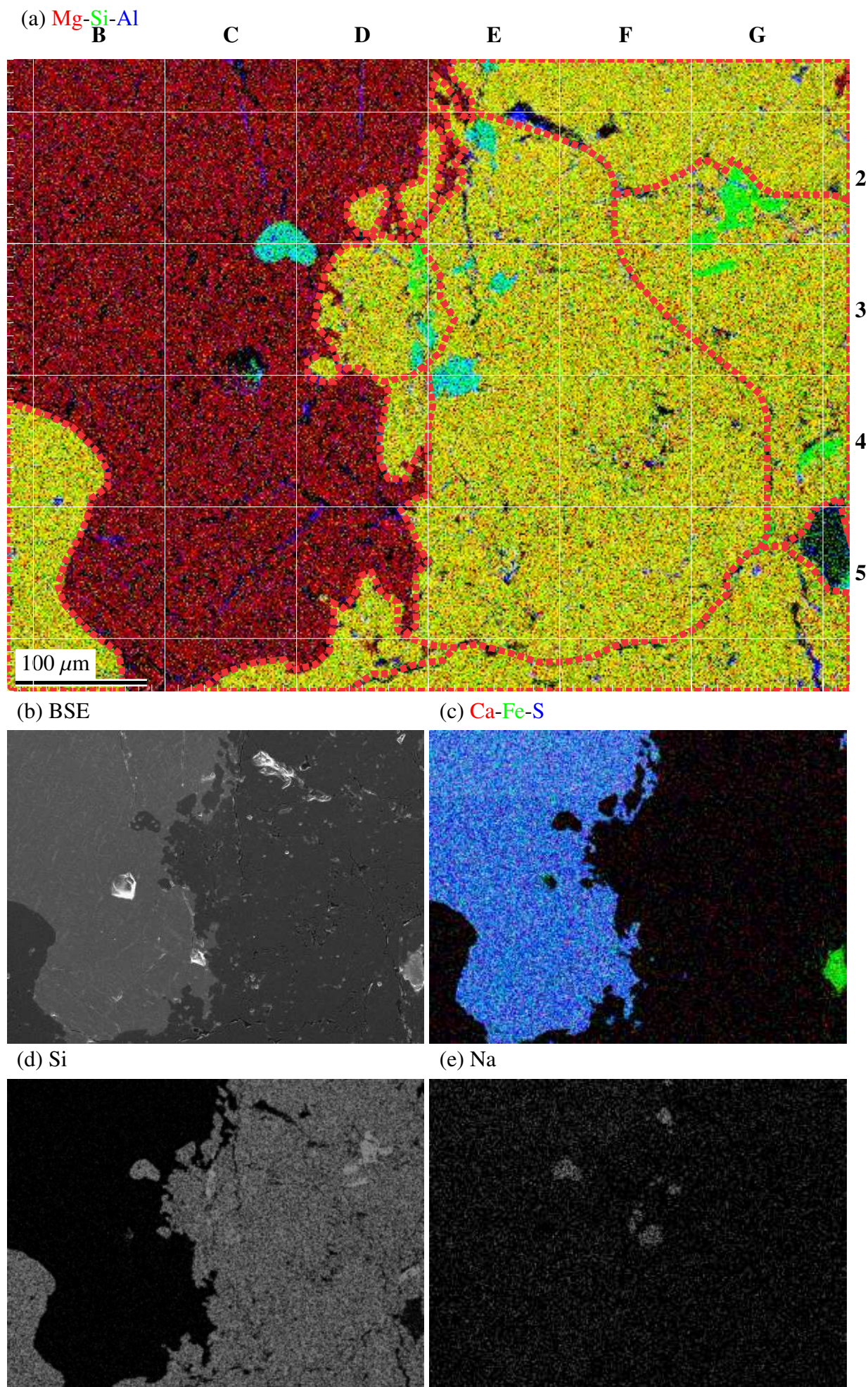
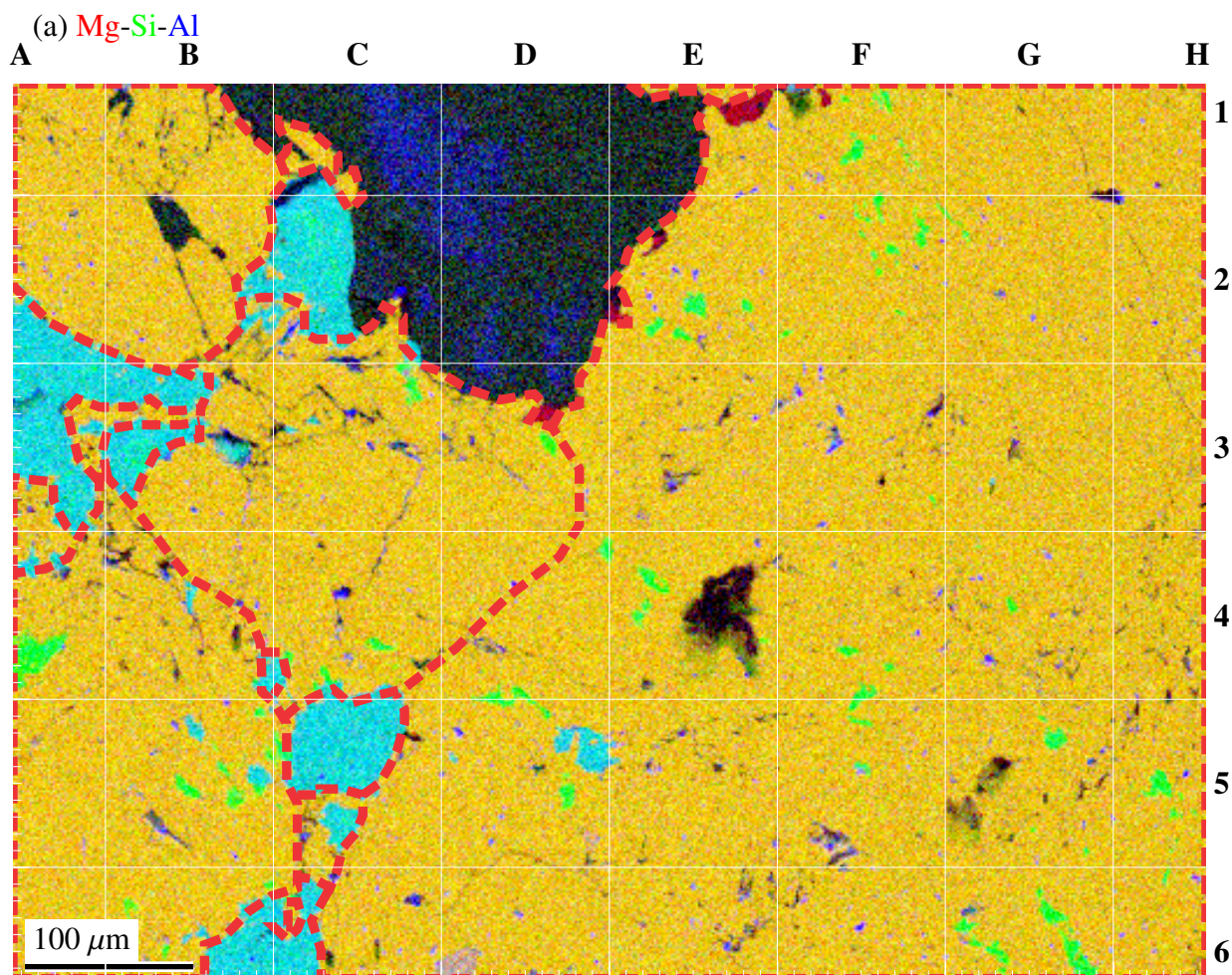
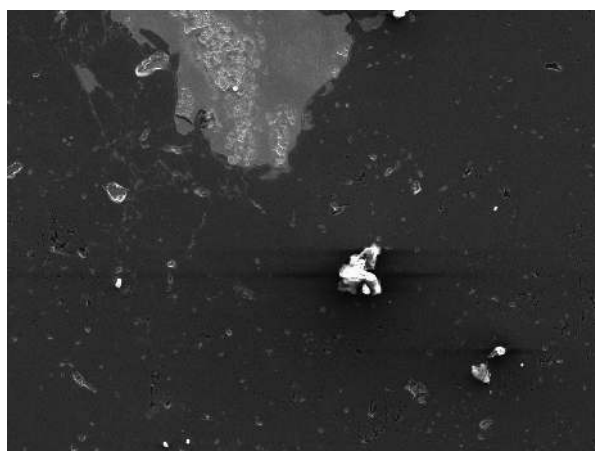


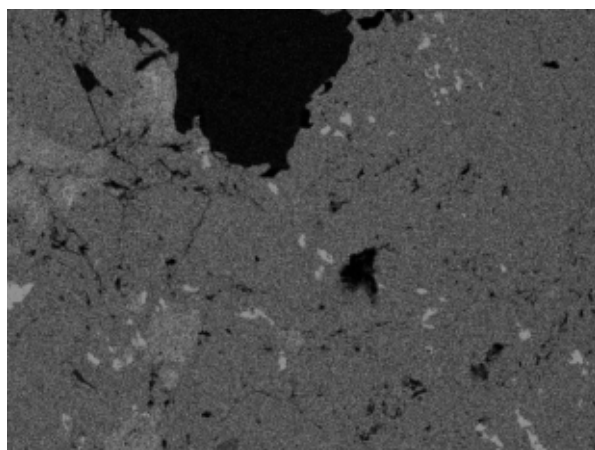
Figure 2.181: Site-13 of NWA8173b (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.169.



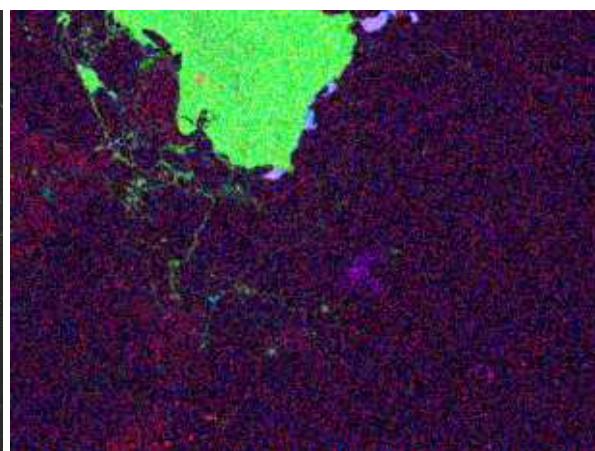
(b) BSE



(d) Si



(c) Ca-Fe-S



(e) Na

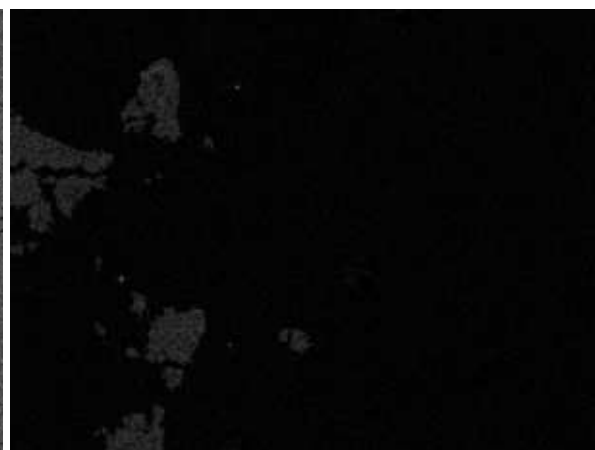


Figure 2.182: Site-14 of NWA8173b (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.169.

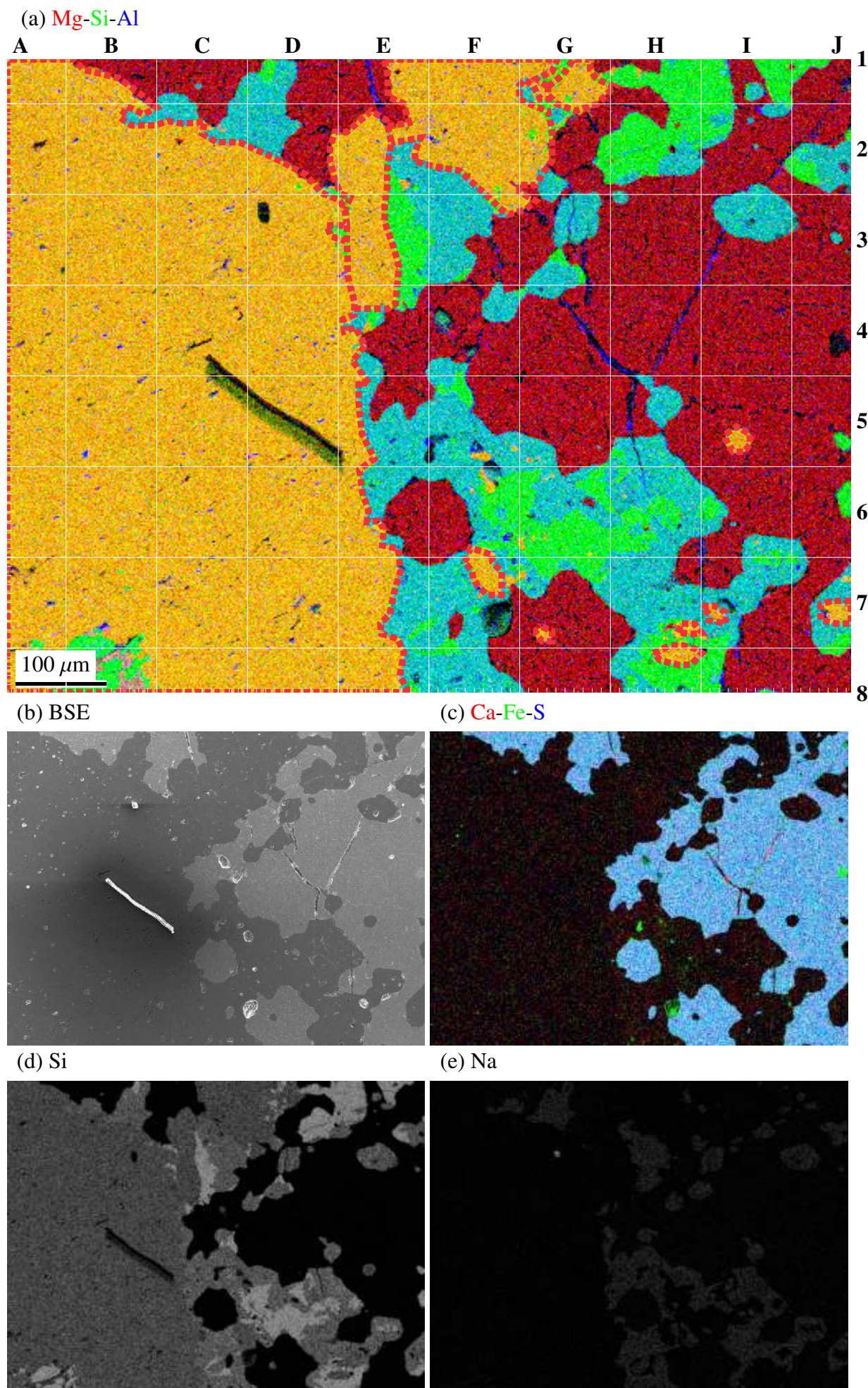


Figure 2.183: Site-15 of NWA8173b (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.169.

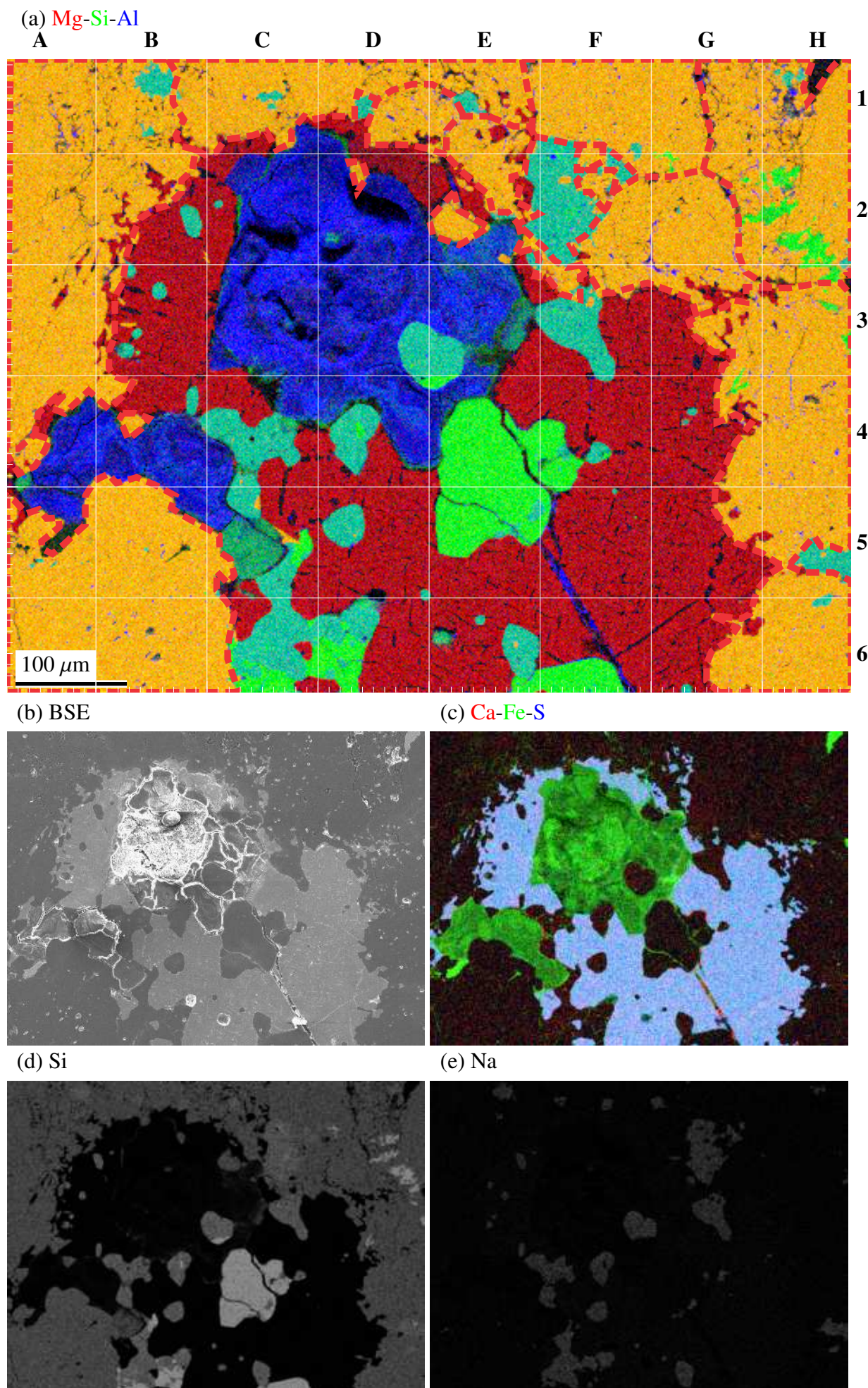


Figure 2.184: Site-16 of NWA8173b (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.169.

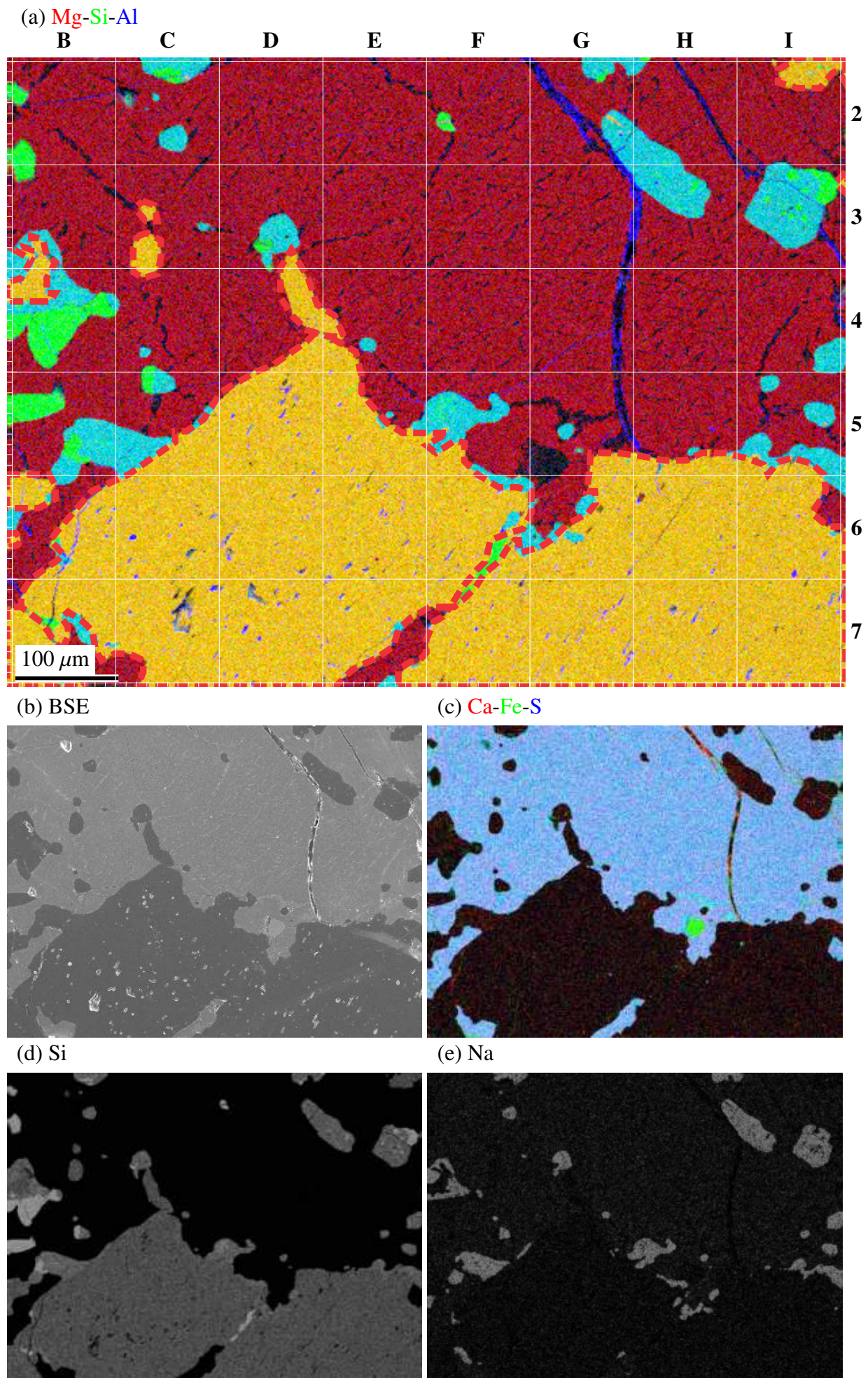


Figure 2.185: Site-17 of NWA8173b (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.169.

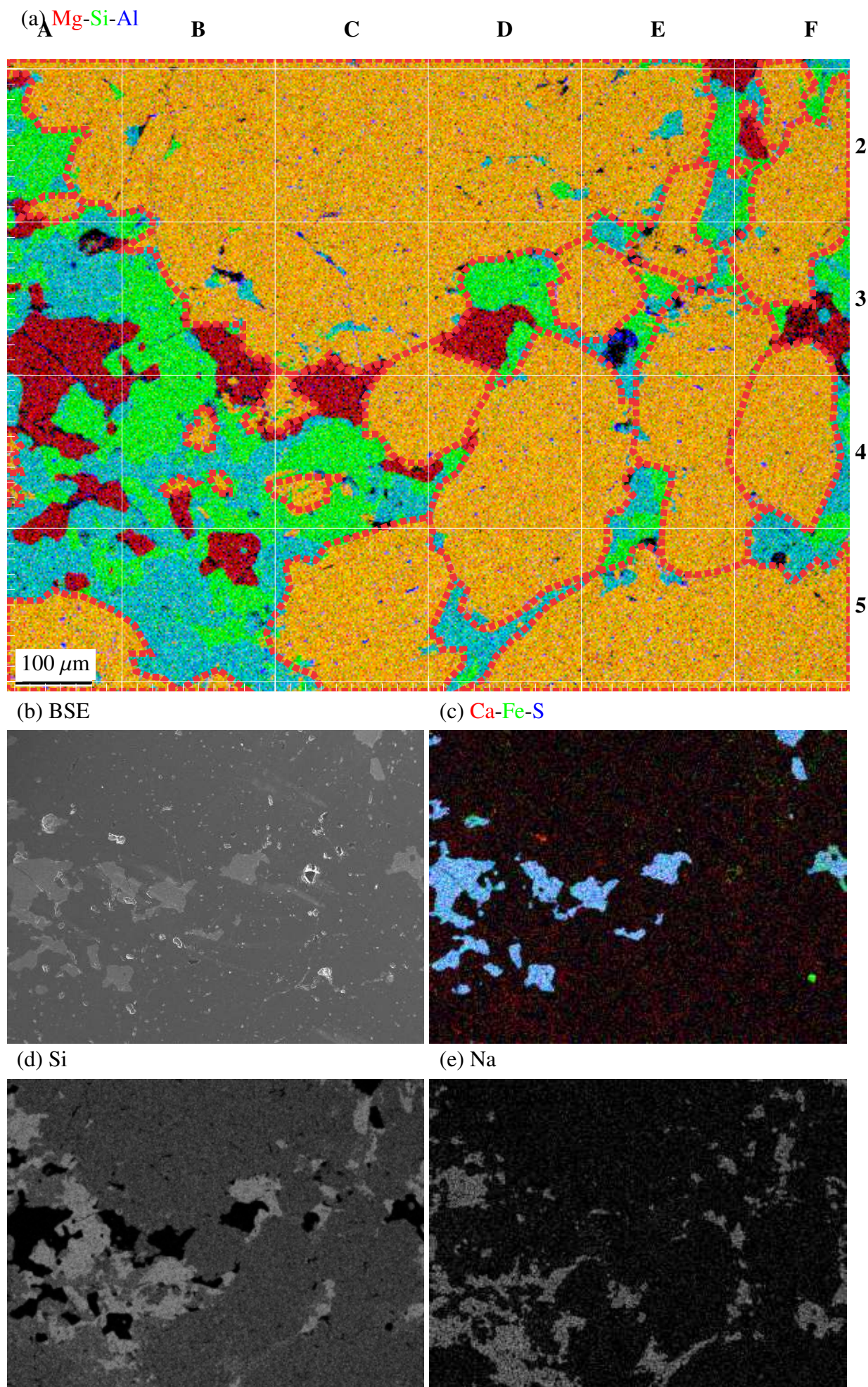


Figure 2.186: Site-18 of NWA8173b (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.169.

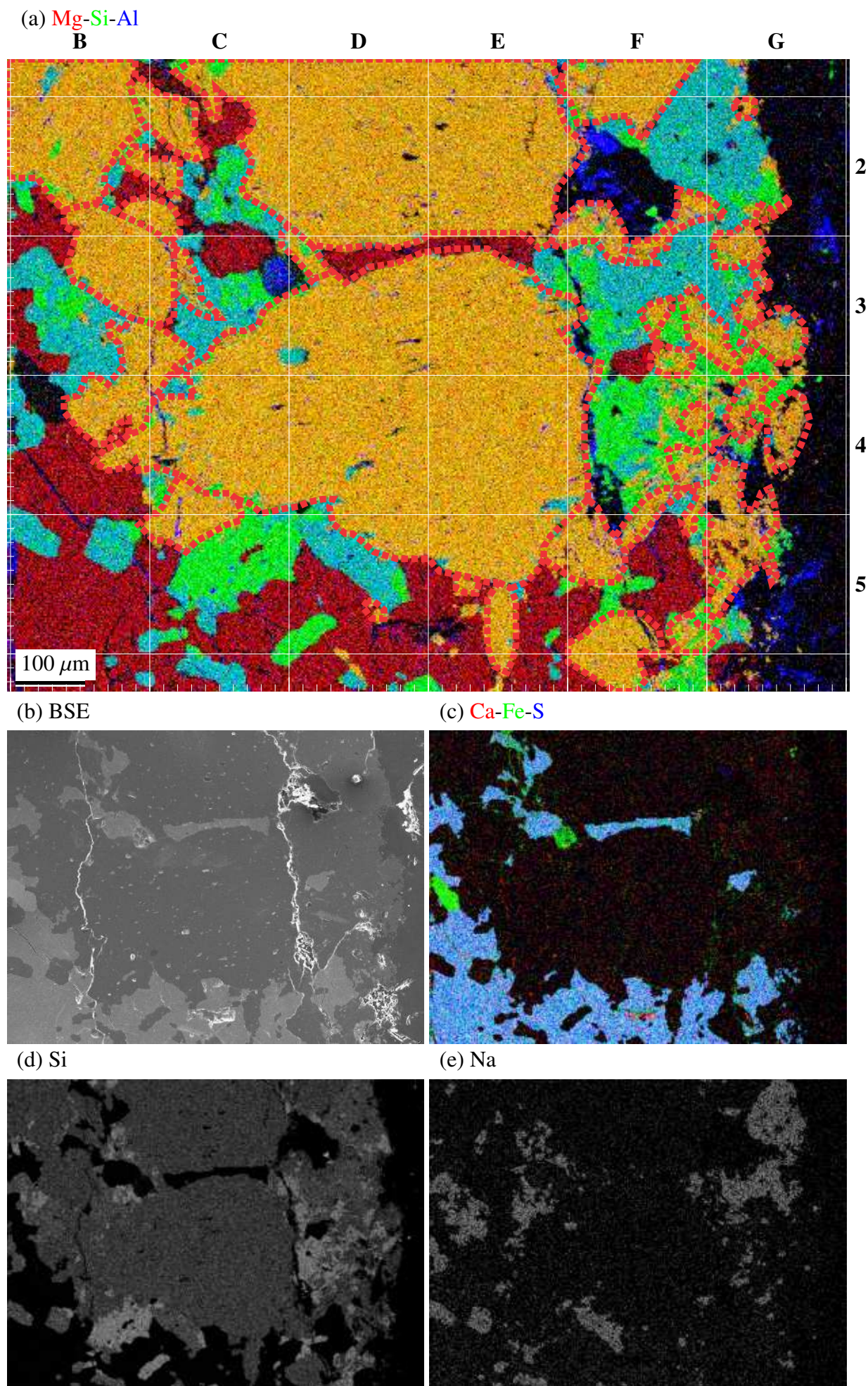


Figure 2.187: Site-19 of NWA8173b (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.169.

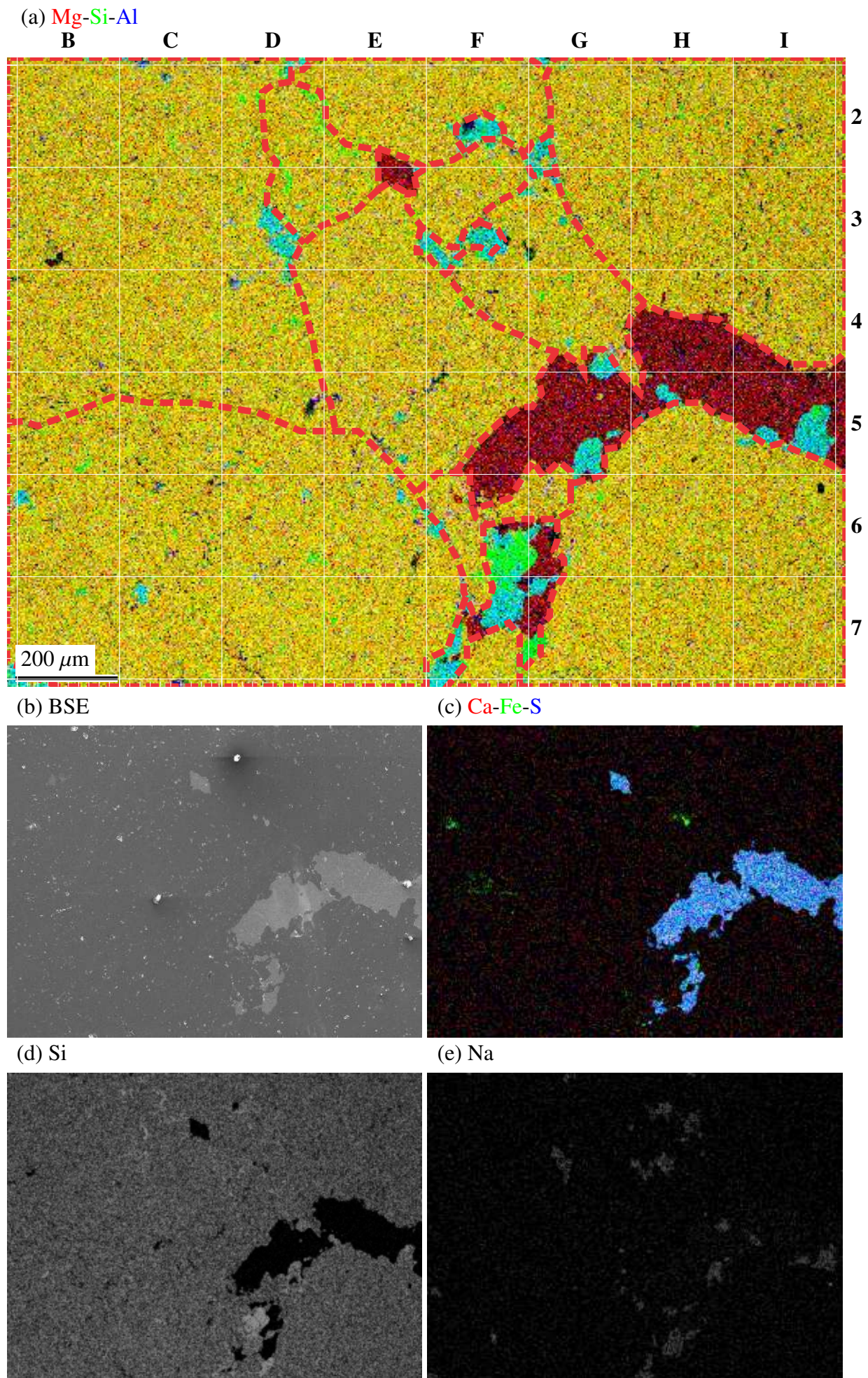


Figure 2.188: Site-20 of NWA8173b (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.169.

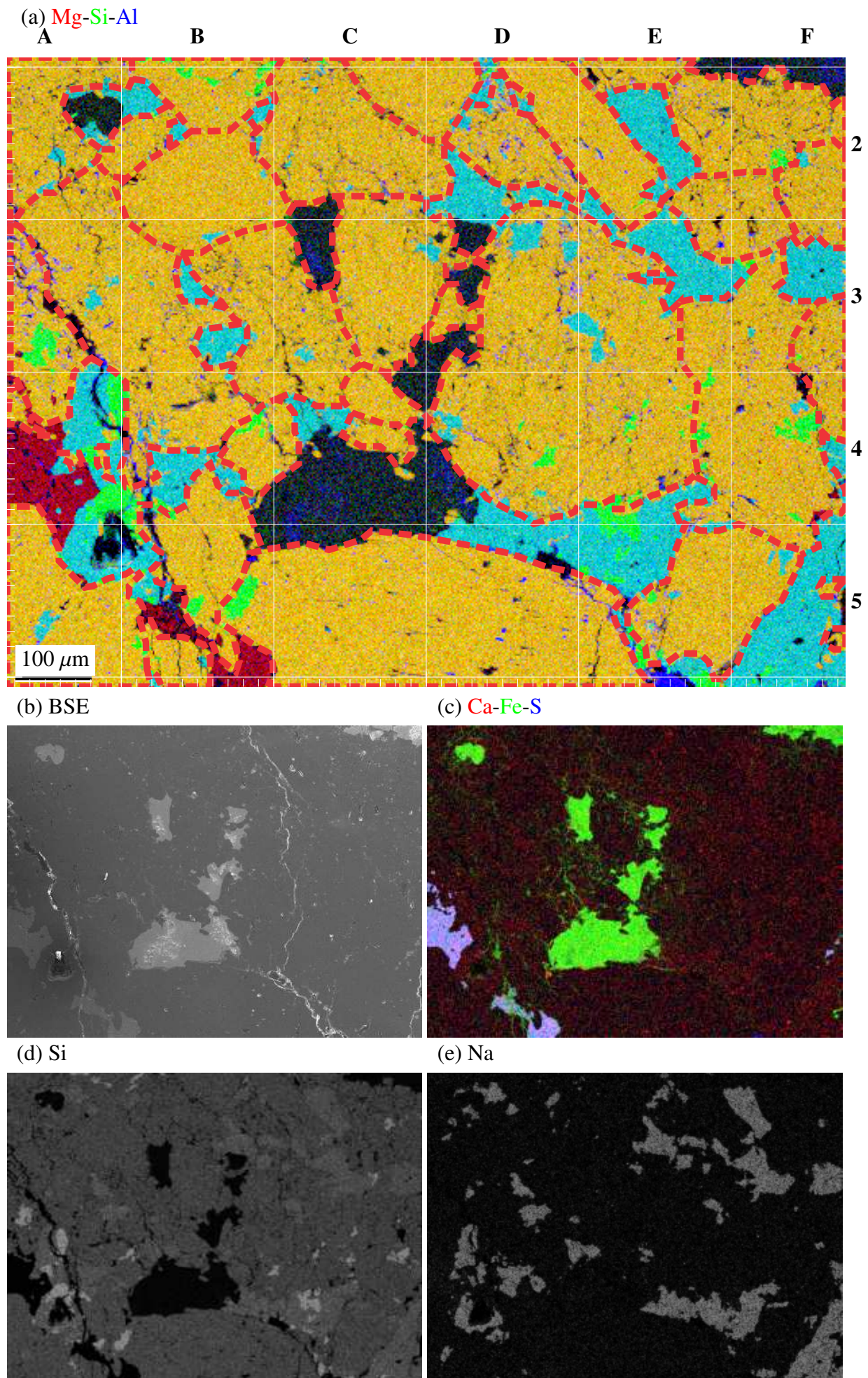


Figure 2.189: Site-21 of NWA8173b (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.169.

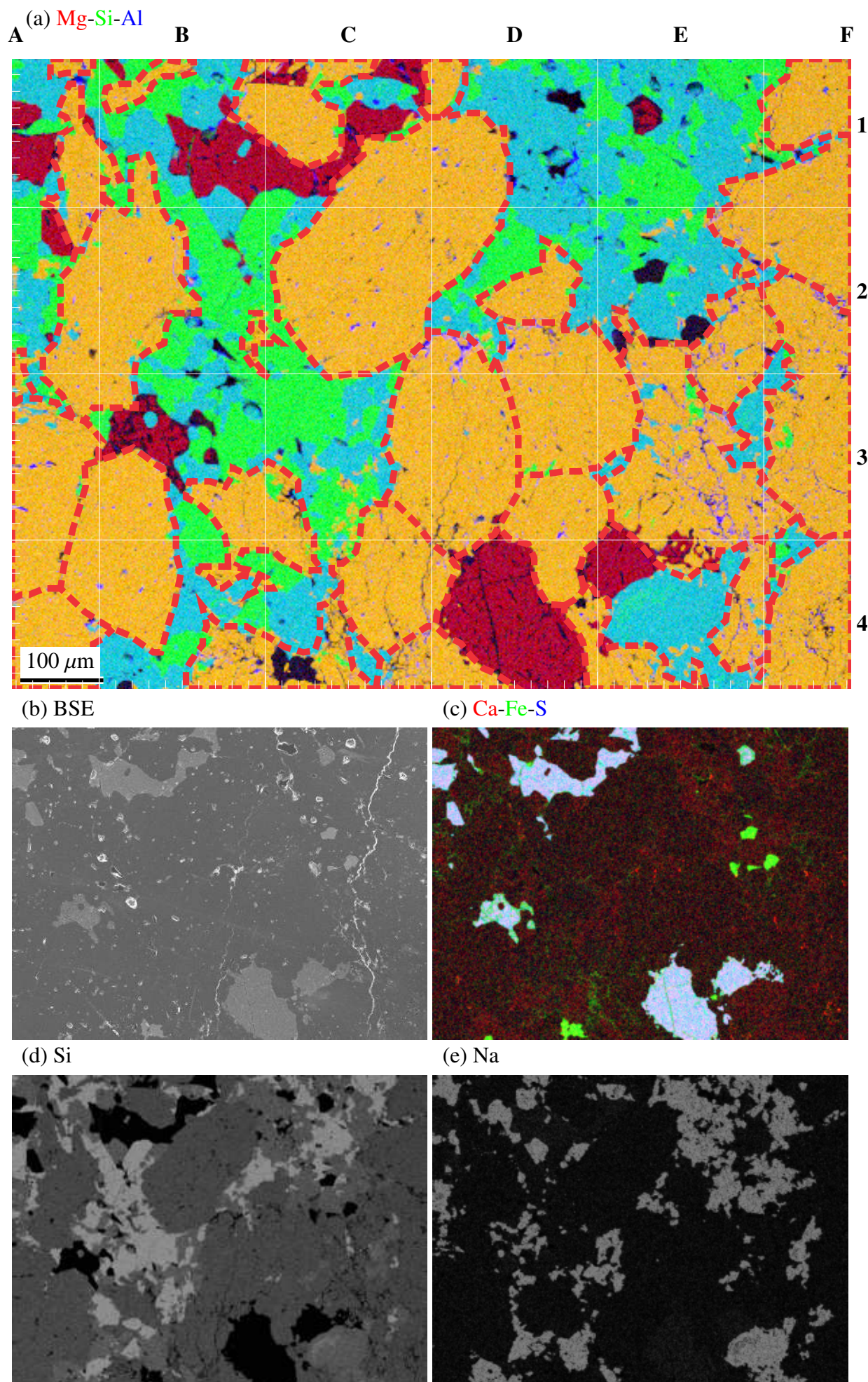


Figure 2.190: Site-22 of NWA8173b (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.169.

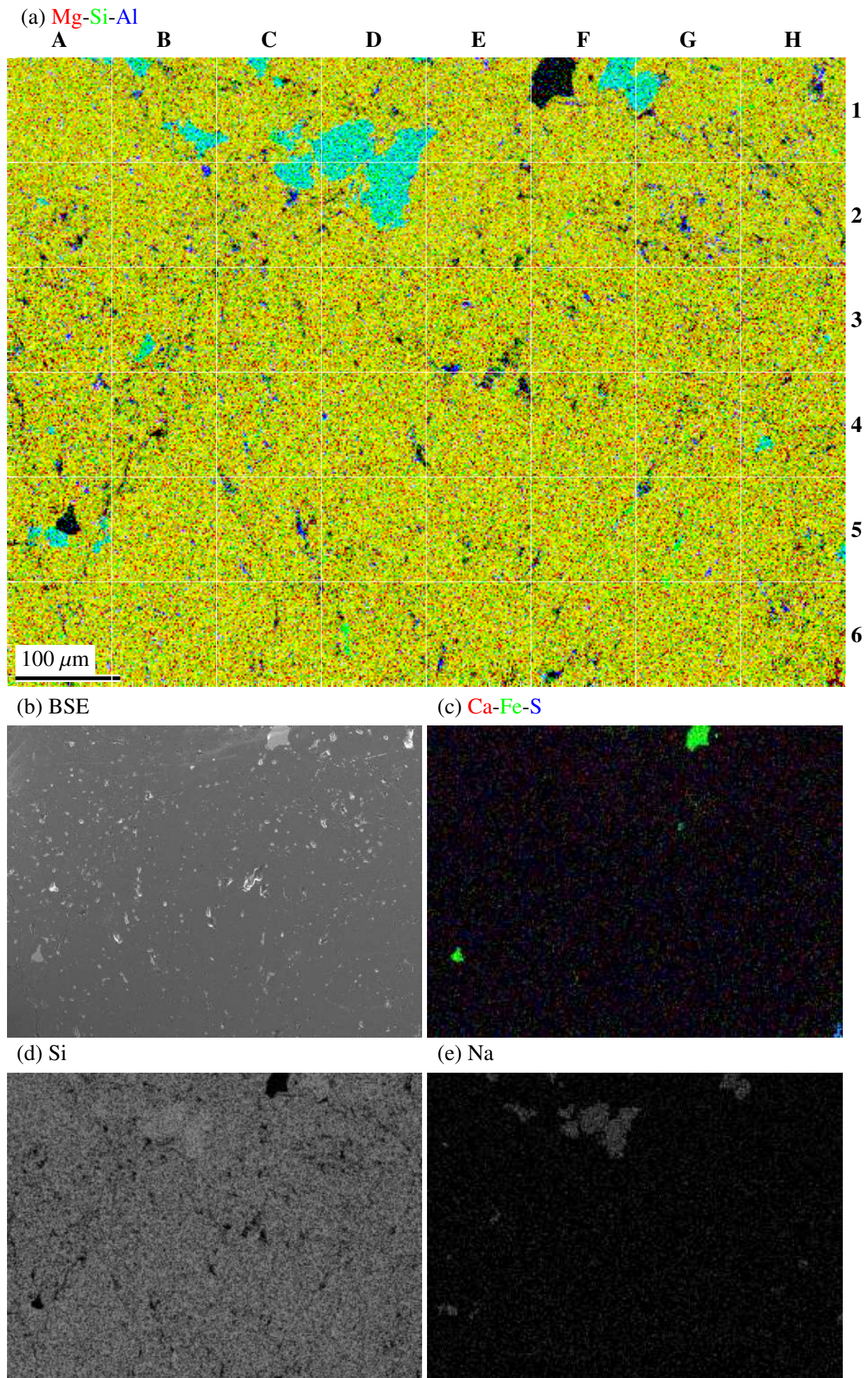


Figure 2.191: Site-23 of NWA8173b (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.169.

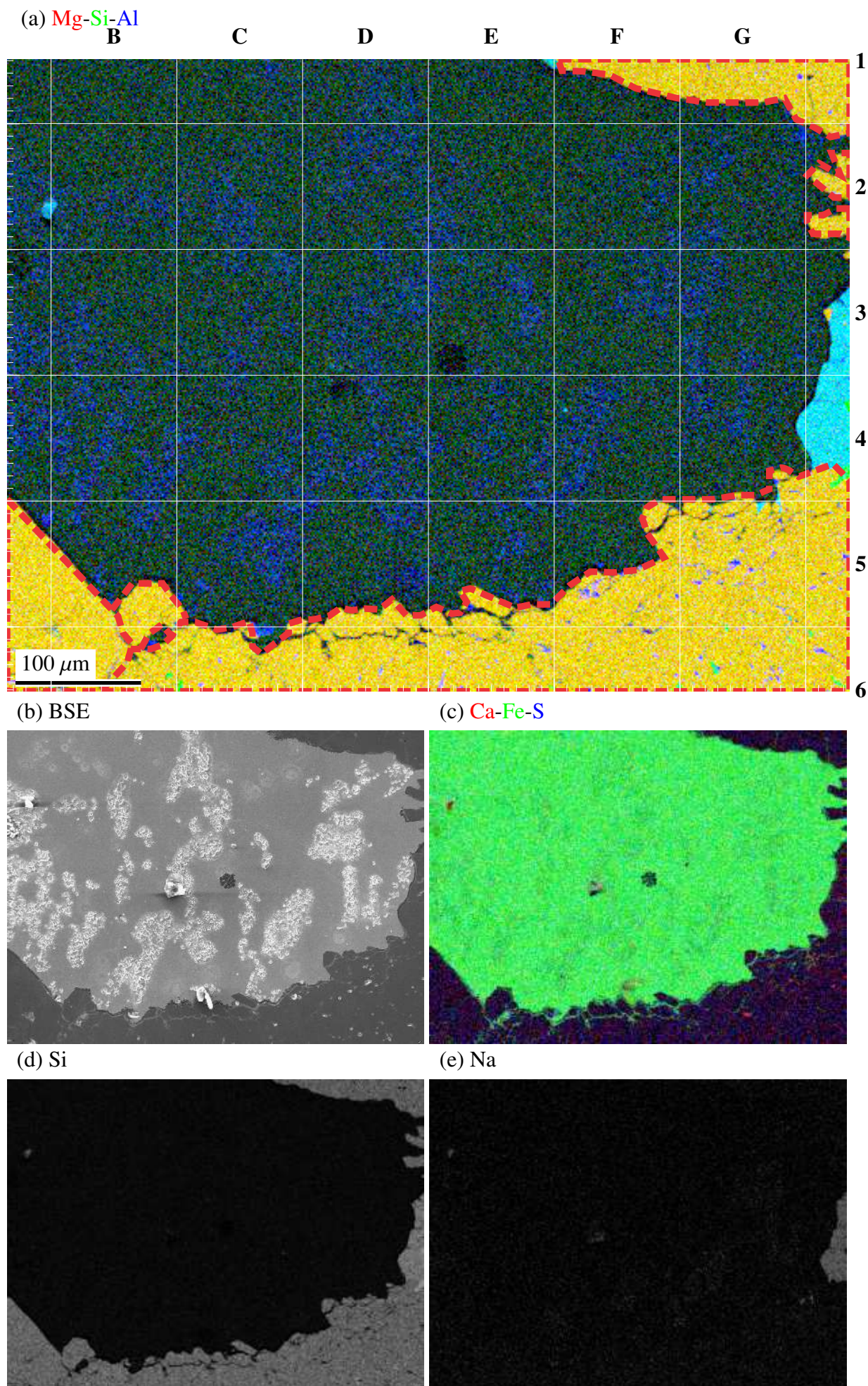


Figure 2.192: Site-24 of NWA8173b (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.169.

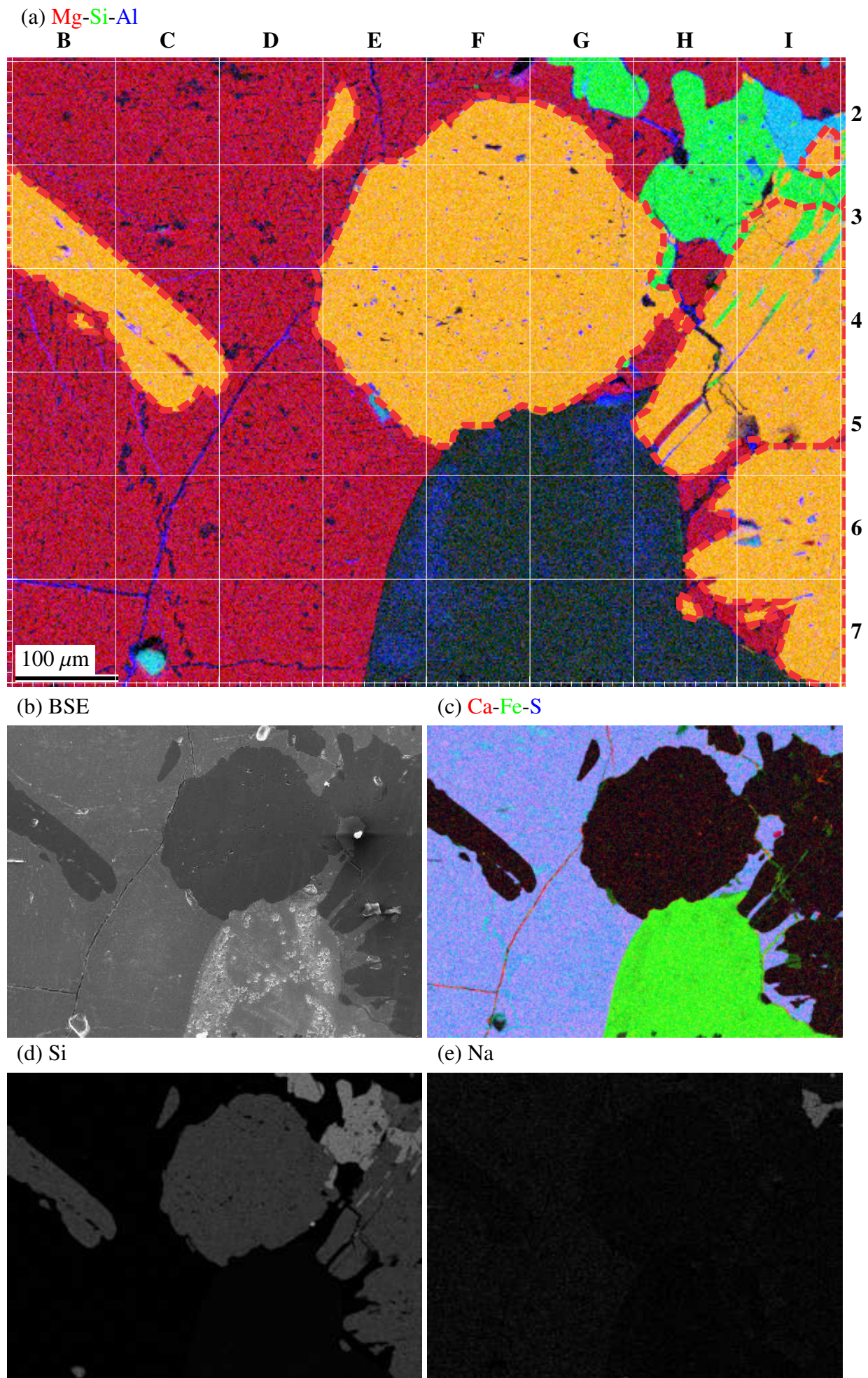


Figure 2.193: Site-25 of NWA8173b (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.169.

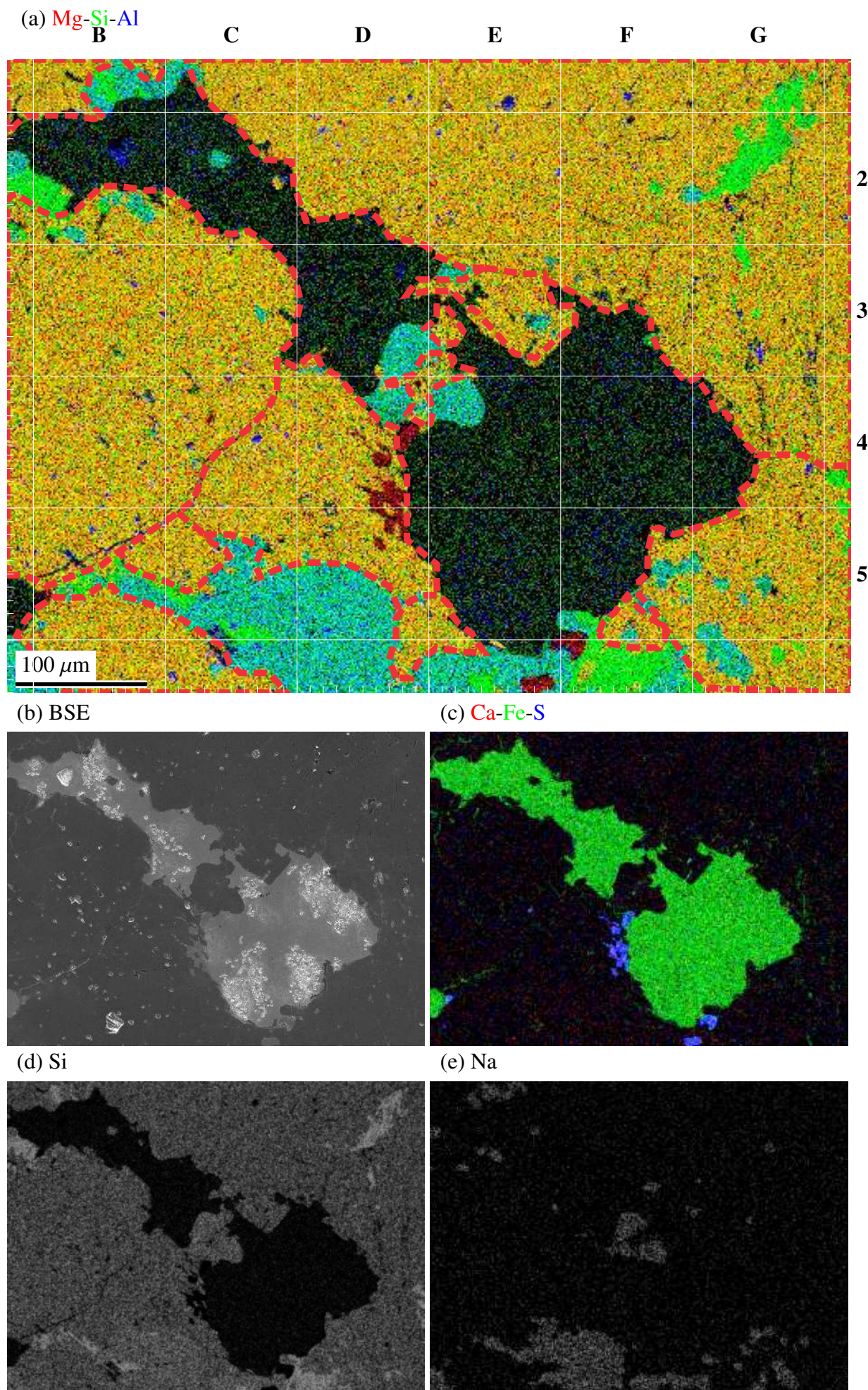


Figure 2.194: Site-26 of NWA8173b (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.169.

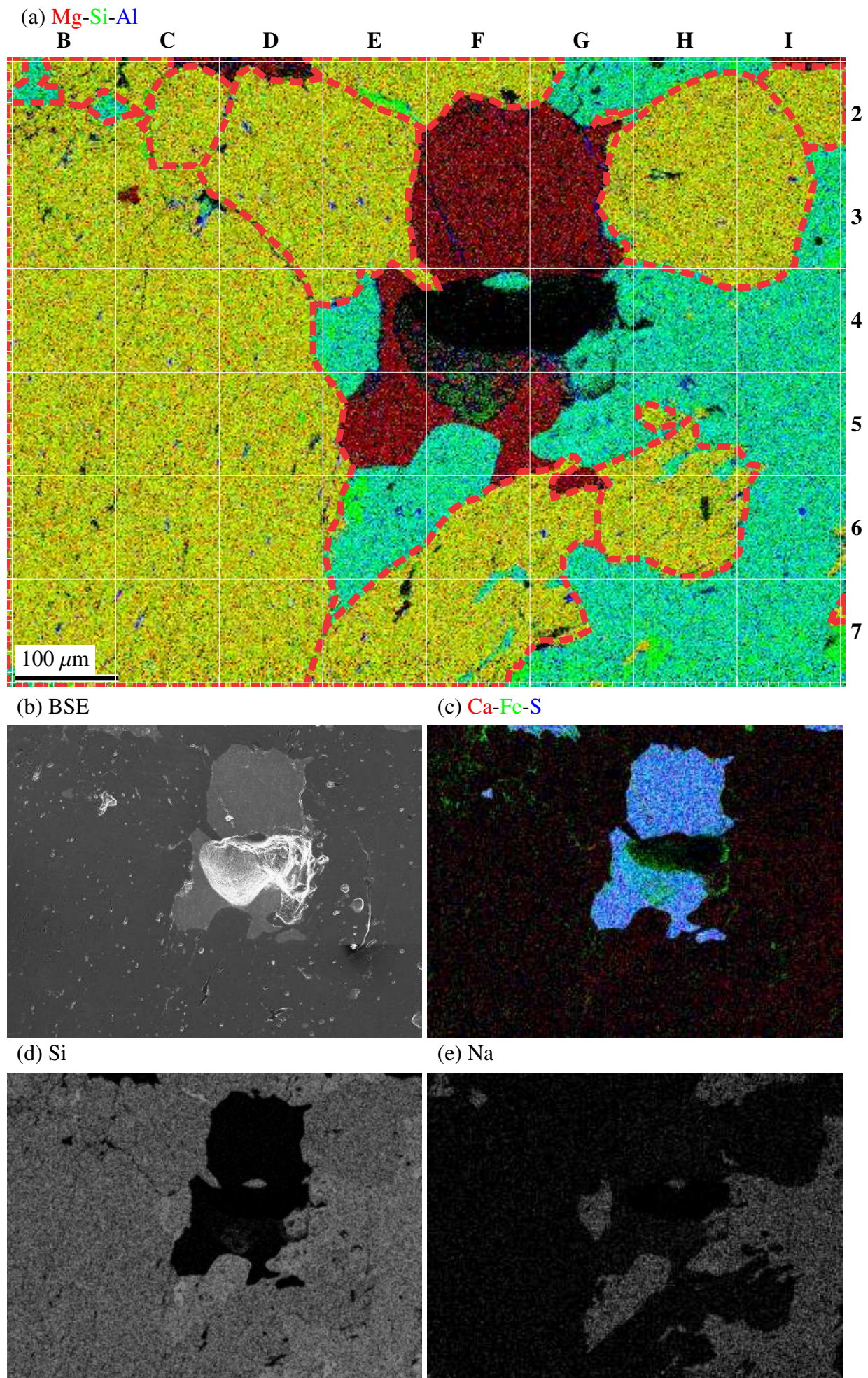


Figure 2.195: Site-27 of NWA8173b (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.169.

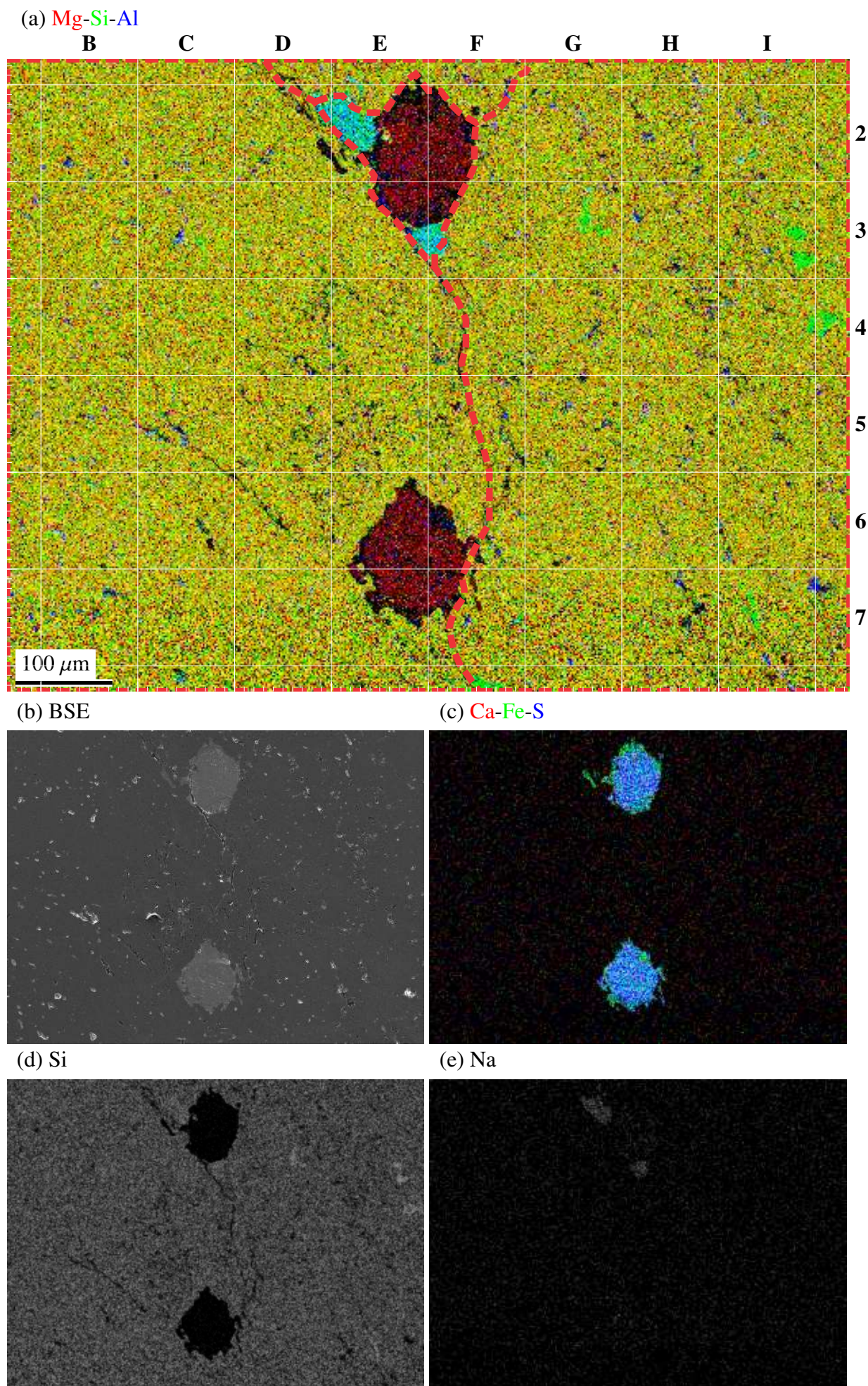


Figure 2.196: Site-28 of NWA8173b (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.169.

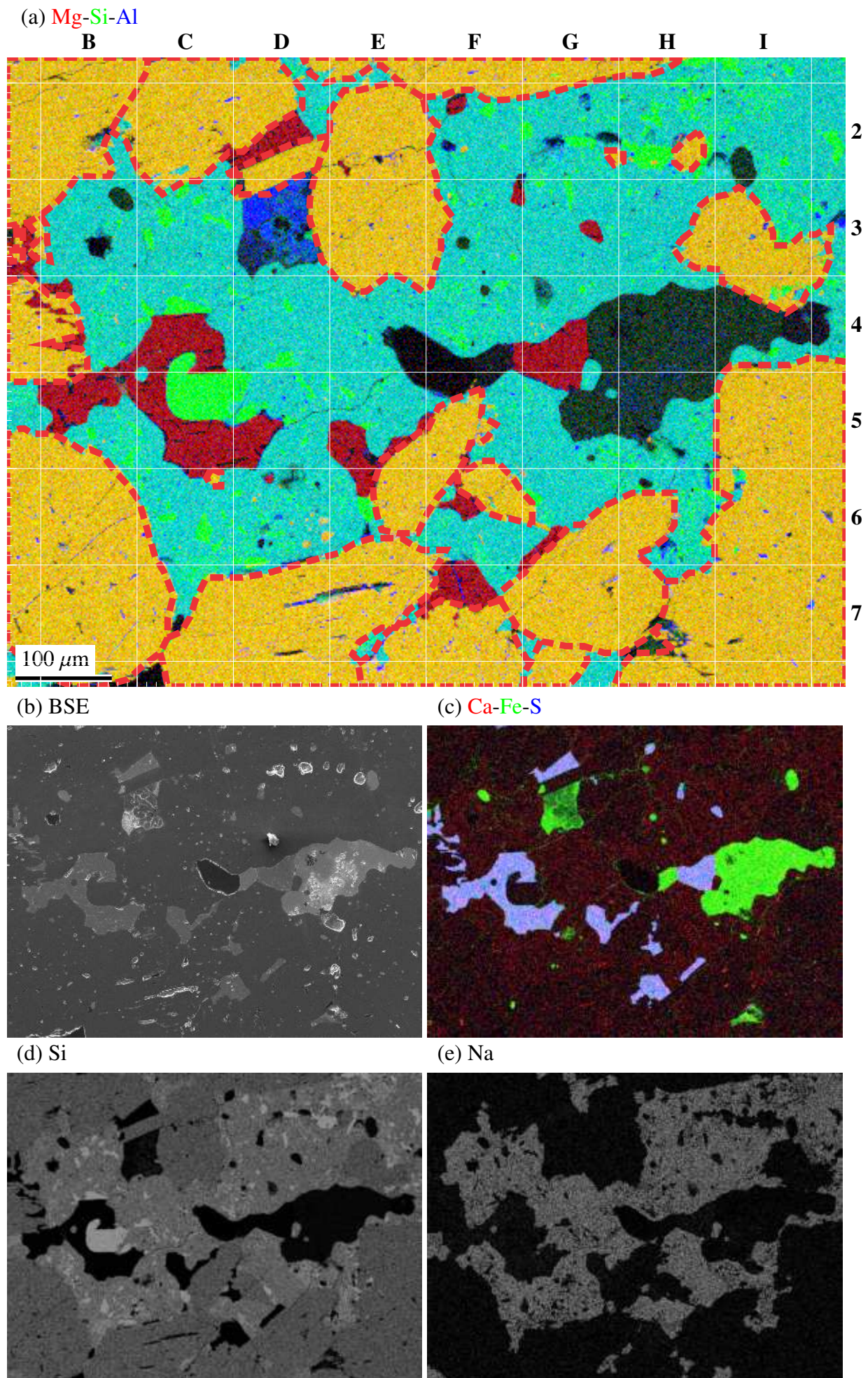


Figure 2.197: Site-29 of NWA8173b (En-rich-achon ung). (a) Mg:Si:Al image with low-Ca pyroxene bodies outlined, (b) BSE, (c) Ca:Fe:S image, and EDS maps of (d) Si, and (e) Na are shown. For phases, see Figure 2.169.

Chapter 3

The Li- and O-isotope composition of a Si-rich reservoir, estimated from the chondrule components of the Sahara 97103 (EH3)

3.1 Introduction

Enstatite chondrites have been proposed to be representative of the materials that accreted to form the Earth (Javoy, 1995; Javoy et al., 2010; Boyet et al., 2018). This is because the Earth and enstatite chondrites share isotopic similarities for many elements, including O, N, Ca, Ti, Cr, Ni, Mo, Ru, Os (Javoy et al., 1984; Clayton, 1993; Meisel et al., 1996; Dauphas et al., 2004; Trinquier et al., 2007, 2009; Regelous et al., 2008; Fischer-Gödde and Kleine, 2017; Huang and Jacobsen, 2017). Recently Dauphas (2017) proposed that enstatite-chondrite-type material represents at least 70% of the building blocks of the Earth. Clesi et al. (2016) proposed that the Earth could have been accreted from 85 to 90% of material similar to that of EH chondrites, based on the FeO content of Earth's present day mantle. Piani et al. (2020) also suggested that the Earth's water could have been inherited from enstatite chondrite-like material.

Enstatite chondrites are characterized by abundant metal, troilite (FeS) and oldhamite (CaS), with niningerite [(Mg,Fe,Mn)S] and alabandite (MnS) observed in EH and EL chondrites, respectively. Enstatite chondrites formed under a reduced environment, such as the protoplanetary disk close to the Sun (Rubie et al., 2015). Although most minerals in enstatite chondrites are reduced, some FeO-bearing pyroxene is also present (Weisberg et al., 1994). The O-isotope compositions of FeO-bearing pyroxenes

from unequilibrated enstatite chondrites (UEC) are similar to those of coexisting pure enstatite, this indicates that they formed in the same isotope reservoir, rather than migrating from the ordinary or carbonaceous chondrite forming regions (Kimura et al., 2003; Weisberg et al., 2011). Since FeO-bearing pyroxenes are enclosed by enstatite, they will have formed prior to enstatite in a more oxidized environment. This implies that the enstatite-chondrite-chondrule forming-region was originally more oxidizing, and/or the precursors of enstatite chondrules had chemical compositions similar to the precursors of the ordinary and carbonaceous chondrites (Weisberg et al., 2021). This is supported by Simon et al. (2016). In their study they determined the valence state of Ti in olivine and pyroxene grains in an array of ordinary and enstatite chondrites with petrological types ranging from 3 to 6 and concluded that enstatite chondrites formed from initially more oxidized precursors (Simon et al., 2016).

The Mg/Si ratios of enstatite chondrites differs from those of carbonaceous and ordinary chondrites. The Mg/Si ratio of enstatite chondrites is 0.73 and 0.88 for EH and EL respectively, while that of ordinary chondrites is 0.96, 0.93, and 0.94 for H, L, and LL, and that of carbonaceous chondrites is 1.07, 1.05, 1.10, and 1.06 for CI and CV, CM and CO, CK, and CH (Dauphas et al., 2015). Weisberg et al. (1994) suggested that the precursor material of enstatite chondrites was enriched in olivine, with a composition similar to an ordinary chondrite. To produce enstatite from these olivine-rich precursor chondrules, the Mg/Si ratios need to be reduced. Libourel et al. (2006) and Chaussidon et al. (2008) suggested that pyroxene in chondrules from carbonaceous chondrites formed by addition of Si to an olivine dominated precursor chondrule, through interaction between a Si-rich gas and chondrule melt.

O-isotope compositions of chondrules provide essential constraints on the physico-chemical conditions within the protoplanetary disk. These compositions can be used to gain an understanding of several different processes such as the nature of chondrule precursors, variations in the dust-to-gas ratio, and high-temperature interactions between gas and molten droplets. Chondrules preserve records of extensive thermal processing of early solar system materials, such as the CO-rich nebular gas, silicate dust, and H₂O ice (Tenner et al., 2018, references therein). The O-isotope composition of the precursors of the chondrules will most likely differ from each other and the modern chondrules. This will have contributed to variations in O-isotope compositions within and among the different chondrite groups. As one approach to understand the O-isotope composition of the gas, Marrocchi and Chaussidon (2015) and Tanaka and Nakamura (2017) estimated the O-isotope compositions of the initial gas in the carbonaceous-chondrite-chondrule forming-region and the enstatite-chondrite-chondrule-forming region respectively. The initial gas of the carbonaceous-chondrite-chondrule forming-region was determined to be ($\delta^{18}\text{O}$, $\delta^{17}\text{O}$)=(10‰, 9‰) (Marrocchi and Chaussidon, 2015) and the initial gas of the enstatite-chondrite-chondrule-forming region was determined to be (21‰, 20‰) (Tanaka and Nakamura, 2017). These values were estimated by employ-

ing a evaporation-driven gas-melt interaction model (Marrocchi and Chaussidon, 2015; Tanaka and Nakamura, 2017).

The difference in the O-isotope composition of the gas between the carbonaceous-chondrite-chondrule-forming region and the enstatite-chondrite-chondrule-forming region implies large-scale isotope heterogeneity in the gaseous reservoir across the solar nebula. The Si-rich gas could contain volatiles such as alkali elements including Li (Wai and Wasson, 1977). Based on their thermodynamic properties, an alkali element X exists as gaseous forms of X, X_2O , XO, and X_2SiO_3 (Nakasgawa et al., 1981). Thus, the isotope compositions of the alkali elements in chondrules could provide additional constraints for the characterization of the Si-rich gas that they interacted with. Maruyama et al. (2009) determined that the Li-isotope composition of olivine grains in the chondrules of the CV3 meteorite Allende varied from -32‰ to 21‰ . In addition to the chondrule olivines in Allende, Liu et al. (2023) also determined the Li-isotope compositions of olivines in the chondrules of the CO3 meteorite Yamato 81020, and the CM meteorite Asuka 12236. They determined that the $\delta^7\text{Li}$ olivines in CV3, CO3 and CM chondrules varied from -11‰ to 31‰ , from 6‰ to 16‰ , and from -20‰ to 10‰ , respectively (Liu et al., 2023). Kunihiro et al. (2019b) estimated the Li-isotope composition of a S-rich gas in the carbonaceous-chondrite-chondrule-forming region from the olivines and enstatites in the chondrules and corresponding igneous rims of the CV3 Allende. Their results showed that the Li-isotope composition of the Si-rich gas in the carbonaceous-chondrite-chondrule-forming region during igneous rim formation was determined to be $\delta^7\text{Li} = -11\text{‰}$ (Kunihiro et al., 2019b).

Seitz et al. (2007); Pogge von Strandmann et al. (2011) determined that the Li-isotope composition of the bulk enstatite chondrites. The mean $\delta^7\text{Li}$, calculated from these compositions, was $1.9\text{‰} \pm 1.5\text{‰}$ (2σ , Tomascak et al., 2016). These values differ significantly from those of the Earth, which were determined to range 3.2‰ to 3.5‰ (Seitz et al., 2007; Magna et al., 2015). This makes it difficult to say for certain that enstatite chondrites are the major building blocks of Earth. Compared with whole enstatite chondrites, the enstatite chondrules are generally depleted in volatile elements including Na, K, and Cs (Grossman and Wasson, 1985). This is also true for ordinary and carbonaceous chondrules (Hewins, 1997), and are interpreted to be due to open-system melting. Nevertheless, Li-isotope heterogeneity is maintained in the olivine grains of these chondrules (Chaussidon and Robert, 1998; Nakamura et al., 2019; Kunihiro et al., 2019b; Liu et al., 2023). Low-Ca pyroxene incorporates Li via $(\text{Li}, \text{R}^{3+})/\text{Si}$ exchange in tetrahedrally coordinated sites and/or $(\text{Li}, \text{R}^{3+})/(\text{Mg}, \text{Fe})$ exchange in the M1 sites (van Kan Parker et al., 2010). Thus, the Li-isotope composition may provide insights into the reservoir that was involved in the formation of enstatite-chondrite chondrules.

In this study, the Li-isotope composition of the Si-rich gas in the enstatite-chondrite-chondrule-forming region is estimated in order to evaluate Li-isotope heterogeneity across the solar nebula. Since enstatite may have been produced by the interactions

between an SiO_2 component, provided by the gas in the melt and an olivine component in the melt, the Li-isotope compositions of enstatite and olivine will be determined. The O-isotope composition of olivines are also determined to evaluate if the olivine is relict, and should have thus reacted with SiO_2 provided by the Si-rich gas.

3.2 Experimental

3.2.1 Sample description

Six chondrules and aggregates of chondrule fragments, were selected from a thin section 20150515144722-631984 of the Sahara 97103 EH3 chondrite. This chondrite was chosen because the O-isotope composition of the whole rock chondrite, whole chondrules, and aggregates of enstatite were determined previously by Tanaka and Nakamura (2017). Weisberg et al. (2011) and Jacquet et al. (2015) have analyzed chondrules from Sahara 97096, which is paired with Sahara 97103.

The chondrules and chondrule-fragment aggregates are categorized into objects without major olivine (I6p and D6a) and with major olivine (D3g, J5l, C5b, and K4). The two aggregates (D6a and K4) are composed of two separate fragments each. Each fragment (D6a-0, D6a-1, K4-0, and K4-1) is treated separately.

3.2.2 Major-element composition

The major-element compositions of low-Ca pyroxene, olivine, glass, and silica were determined using the JEOL JXA-8530F electron-probe microanalyzer (EPMA) in wavelength dispersive mode. Analyses were conducted using an electron beam with a 15 kV acceleration voltage and a 12 nA beam current. Quantitative analyses were corrected by the oxide ZAF method, and calibrated using silicate, sulfide, oxide, and synthetic oxide minerals, assembled on a standard ASTIMEX, MINM25-53+FC mount, from Astimex Standards Ltd., Canada.

When the major-element composition of the spot by trace-element, O-isotope, and Li-isotope analysis was not determined in advance by EPMA, a JEOL JSM-7001F scanning electron microscope (SEM) equipped with an EDS (energy dispersive X-ray spectrometer) and Oxford Aztec X-Max was used to determine the major-element composition. The accelerating voltage was set to 15 kV, with the primary beam current set to 3 nA, and an integration time of 50 s. The composition was normalized so that the total was 100%.

For the major-element analyses of glass, SEM images were used to accurately probe areas of the glass that lacked micro-crystals. For areas that contained a large number of micro-crystals, the glass was probed twice, avoiding the micro-crystals. These areas

were then checked to see if the major-element compositions were consistent. The trace-element, O-isotope, and Li-isotope analyses were conducted on the areas of the glass that lacked micro-crystals.

The trace-element, O-isotope, and Li-isotope measurements were carried out as close to each other as was viable. However, in some cases spot locations differed by 30 μm . The craters after trace-element, O-isotope, and Li-isotope analyses were observed using the SEM. Each spot was checked for holes, fractures, inclusions, and to ensure the intended target had been probed. All the locations of the trace-element, O-isotope, and Li-isotope analyses are shown in Figures 3.21-3.26.

The polymorph of the silica phase in the chondrules was determined by micro-Raman spectroscopy using a Thermo Scientific DXR. The system was outfitted with a 523 nm Nd-YVO₄ laser and a confocal optical microscope. The laser system was equipped with a 1800 lines/mm grating that covered the wavenumber range of 50–1800 cm^{-1} . Each Raman spectrum was collected using 10 mW of power. The estimated spatial resolution was 0.7 μm and the estimated spectral resolution was 3.2 to 3.9 cm^{-1} .

3.2.3 Trace-element composition

The trace-element compositions of Li, Sr, Y, Zr, Nb, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Hf, and Pb were determined by secondary ion mass spectrometry (SIMS), using a Cameca ims-1280 at the Pheasant Memorial Laboratory (PML) using a procedure similar to that described in Kunihiro et al. (2021). The thin section was coated in 75 nm of Au in order to prevent charging of the sample surface. The elemental abundances were estimated from the ion intensities, by measuring the yields of metal and oxide ions, relative to reference isotopes $^{30}\text{Si}^+$, $^{24}\text{Mg}^+$ and $^{40}\text{Ca}^+$, and the concentration of Si, Mg, and Ca. The primary impact voltage was –23 keV, with the secondary voltage being 10 kV and the energy offset was set to –45 eV. The energy band-pass was set from –10 to 40 eV. The entrance slit width and the contrast aperture dimension were both set to 400 μm . The field aperture dimension was set to 5000 $\times$ 5000 μm^2 . The exit slit width was set to 1200 μm . The background monitor examined each cycle at mass 5.7.

The metal and oxide yields of silicates were estimated by analyses on a suite of five reference materials (two glasses, plagioclase, low-Ca pyroxene, and high-Ca pyroxene), assuming that the metal and oxide yields were equal for all matrices analyzed, the isobaric interferences were dominated by the oxides, and the concentration range was immaterial. The metal yield of sulfide is assumed to be identical to that of silicates and the oxide yield of sulfide is zero.

3.2.4 Oxygen-isotope composition

The O-isotope compositions of low-Ca pyroxene, olivine, glass, and silica were determined by SIMS with the Cameca ims-1280, using a procedure similar to that described in Kunihiro et al. (2019b). The isotope compositions of low-Ca pyroxene, olivine, glass, and silica were determined relative to the working standards: ref-opx-tz1001 (low-Ca pyroxene), ref-ol-sc (olivine), ref-gl-ab100 (glass), and ref-qtz-NBS28 (quartz). The matrix effect of the glass relative to ref-gl-ab100 was estimated by analyses on a series of glasses that varied in their albite component. The matrix effect relative to ref-gl-ab100 was estimated as a function of Na as, $\Delta\delta^{18}\text{O}^{\text{mtx}} = -5.42\text{‰} \times X_{\text{Na}} + 5.42\text{‰}$, where X_{Na} corresponds to albite components that vary from 0 to 1. The matrix effect of silica relative to ref-qtz-NBS28 was estimated by analysis of ref-crs-sj1 (cristobalite) and ref-qtz-NBS28 and was $\Delta\delta^{18}\text{O}^{\text{mtx}} = -0.24\text{‰}$. We found that the matrix effects were mass-dependent. Thus we calculated the matrix effects for $\delta^{17}\text{O}$ from that of $\delta^{18}\text{O}$ ($\Delta\delta^{17}\text{O}^{\text{mtx}} = 0.52 \times \Delta\delta^{18}\text{O}^{\text{mtx}}$) and no correction was applied for $\Delta^{17}\text{O}$.

A Cs^+ primary beam (100 pA) of 20 keV for a scanned area of $5 \times 5 \mu\text{m}^2$, yielded a typical crater of $6 \times 6 \mu\text{m}^2$. Secondary O^- was accelerated to -10 kV and a normal incident electron gun was used to compensate positive charging on the sputtered area. To minimize the generation of $^{16}\text{OH}^-$ secondary ions, a pressure of less than 1.5×10^{-9} Torr was maintained in the specimen chamber using a cold trap filled with liquid nitrogen. A contrast aperture of $400 \mu\text{m}$ was used. The width of the entrance was set to $60 \mu\text{m}$. An optical gate of $3000 \times 3000 \mu\text{m}^2$, corresponding to $23 \times 23 \mu\text{m}^2$ on the surface of the sample, was inserted and an energy bandpass was set from -10 to 40 eV. The mass-resolution was set to 7000 for $^{17}\text{O}^-$ and 2400 for $^{16}\text{O}^-$ and $^{18}\text{O}^-$. The contribution of $^{16}\text{OH}^-$ to the $^{17}\text{O}^-$ signal was estimated and corrected as follows: by scanning the low-mass side of the $^{16}\text{O}^-$ peak, the ratio of the counts of the low-mass tail to the counts of the peak was estimated. At the end of each analysis, the $^{16}\text{OH}^-$ signal was measured automatically by deflecting the beam into an axial EM using the DSP2-X deflector. The contribution of the hydride tail to the $^{17}\text{O}^-$ signal was estimated based on the established ratio and a correction was applied (less than 0.1‰). The pre-sputtering time was 190 s, included auto peak-centering. Signal intensities were simultaneously determined by a Faraday cup mounted on trolley L2 ($^{16}\text{O}^-$) and pulse counting with electron multipliers located on axial ($^{17}\text{O}^-$) and trolley H1 ($^{18}\text{O}^-$). Typical ion intensities for $^{16}\text{O}^-$, $^{17}\text{O}^-$, and $^{18}\text{O}^-$ were 50 M, 20 k, and 100 k cps, respectively. The ion-integration times were 14.5 seconds in each cycle, with each run consisting of 40 cycles. The typical external precision was estimated by repeating the analyses of a working standard, and was found to be 0.3‰ (1σ) for both $\delta^{18}\text{O}$ and $\delta^{17}\text{O}$.

3.2.5 Lithium-isotope composition

The lithium-isotope compositions of enstatite, olivine, and glass were determined by SIMS with the Cameca ims-1280 using a procedure similar to that described in Kunihiro et al. (2019b).

The isotope compositions of enstatite, olivine, and glass were determined relative to the working standards: ref-en-sl1 (enstatite), ref-ol-sc (olivine), and ref-ol-sc, respectively. The matrix effect of the glass was estimated using ref-pl-byt (plagioclase) relative to ref-ol-sc. No correction was applied to the the glass in order to account for matrix effect as the matrix effect of ref-pl-byt was determined to be negligible and was within or comparable to analytical reproducibilities for the working standard. A previous study inferred that depending upon the FeO content in olivine, there was a significant matrix effect on the olivine grains (Bell et al., 2009). Thus the matrix effect on olivines in this study was estimated as a function of the Mg/(Mg+Fe) ratio, relative to ref-ol-sc ($\frac{\text{Mg}}{\text{Mg}+\text{Fe}} = 0.91$) to be $\Delta\delta^7\text{Li} = -6.82 \times (\frac{\text{Mg}}{\text{Mg}+\text{Fe}} - 0.91)\text{‰}$. The Mg/(Mg+Fe) ratio of olivine ranges from 0.983 to 0.997. Therefore, the matrix effect was estimated to be from -0.5‰ to -0.6‰ . This is consistent to or lower than the analytical uncertainty, thus no corrections were required.

The primary O^- ion beam was accelerated to -23 keV with the beam current ranging from 1 to 10 nA in order to maintain the secondary ion intensity. A contrast aperture of $400\text{ }\mu\text{m}$ was used and an optical gate of $3000 \times 3000\text{ }\mu\text{m}^2$, which corresponds to $23 \times 23\text{ }\mu\text{m}^2$ on the sample surface, was inserted. An energy bandpass was set from -10 to 40 eV. The width of the entrance and exit slits were set to 200 and $1000\text{ }\mu\text{m}$, respectively. The intensity ratios of $^6\text{Li}^+$ and $^7\text{Li}^+$ were determined by axial EM with peak jump. The integration time for ions were 4 s (for $^6\text{Li}^+$) and 1 s (for $^7\text{Li}^+$) in each cycle, with each run comprised of 77 cycles.

Trace-element analysis was used to determine the Li concentration the spots, with the Li concentration of some exceptions were determined using $^7\text{Li}^+$ value and the primary ion-probe current ($^7\text{Li}^+/I_{\text{pri}}$). In these cases it was assumed that the ion intensity was proportional to concentration.

3.3 Results

3.3.1 Petrography

BSE images and Mg-Si-Al element maps of the six studied EH3 chondrules are shown in Figures 3.1 and 3.2. Representative major-element compositions of low-Ca pyroxene, olivine, and glass are shown in Table 3.1. The Mg/(Mg+Fe) ratio of low-Ca pyroxene and olivine is shown in Figure 3.3. Chondrules I6p, D3g, and J5l are olivine-bearing chondrules. Their olivine abundances are significantly less compared to the abundances

of low-Ca pyroxene in the same chondrule. A ‘typical range’ in the $\text{Mg}/(\text{Mg}+\text{Fe})$ ratio of low-Ca pyroxene and olivine is defined from these chondrules. The ranges are $\text{En } 98.6 \pm 0.54$ (2σ) and $\text{Fo } 99.3 \pm 0.46$ (2σ) for the low-Ca pyroxenes and olivines respectively. Figure 3.4 shows the variations in the major-element compositions of the glasses in the chondrules.

I6p (Figures 3.1a, 3.2a) is a rounded porphyritic pyroxene (PP) chondrule. It is the smallest chondrule like object examined in this study, with a diameter of $360 \mu\text{m}$. Two enstatite grains (yellow area in Figure 3.2a) dominate most of the chondrule. The larger grain (220 by $280 \mu\text{m}$) is subhedral and located in the bottom right of the chondrule. A $10\text{-}\mu\text{m}$ -sized crescent-shaped olivine is enclosed by this enstatite. The smaller euhedral grain (120 by $120 \mu\text{m}$) is located in the bottom left of the chondrule. Mesostasis (60 by $360 \mu\text{m}$) consisting primarily of glass and silica (band of $10 \mu\text{m}$ in width and $100 \mu\text{m}$ in length, green area in Figure 3.2a) dominated the top of the chondrule. Also contained in the mesostasis is enstatite ($5 \mu\text{m}$ to $30 \mu\text{m}$ in size), high-Ca pyroxene (HPx) and FeS (dark area in Figure 3.2a). A CaS and FeS aggregate ($30 \mu\text{m}$ in size, dark area in Figure 3.2a) is present between the two enstatite grains and the mesostasis. The silica was identified as cristobalite using Raman spectroscopy. At the bottom edge of the chondrule is an aggregate of FeS and Fe,Ni metal.

The $\text{Mg}/(\text{Mg}+\text{Fe})$ ratio of the enstatite in I6p was determined to be 98.7 . This is within the typical range for enstatites examined in this study (Figure 3.3). The glass was determined to be Na-enriched with a composition that varies from $\text{An}_{1.3}\text{Ab}_{90.4}\text{Or}_{8.3}$ to $\text{An}_{0.3}\text{Ab}_{97.4}\text{Or}_{2.3}$ (Figure 3.4).

D6a (Figures 3.1b, 3.2b) is an elongated aggregate (470 by $2000 \mu\text{m}$) comprised of two PP chondrule fragments in contact with each other. It represents the second largest object examined in this study. Both chondrule fragments are characterised by a lack of olivine. The bottom left PP fragment (430 by $470 \mu\text{m}$) is referred to as D6a-0. Low-Ca pyroxene (from 5 to $90 \mu\text{m}$) is the dominate phase, with abundant FeS and Fe,Ni-metal along with inter-filling mesostasis. The mesostasis is comprised of Na-rich glass, Fe,Ni-metal ($20 \mu\text{m}$), MgS, and FeS (from 5 to $70 \mu\text{m}$). The $\text{Mg}/(\text{Mg}+\text{Fe})$ ratio of D6a-0 low-Ca pyroxenes varies from 90.6 to 98.2 . Two low-Ca pyroxene grains ($50 \mu\text{m}$) enclosing cristobalite at the bottom of the chondrule fragment were determined to have $\text{Mg}/(\text{Mg}+\text{Fe})$ ratios of 90.6 and 92.8 . These grains were identified as FeO-rich pyroxenes based on the definition suggested by Kimura et al. (2003). Close to the boundary between the two chondrule fragments is a low-Ca pyroxene grain with a composition of $\text{En } 96.5$. This is similar to the compositions of the low-Ca pyroxenes in the upper fragment. The composition of the glass in D6a-0 ranges from $\text{An}_{9.8}\text{Ab}_{77.5}\text{Or}_{12.7}$ to $\text{An}_{0.0}\text{Ab}_{98.5}\text{Or}_{1.5}$.

The top right PP chondrule fragment is referred to as D6a-1. It is 680 by $1360 \mu\text{m}$ and characterised by abundant cristobalite. The core is dominated by Euhedral enstatite grains (5 to $100 \mu\text{m}$), while the enstatites in the rim domain at the top and right side of

the chondrule are elongated bars with widths that vary from 50 to 100 μm . Inter-filling between the enstatites is abundant mesostasis comprised of cristobalite (5 to 80 μm), Na-rich glass, and FeS (3 to 30 μm). No metal was observed in this fragment. The Mg/(Mg+Fe) ratio of the D6a-1 enstatites varies from 96.3 to 97.2 with an average of 96.8 (0.1 1σ). This average is lower than the typical ratio but the variation is consistent with the typical ratio variation.

D3g (Figures 3.1c, 3.2c) is a rounded porphyritic olivine-pyroxene (POP) chondrule with a diameter of 420 μm . It is separated into a core and rim domain. The core is dominated by an aggregate of olivine grains ranging from 10 to 50 μm , with enstatite and glass inclusions contained within the olivine. The rim is dominated by euhedral enstatite grains that vary from 30 to 170 μm . The mesostasis in the rim is comprised of Na-rich glass, minor high-Ca pyroxene (<5 μm), cristobalite (5 to 30 μm), FeS (5 to 10 μm), and Fe,Ni-metal (5 μm). The olivine Mg/(Mg+Fe) ratio was determined to range from 99.3 to 100.0 with an average of 99.6 (0.2 1σ). Most of the olivines grains exhibit compositions that are within the typical range. The Mg/(Mg+Fe) ratio of enstatite varies from 97.3 to 99.0, with most of the ratios falling within the typical range. An enstatite grain with a composition of En 97.4 (lower than the typical range) in the top left of the chondrule encloses cristobalite and is surrounded by FeS and metal. The glass composition varies from $\text{An}_{46.2}\text{Ab}_{53.8}\text{Or}_{0.0}$ to $\text{An}_0\text{Ab}_{97.7}\text{Or}_{2.3}$. The rim domain glass is Na-enriched relative to the glass in the core domain which is Ca-enriched.

J5l (Figures 3.1d, 3.2d) is an irregularly shaped POP chondrule with a diameter of 560 μm . The core is dominated by a subhedral olivine (170 to 200 μm), surrounded by a shell of enstatite grains (35 to 170 μm). Contained in the olivine is minor MgS (5 to 10 μm). Enclosed by the enstatites are anhedral olivine grains (10 to 30 μm). Inter-filling between the enstatite grains is mesostasis comprised of Na-rich glass, high-Ca pyroxene (5 μm), FeS (5 to 50 μm), and cristobalite (5 μm). Minor MgS (5 to 50 μm) in the lower right of the chondrule is observed with an aggregate of FeS and metal between enstatite grains. The Mg/(Mg+Fe) ratio of the olivine is 99.3 ± 0.1 (1σ). This is within the typical range. The Mg/(Mg+Fe) ratio of enstatite varies from 98.3 to 98.9 and it is within the typical range. The composition of the glass varies from $\text{An}_{41.3}\text{Ab}_{57.5}\text{Or}_{1.2}$ to $\text{An}_{1.1}\text{Ab}_{93.9}\text{Or}_{5.0}$.

C5b (Figures 3.1e, 3.2e) is a rounded POP chondrule with a diameter of 800 μm . An aggregate of olivine grains (400 μm in size) is located in the bottom right of the chondrule. Anhedral olivine grains (10 to 40 μm), that are poikilitically surrounded by euhedral enstatite are located in the top, left, and bottom of the chondrule. The size of the enstatite varies from 10 to 30 μm . The mesostasis that inter-fills between the enstatite grains consists of Na-rich glass, high-Ca pyroxene (from 1 to 5 μm in size), cristobalite (5 μm in size), FeS (5 to 20 μm in size), and CaS (5 μm in size). No Fe,Ni-metal was observed in this chondrule. An aggregate of enstatite that is 100 by 500 μm in size, and which is located above the largest olivine aggregate, includes CaS between the

enstatite grains. The $\text{Mg}/(\text{Mg}+\text{Fe})$ ratio of the olivine varies from 98.8 to 99.7 (average and 1σ are 99.2 and 0.1) and is consistent with the typical range. The $\text{Mg}/(\text{Mg}+\text{Fe})$ ratio of enstatite varies from 98.1 to 99.9 (average and 1σ are 98.6 and 0.13). Two enstatite grains located in the aggregate of enstatite with CaS, show En 99.8 and 99.9, which are higher than the typical range. The composition of glass varies from $\text{An}_{39.0}\text{Ab}_{59.1}\text{Or}_{1.9}$ to $\text{An}_{0.3}\text{Ab}_{98.6}\text{Or}_{1.1}$. The glass in the rim is enriched in Ab, while that in the core is enriched in An.

K4 (Figures 3.1f, 3.2f) is a rounded aggregate with two lithologies. It is the largest among the studied objects. The aggregate is divided into two chondrules. The inner domain and outer domain are referred to here as K4-0 and K4-1. The shape of K4-0 is irregular and its diameter is $1000\ \mu\text{m}$. It is dominated by enstatite (30 to $170\ \mu\text{m}$ in size). This chondrule is characterized by abundant MgS. Anhedral olivine occurs inside of the enstatite in the right of the chondrule (15 to $200\ \mu\text{m}$ in size). The mesostasis consists of K-rich glass, Na-rich glass, high-Ca pyroxene ($5\ \mu\text{m}$ in size), MgS (5 to $60\ \mu\text{m}$ in size), and FeS (5 to $100\ \mu\text{m}$ in size). MgS occurs within enstatite grains throughout the whole area, especially towards the right, but also towards the top right of the area. No Fe,Ni-metal is observed. A $30\text{-}\mu\text{m}$ -sized silica grain (phase unsuccessfully determined) is located to the top of the chondrule. The $\text{Mg}/(\text{Mg}+\text{Fe})$ ratio of an olivine in K4-0 is 99.5. This is within the typical range. The $\text{Mg}/(\text{Mg}+\text{Fe})$ ratio of the enstatite in K4-0 varies from En 98.2 to 100.0 (average and 1σ are 99.1 and 0.8). The enstatite forms two clusters (see Figure 3.3). The lower cluster is within the typical range, while the higher cluster falls outside of the range. The composition of the K-rich glass varies from $\text{An}_{0.0}\text{Ab}_{68.9}\text{Or}_{31.1}$ to $\text{An}_{0.0}\text{Ab}_{37.2}\text{Or}_{62.8}$. The composition of the Na-rich glass varies from $\text{An}_{48.6}\text{Ab}_{49.0}\text{Or}_{2.4}$ to $\text{An}_{44.1}\text{Ab}_{54.4}\text{Or}_{1.5}$. K4-1 is a POP chondrule. The diameter of K4-1 is $1500\ \mu\text{m}$. It is dominated by enstatite (45 to $240\ \mu\text{m}$ in size). Two occurrences of olivine grains (15 to $186\ \mu\text{m}$ in size) are observed (see also Figure 3.10bc). An euhedral olivine occurs in the mesostasis surrounded by glass. An euhedral olivine shown in Figure 3.10bc encloses glass, forming an inclusion. Other anhedral olivines are enclosed in enstatite. Mesostasis inter-fills the olivines and the enstatites. It consists of Na-rich glass, high-Ca pyroxene ($5\ \mu\text{m}$), FeS (5 to $60\ \mu\text{m}$ in size), and aggregates of FeS and Fe,Ni-metal. The $\text{Mg}/(\text{Mg}+\text{Fe})$ ratio of anhedral olivine varies from 98.6 to 99.3 (the average and 1σ are 99.2 and 0.1) and euhedral olivine varies from 98.3 to 99.3 (the average and 1σ are 98.8 and 0.2). Their averages are within the typical range, but some of the $\text{Mg}/(\text{Mg}+\text{Fe})$ ratios are smaller than the typical range. The $\text{Mg}/(\text{Mg}+\text{Fe})$ ratio of enstatite in K4-1 varies from 97.7 to 98.4 (average and 1σ are 98.3 and 0.1). Besides one spot (En 97.7), the $\text{Mg}/(\text{Mg}+\text{Fe})$ ratio is consistent with the typical range. The composition of the Na-rich glass varies from $\text{An}_{61.1}\text{Ab}_{38.2}\text{Or}_{0.7}$ to $\text{An}_{8.9}\text{Ab}_{86.5}\text{Or}_{4.6}$.

3.3.2 Trace-element composition

Trace-element compositions of chondrule constituents are shown in Figures 3.5 (REE) and 3.15 (all trace elements), and Table 3.5. In this section, oldhamite bearing chondrules are indicated with the symbol †.

Two phases with abundant REE are oldhamite and glass. Oldhamite grains occur in †I6p, †C5b, and †K4-0, and those in †I6p and †C5b were probed. The REE concentration of oldhamite plots in the range between $1\times\text{CI}$ and $20\times\text{CI}$, forming negative slopes. In the REE pattern of oldhamite in †C5b, there are positive peaks in Eu and Yb. Meanwhile, in the REE pattern of oldhamite in †I6p, there is a negative peak for Eu and a positive peak for Yb. The REE concentration of oldhamite in †C5b extends the lower limit of the oldhamites observed in EH3 (Figure 3.5f). The REE concentration of glass plots in the range between $1\times\text{CI}$ and $10\times\text{CI}$, forming a positive slope or a slope of zero. The REE pattern of glass is with or without negative peaks in Sm, Eu, and Yb. Ninningerite grains were probed in D6a-0, †C5b, and †K4-0. The REE concentration plots in the range between $0.01\times\text{CI}$ and $1\times\text{CI}$, forming positive slopes.

The chondrules were classified into two groups (S and F). Group S (after spikes) is defined by the existence of negative Eu and Yb peaks in the glass or enstatite (†I6p, D6a-1, D6a-0, D3g, and †C5b; Figure 3.5a,b,c,d,g). Group F (after flat) is defined by a lack of negative Eu and Yb peaks in the glass or enstatite (J5l, K4-1, and †K4-0; Figure 3.5e,h,i).

In group S, the REE patterns of the glass in †I6p and D6a-1 have a positive slope. The glass in †C5b has a flat REE pattern. The LREE of the glass in D3g shows a positive slope. The REE patterns of glass in †I6p, D3g, and †C5b are depleted not only in Eu and Yb, but also in Sm. The REE concentration of enstatite plots in the range between $0.1\times\text{CI}$ and $1\times\text{CI}$, and the REE pattern forms a positive slope. The REE pattern of olivine in D3g is similar to that of enstatite, and there are negative peaks in Eu and Yb. In †C5b, the REE concentration of olivine is ten times lower than that in enstatite. Cristobalite was only probed in D6a-1. The REE concentration of the cristobalite plots around the $1\times\text{CI}$ with a negative slope and negative Eu peak.

In group F, the glass is characterized by a flat REE pattern. In the REE pattern of enstatite there are positive slopes, as observed in Group S. The REE concentration of the enstatite grains plots in the range between $0.01\times\text{CI}$ and $1\times\text{CI}$. The REE pattern of olivine in J5l is similar to that of enstatite, with an abundance slightly lower than that of enstatite. The REE pattern of the olivine in K4-1 is flat. The REE concentration of euhedral olivine is lower than that of anhedral olivine. The REE concentrations of the enstatite and K-rich glass in †K4-0 plot in the range between $0.01\times\text{CI}$ and $1\times\text{CI}$, forming a positive slope, which is consistent with ninningerite.

3.3.3 Estimated REE composition of chondrule melt

The trace-element composition of the olivine- and enstatite-rich melts (Table 3.6 and Figures 3.16 and 3.17) were estimated from the trace-element compositions of the olivines and enstatites of the chondrules, and the olivine-melt and enstatite-melt coefficients determined by previous studies (Table 3.7).

In I6p the melt estimated from the low-Ca pyroxene ($melt_{lpx}$) exhibit negative slopes, indicating that they are LREE enriched. This differs significantly from the REE pattern of the glass and enstatite in I6p. Concentration of the LREE is similar to that of the CaS. It ranges from 10X to 100x larger than the CI value. With the exception of Ho, most of the REE exhibit larger concentrations compared to the glass, and all REE exhibit larger concentrations compared to the enstatite. Both Eu and Yb were observed to be depleted relative to the other REE. This correlates with the depleted Eu and Yb in the glass and enstatite. Nb is also depleted and has a similar concentration to the Nb in the CaS and low-Ca pyroxene. However, this is not the case for the Nb in the glass.

There is no significant difference between the $melt_{lpx}$ compositions in D6a-0 and D6a-1. Both have negative slopes and are enriched in LREE. Compared to the LREE, the HREE have a flatter pattern. The $melt_{lpx}$ in D6a-0 and D6a-1 ranges from 10X to 100x larger than the CI value. In D6a-1, the HREE pattern of the $melt_{lpx}$ is similar to that of the glass, but their respective LREE patterns deviate from each other. The melt in both D6a-0 and D6a-1 is depleted in Yb, but Eu is not depleted or enriched. Depleted Yb in the $melt_{lpx}$ in D6a-1 correlated with the glass and the enstatite. Nb and Li are both depleted, but Hf and Ho are enriched. The cristobalite deviates significantly from the pattern of the melt.

In D3g the melt estimated from the olivine ($melt_{ol}$) exhibits a steep negative slope, but the $melt_{lpx}$ exhibits a shallow negative slope. Both are LREE enriched but the $melt_{ol}$ is heavily enriched in LREE compared to the $melt_{lpx}$. However, there is no significant difference between the two melts for the concentrations of most of the HREE. The $melt_{ol}$ ranges from 10x to >3000x larger than the CI value. The $melt_{lpx}$ ranges from 10x to 100x the CI value. Both melts are depleted in Sm, Eu, and Yb. This correlates with glass, low-Ca pyroxene, and olivine. The $melt_{lpx}$ is significantly depleted Nb and slightly enriched Hf. However, the $melt_{ol}$ slightly depleted Ba and Nb, and significantly depleted Li.

In J5l the $melt_{ol}$ exhibits a steep negative slope, but the $melt_{lpx}$ exhibits a shallow negative slope. The $melt_{ol}$ is enriched in LREE relative to the $melt_{lpx}$. However, both melts exhibit similar HREE concentrations. The $melt_{ol}$ ranges from 10x to >3000x larger than the CI value. The $melt_{lpx}$ ranges from 10x to 100x the CI value. Both melts are enriched in Eu, this correlated with the olivine and low-Ca pyroxene. The $melt_{ol}$ is not depleted or enriched in Yb, but the Yb in the $melt_{lpx}$ is depleted in Yb. These correlate with the olivine and low-Ca pyroxene respectively. Both melts are depleted in Sm. The $melt_{lpx}$ is heavily depleted in Nb, enriched in Zr, Hf and slightly enriched in

Li. The $melt_{ol}$ is depleted in Li, this differs from the olivines which are enriched in Li.

In C5b the $melt_{ol}$ exhibits a steep negative slope, but the $melt_{lpx}$ exhibits a shallower negative slope which is steeper than the $melt_{lpx}$ in the other chondrules. The $melt_{lpx}$ in C5b is LREE enriched compared to the $melt_{lpx}$ of the other chondrules. The $melt_{ol}$ ranges from 10x to >3000x larger than the CI value. The $melt_{lpx}$ ranges from 10x to 100x the CI value. The $melt_{ol}$ is enriched in LREE compared to the $melt_{lpx}$. Most of the HREE in the $melt_{ol}$ exhibit slightly smaller concentrations compared to the $melt_{lpx}$. The $melt_{ol}$ is enriched in La, slightly depleted in Sm and Eu while Yb is not depleted or enriched and Li is depleted. Whereas in the $melt_{lpx}$ La is not enriched or depleted, Sm is slightly enriched, Eu, Yb, and Li are not enriched or depleted. This differs from the glass which is depleted in Eu and Yb, this correlates with the CaS.

In K4-0, only $melt_{lpx}$ was present. Compared to the previous chondrules, the $melt_{lpx}$ pattern is fairly flat, though the LREE have larger concentrations compared to the HREE. The $melt_{lpx}$ is enriched Eu and depleted Yb, with Sm neither enriched or depleted. Ce is slightly depleted and Ho is slightly enriched $melt_{lpx}$. The $melt_{lpx}$ concentration ranges from 10x to 50x the CI value.

In K4-1 the compositions for both the melt estimated from the anhedral olivine ($melt_{ol}$), the melt estimated from euhedral olivine ($melt_{euhedral-ol}$), and the melt estimated from euhedral olivine ($melt_{lpx}$). The $melt_{euhedral-ol}$ and $melt_{ol}$ range from 10x to >3000x larger than the CI value. The $melt_{lpx}$ ranges from 10x to 100x the CI value. Both $melt_{euhedral-ol}$ and $melt_{ol}$ are negatively sloped whereas the $melt_{lpx}$ has a flat pattern. All three melts have larger LREE concentrations compared to HREE concentrations. The LREE concentrations are larger in the $melt_{ol}$ compared to the low-Ca pyroxene-rich melt. The $melt_{ol}$ has larger LREE compositions compared to $melt_{euhedral-ol}$. The HREE in all three melts have similar concentrations to each other and the glass. The $melt_{ol}$ is depleted in Sm, not enriched or depleted in Eu and Yb, whereas the $melt_{euhedral-ol}$ and $melt_{lpx}$ are not enriched or depleted in Sm, enriched in Eu and depleted in Yb. Both $melt_{ol}$ and $melt_{euhedral-ol}$ are depleted in Li, but the $melt_{lpx}$ not depleted or enriched in Li.

3.3.4 Oxygen-isotope composition

All individual analyses are shown in Figure 3.6 and Table 3.4. The O-isotope compositions for each chondrule are summarized in Table 3.2. The O-isotope compositions of chondrule constituents (the average and range of each phase) are shown by individual chondrules in Figure 3.7, together with whole chondrites and whole chondrules (Clayton et al., 1984; Tanaka and Nakamura, 2017; Weisberg et al., 2021). All individual analyses within an individual chondrule are shown in Figure 3.18. While whole enstatite-chondrites plot along the terrestrial fractionation (TF) line (e.g., Weisberg and Kimura, 2012, Figure 3.7f), the majority of the values for enstatite and olivine plot along the PCM line (Ushikubo et al., 2012), with most data clustering at the intersection of

the PCM and TF lines (Figure 3.6).

Most of the chondrules show variation within and among phases (Figure 3.7) similar to Weisberg et al. (2021), with the exception of ALH 81189 C1 and ALH 85159 C51. The O-isotope composition of enstatites, with the exception of J51, plot on the intersection of the PCM and TF lines, showing variation from 0.5‰ to 3‰ in $\delta^{18}\text{O}$. The mean $\Delta^{17}\text{O}$ of enstatites, with the exception of J51, is $0.1\text{‰} \pm 0.27\text{‰}$ (1σ). The mean $\Delta^{17}\text{O}$ of J51 is 1.2‰ higher than that of the others. Two FeO-rich pyroxenes were analyzed in D6a-0. Their O-isotope compositions are indistinguishable from those of other enstatite grains. Olivine grains were analyzed in four chondrules. The O-isotope composition of the olivine grains plot along the PCM line, demonstrating variation in $\delta^{18}\text{O}$ from 2‰ to 7‰. The mean of $\Delta^{17}\text{O}$ varies from -0.4‰ to 0.6‰ . There is no difference between anhedral olivine and euhedral olivine in K4-1. The O-isotope composition of the glass plots on a slope of 0.5, with a mean value of $\Delta^{17}\text{O}$ that is identical to that of enstatite in each chondrule, or which is elevated, ranging up to 1.3‰. The variation of $\delta^{18}\text{O}$ in each chondrule varies up to 3.5‰. The K-rich glass in K4-0 is depleted in ^{16}O , with variation in $\delta^{18}\text{O}$ of 3.5‰. The O-isotope compositions of cristobalite were determined in I6p, D6a-1, D6a-0, and C5b. They plot on the TF line, between the intersection of the PCM line, and $\delta^{18}\text{O}=10.8\text{‰}$.

The O-isotope compositions of enstatite, olivine, glass, and cristobalite do not necessarily plot in the same cluster. In I6p, the glass shows variation along a slope of 1 (Figure 3.7a). The variation in enstatite in D6a-1 is slightly larger than that in I6p (Figure 3.7b). In D6a-0, while no significant variation is observed within enstatite, cristobalite shows heavier $\delta^{18}\text{O}$ (10.8‰) on the TF line (Figure 3.7c). In D3g, enstatite and olivine plot in the same cluster and the glass is elevated in $\Delta^{17}\text{O}$ by 1.2‰ (Figure 3.7d). In J51, C5b, K4-1, and K4-0, both enstatite and glass (but not K-rich glass) plot in the same cluster (Figure 3.7e,g,h,i). Note that in J51, the mean O-isotope composition of enstatite and glass are $\Delta^{17}\text{O}$ 1.2‰ and 1.1‰, respectively (Figure 3.7e). In K4-1, all enstatite, euhedral olivine, anhedral olivine, and glass plot in the same cluster (Figure 3.7h).

3.3.5 Lithium-isotope composition

All analyses are shown in Figure 3.8 and Table 3.4. The Li isotope-composition and concentration for individual chondrules are summarized in Table 3.3 and shown in Figure 3.9, together with those for the Allende CV chondrules (Maruyama et al., 2009; Kunihiro et al., 2019b).

Enstatite scatters both in $\delta^7\text{Li}$ and [Li] (Figure 3.8). The majority of enstatite plots in an area that has a smaller $\delta^7\text{Li}$ and higher [Li] relative to whole EH3 chondrites, determined by Seitz et al. (2007) ($\delta^7\text{Li} = 2.9\text{‰}$, $[\text{Li}] = 1.5 \mu\text{g} \cdot \text{g}^{-1}$). In this area, enstatite shows a positive trend. The majority of olivine grains plot in an area that has

both smaller $\delta^7\text{Li}$ and $[\text{Li}]$ relative to whole EH3 chondrites. The glass shows the largest variation in both $\delta^7\text{Li}$ and $[\text{Li}]$. In general, the $\delta^7\text{Li}$ of the glass is consistent with, or higher than that of whole EH3 chondrites.

The mean $\delta^7\text{Li}$ of enstatite in each chondrule varies from -3.0‰ (D6a-1) to 2.5‰ (K4-0) and is smaller than that of whole EH3 chondrites. The variation of $\delta^7\text{Li}$ and $[\text{Li}]$ in each phase differs between chondrules. In general, both the $\delta^7\text{Li}$ and $[\text{Li}]$ of olivine grains are smaller than those of enstatite in the same chondrule (Figure 3.9d,e,g,h,i). The $\delta^7\text{Li}$ variation of enstatite in I6p is 0.7‰ (1σ) and the smallest among the chondrules. In D3g an enstatite located in the center of the chondrule is enriched in Li up to $19.0 \mu\text{g} \cdot \text{g}^{-1}$ with $\delta^7\text{Li}$ consistent with that of whole EH3 chondrites. Three analyses of the glass show that $[\text{Li}]$ increases from the core to the rim. In J5l, variation of $\delta^7\text{Li}$ in olivine is observed. However, there is no apparent correlation with their occurrence throughout the chondrule. Glass in the core and rim on K4-1 is either enriched (up to $25.3 \mu\text{g} \cdot \text{g}^{-1}$) or depleted (down to $1.6 \mu\text{g} \cdot \text{g}^{-1}$) in Li.

3.4 Discussion

3.4.1 Did cristobalite form by reduction?

The common occurrence of silica in chondrules from enstatite chondrites, which is a result of their silica-saturated compositions, is one of the characteristic features that distinguish enstatite chondrites from the other chondrite groups (Mason, 1966). Kimura et al. (2005) studied silica polymorphs as a way to understand the thermal histories of enstatite chondrites. They reported cristobalite and tridymite in chondrule mesostases consistent with silica as the liquidus phase after crystallization of enstatite and consistent with melting and rapid crystallization rates for the chondrules.

The silica could form by reduction of Fe from FeO-bearing silicates. The FeO-rich pyroxene in many enstatite chondrites has clearly undergone a process of reduction and the textures suggest that silica is a product of reduction (e.g., Weisberg et al., 1994). Not all of the silica in chondrules may be the result of reduction, but Weisberg et al. (2018) observed that some silica forms parallel aligned lamellae structures in the FeO-rich pyroxene, associated with tiny blebs of Fe-metal, suggesting at least some of the silica is a production of reduction reactions. Note that the O-isotope composition of FeO-rich pyroxenes is similar to that of enstatite (Kimura et al., 2003). The identical O-isotope compositions of FeO-rich pyroxene does not necessarily preclude silica from being a product of reduction or from forming from the melt.

Cristobalite is abundant in the mesostasis of D6a-1, but no Fe,Ni-metal is observed. Cristobalite seems to occur interstitially to pyroxene grains (Figure 3.10a). The texture of cristobalite in D6a-1 indicates that cristobalite crystallized from a melt. Although minor Fe,Ni-metal was observed in I6p, no Fe,Ni-metal was observed next to the band

of silica (Figure 3.2a). Although abundant Fe,Ni-metal was observed in D6a-0, a cristobalite grain was enclosed within enstatite. These petrographical observations suggest the cristobalite observed in this study was not a product from the reduction of FeO-rich silicate. We conclude that the cristobalites are not produced by reduction, but instead the formation of cristobalite was driven by Si enrichment relative to Mg.

As the last crystallizing phase, silica may have exchanged oxygen with and preserved the composition of the ambient nebular gas. It is also possible that silica condensed from a late stage Si-rich nebular gas, as suggested for silica-rich rims on some chondrules in CR chondrites (Krot et al., 2004a,b). Alternatively, the difference in isotope composition could reflect the thermal condition in the Solar nebula or asteroid (Weisberg et al., 2021).

In this study, the $\Delta^{17}\text{O}$ of cristobalite was found to be indistinguishable from that of low-Ca pyroxene in the same chondrule as well as from Weisberg et al. (2021). Cristobalite from four different chondrules (I6p, D6a-1, D6a-0, and C5b) form an array that expands a cluster of low-Ca pyroxene grains. An array plots on the TF line from $\delta^{18}\text{O}=5.5\text{‰}$ to 10.8‰ (Figure 3.6).

Weisberg et al. (2021) found that $\delta^{18}\text{O}$ of cristobalite is 3‰ higher than pyroxene, which corresponds to a temperature of equilibrium of 630°C using oxygen isotope thermometry (Zheng, 1993). This temperature seems to be too low since cristobalite is a high temperature polymorph of silica (Kimura et al., 2005). In this study, the $\delta^{18}\text{O}$ of silica distributed from equal to or 5‰ higher than that of low-Ca pyroxenes. The difference in 5‰ in $\delta^{18}\text{O}$ corresponds to a temperature of 380°C using O-isotope thermometry (Zheng, 1993). Again, this temperature seems to be too low. Although Weisberg et al. (2021) could not exclude an involvement of instrumental fractionation during analysis, we infer that the difference in $\delta^{18}\text{O}$ by 5‰ between enstatite and cristobalite cannot be due to the instrumental fractionation because we determined the O-isotope composition relative to a standard of cristobalite.

The lower limit of the difference between enstatite and cristobalite is estimated to be less than 0.3‰ in $\delta^{18}\text{O}$, which corresponds to analytical uncertainty. The difference of 0.3‰ in $\delta^{18}\text{O}$ corresponds to 1800°C . Therefore, the O-isotope compositions of the silica suggests it crystallized within the temperature range of 380°C to 1800°C or above. Cristobalite with an O-isotope composition consistent with enstatite should have obtained its isotope composition prior to its accretion to the asteroid.

Enstatite chondrites experienced thermal metamorphism accompanied by increasing recrystallisation and textural/mineralogical equilibration and peak temperatures are around 525°C and 640°C for the Qingzhen (EH3) and Indarch (EH4) chondrites (Huss and Lewis, 1994), respectively. The metamorphism of Sahara 97096 (paired with Sahara 97103 surveyed in this work) is lower than Qingzhen (Quirico et al., 2011) and any other chondrites examined by their study. The O-isotope diffusion-rate of silica is faster than that of olivine and pyroxene (e.g., Cole and Chakraborty, 2001). Cristobalite

with higher $\delta^{18}\text{O}$ could be obtained during low temperature parent-body heating while maintaining the O-isotope compositions of olivine and pyroxene grains.

Tanaka and Nakamura (2017) determined the O-isotope compositions of the whole Sahara 97103 EH3 chondrite, whole chondrules, and aggregates of enstatite (reference symbols in Figure 3.7a-e,g-i). The values plot on the intersection between the PCM and TF lines with a variation 0.3‰ (1σ) in $\delta^{18}\text{O}$. Even though the enstatite chondrite is dominated by chondrules or enstatite, the $\delta^{18}\text{O}$ of the whole chondrite ($\delta^{18}\text{O}=6.2\text{‰}$) is 0.5‰ higher than that of the average of the chondrules and aggregates of enstatite. Assuming the object with the lowest $\delta^{18}\text{O}$ by Tanaka and Nakamura (2017) was silica-free pure-enstatite, the O-isotope composition of the mixture of enstatite and silica is calculated using the modal abundance of enstatite and silica to be 60.4 and 1.6 vol% in EH3 (Weisberg and Kimura, 2012) and the O-isotope compositions of enstatite and silica to be $\delta^{18}\text{O}=5.5\text{‰}$ (Tanaka and Nakamura, 2017) and $\delta^{18}\text{O}=10.8\text{‰}$ (observed in D6a-0). The O-isotope composition of the mixture is estimated to be 5.6‰ . The inconsistency cannot be explained by silica being the heavier component. There must be an unknown phase with an isotopically heavy O-isotope composition besides silica. Whole rock may not be representative of pure enstatite whole rock. Terrestrial weathering is possible, however, textures that might suggest significant weathering took place were not observed.

3.4.2 Is olivine relict?

Relict grains that survived chondrule melting have been identified in chondrules from carbonaceous, ordinary, and enstatite chondrites. They are generally identified as grains having petrologic features that are in gross petrologic and chemical disequilibrium with their host chondrule. For example, FeO-rich grains in type-I chondrules were among the first materials interpreted to be relict crystals (e.g., Nagahara, 1981). MgO-rich relicts in type-II FeO-rich chondrules have also been identified and in some cases have been shown to have more ^{16}O -rich O-isotope compositions than other minerals in the same chondrule (Yurimoto and Wasson, 2002; Jones et al., 2004; Kunihiro et al., 2004, 2005; Ushikubo et al., 2012; Pinto et al., 2024).

Grains of FeO-rich pyroxene and olivine, some of which have dusty inclusions, have been identified in enstatite chondrules (Leitch and Smith, 1982; Lusby et al., 1987; Weisberg et al., 1994, 2011; Kimura et al., 2003). In D6a-0 (Figures 3.1b, 3.2b), FeO-rich pyroxene grains (Figure 3.3) were observed with enstatite grains. The O-isotope compositions of the FeO-rich pyroxene and enstatite grains in D6a-0 have isotope compositions on the TF line (Figure 3.7c) and they are indistinguishable. The O-isotope composition does not necessarily suggest that the FeO-rich pyroxene is relict.

Anhedral olivines in I6p, D3g, J5l, and C5b are poikilitically enclosed by enstatite (Figure 3.2a,c,d,e). Thus, they are out of textural equilibrium with the surrounding

enstatite. Olivine grains in D3g, J5l, and C5b show a range of O-isotope compositions (Figure 3.7d,e,g). A subhedral 170-200- μm -sized olivine is observed in J5l. It is located at the center of the chondrule with both blocky and rounded edges. The mean $\Delta^{17}\text{O}$ of enstatite grains in J5l is 1.2‰, which is elevated relative to the TF line. The mean $\Delta^{17}\text{O}$ is close to that of the “second trend line” inferred from an array of chondrules by Weisberg et al. (2021), and it is a line with a slope of 0.5 and a $\Delta^{17}\text{O}$ of 0.9‰. The O-isotope compositions of olivine grains, including the largest grain in J5l, plot on the PCM line from $(\Delta^{17}\text{O}, \delta^{18}\text{O}) = (-2.0‰, 1.5‰)$ to $(1.4‰, 8.1‰)$ and they do not plot on the second trend line. Note that the olivine with the heaviest O-isotopes in J5l is similar to that of the heaviest enstatite in C5l from ALH 85159 $(\Delta^{17}\text{O}, \delta^{18}\text{O}) = (1.6‰, 8.2‰)$ by Weisberg et al. (2021).

The variation (1σ) of $\Delta^{17}\text{O}$ in olivine and enstatite in J5l is (0.78‰, 0.47‰) and that in C5b is (0.73‰, 0.39‰), respectively. In these chondrules, the variation of $\Delta^{17}\text{O}$ in olivine is larger than that of enstatite. The O-isotope heterogeneity is maintained in olivine grains. Considering the textural evidence and the O-isotope compositions, we conclude that the olivine grains in D3g and J5l are relict grains. We cannot definitively state that the olivine grains in I6p and D3g are relict grains, but it can be said that at least the olivine predates the enstatite. The existence of relict grains suggests incomplete melting for chondrule J5l and C5b, and the survival of minerals from previous generations of chondrules. Indeed, chondrule recycling has been proposed for chondrules in other chondrite groups (e.g., Jones, 1996). The range in the O-isotope compositions of relict olivine in J5l (Figure 3.7e) could reflect the addition of heavy isotopes from a more volatile precursor material (e.g., cosmic symplectite or organic matter, Sakamoto et al., 2007; Hashizume et al., 2011; Tenner et al., 2015; Marrocchi et al., 2024b) prior to the latest chondrule formation. For clarity, the term “the latest chondrule formation” is used here to refer to the last, or the most recent major melting event that is recorded in each chondrule.

Now it will be discussed if the olivine grains in K4-1 are relict. Zoomed in images of the BSE and Mg-Si-Al element map shown in Figures 3.10b,c demonstrate a textural relationship between olivine, enstatite, and glass. As described already, two occurrences of olivine are observed. An olivine in K4-1 is anhedral and politically surrounded by enstatite in the periphery of the chondrule. Another olivine is euhedral and enclosed by glass in the mesostasis. The texture suggests that the anhedral olivine predates the formation of the surrounding enstatite and that the euhedral olivine precipitated from a melt. Soulié et al. (2016) explained two occurrences of olivine by interaction of pre-existing olivine and Si-rich gas as below. A chondrule, consisting of olivine and melt, interacts with Si-rich gas at high temperature. SiO entering the chondrule promotes both the chemical zonation of the mesostasis, and the disequilibrium between liquid and olivine, starting olivine resorption. Olivine saturation in the mesostasis of chondrule core is reached and olivine crystallizes as an overgrowth onto the pre-existing

olivine and possibly as newly grown crystals. At the periphery of the chondrule, olivine saturation is delayed by the entrance of silica and continues to resorb. Enstatite starts to crystallize at the periphery of the chondrule. As a result of cooling, the remaining melt in the centre of the chondrule forms a mesostasis. Thus, the final texture of the chondrule is generated, with euhedral olivine grains embedded in mesostasis at the chondrule center, and anhedral small olivine grains at the chondrule margins, which are poikilitically embedded in large euhedral enstatite grains. Note that the pre-existing olivines could have crystallized as a liquidus phase in the early stage of the same thermal event (Libourel et al., 2006) and they are not necessarily relict.

The O-isotope compositions of enstatite, anhedral olivine, and euhedral olivine plot in the same cluster with variation of $\delta^{18}\text{O}$ consistent with each other (Figure 3.7h). Weisberg et al. (2011) inferred that in most of the cases, the $\text{Mg}/(\text{Mg}+\text{Fe})$ ratio and O-isotope compositions of olivine are indistinguishable from those of enstatite, even though the texture of the olivine and enstatite suggests that olivine may be relict. From texture and isotope compositions, we cannot conclude that anhedral olivine (core) and euhedral olivine are relict. The O-isotope composition of melt on K4-1 did not change through formation of olivine and pyroxene as shown for carbonaceous-chondrite chondrules (e.g., Ushikubo et al., 2012; Tenner et al., 2018). We refer to the euhedral olivine as ‘young’ olivine since at least its rim was formed during the latest chondrule formation event. We note that an euhedral olivine is surrounded by not only glass in the mesostasis, but also enstatite (Figure 3.10b,c). Thus, at least the rim of the young olivine should predate the enstatite.

In summary, olivine grains in J5l and C5b are relict. Olivine grains in I6p, D3g, K4-0, and K4-1 are not necessarily relict, but predate the enstatite.

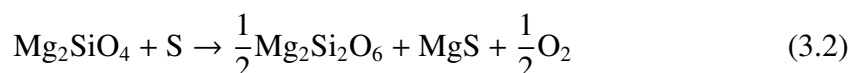
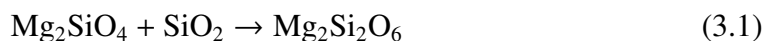
3.4.3 Sulfidation and silicification

The EH3 chondrites contain silica-bearing chondrules with abundant niningerite $[(\text{Mg},\text{Fe},\text{Mn})\text{S}]$, distinguishing them from the silica-bearing chondrules in carbonaceous and ordinary chondrites (Lehner et al., 2010). The occurrence of silica is consistent with the relative enrichment of the Si to Mg in bulk enstatite chondrites compared with bulk carbonaceous and ordinary chondrites (Davis, 2006). One way to decrease the Mg/Si ratio during chondrule-formation (we refer to “silicification”) is the addition of SiO_2 into the Mg-rich chondrule by reaction with SiO gas, one of the dominant gas species when chondrules were heated in the inner Solar nebula (Tissandier et al., 2002; Libourel et al., 2006; Chaussidon et al., 2008). If olivine was removed during fractional condensation from the enstatite-chondrite-chondrule forming-region, the remaining gas could be enriched in Si (Brigham et al., 1986; Petaev and Wood, 1998; Krot et al., 2004a). CR chondrules show silica-bearing rims due to the interaction of molten chondrules with fractionated Si-rich nebular gas (e.g., Tissandier et al., 2002; Krot et al., 2004a).

The oldhamite (CaS) could be condensates from the nebular gas (Croaz et al., 1987). However, positive Eu and Yb peaks are not compatible with the REE patterns that were modeled for the condensation sequence under reducing conditions (Hammouda et al., 2022). Nevertheless, the oldhamite could represent secondary condensates from the residual nebular gas. The positive Eu and Yb peaks are also compatible with experimental oldhamite/melt partitioning (Ingrao et al., 2019) under reduced conditions with the presence of Eu^{2+} and Yb^{2+} . Equilibration of the oldhamite with the chondrule mesostasis, enriched by one order of magnitude in REE above chondritic values, would indeed account for the absolute magnitude of REE concentrations in the enstatite-chondrite-chondrule oldhamite (Jacquet et al., 2015). Based on the micro- and nano-petrographic observations and chemical evidence, Lehner et al. (2013) and Piani et al. (2016) suggested that niningerite and oldhamite were inherited from silicates or oxides based on their texture. The coexistence of FeO-bearing silicates and Fe,Ni-metal, as shown already, is also problematic for the reduced nebula model. Lehner et al. (2013) demonstrated that the formation of niningerite and oldhamite by sulfidation of ferromagnesian silicates with a S-rich gaseous reservoir below the IW buffer. The reaction of silicates with the S-rich gas would result in progressive extraction of Fe, Ca, and Mg into sulfides, with the stoichiometric amounts of silica either reacting with olivine to form enstatite or, when olivine is exhausted, precipitating as free silica. Piani et al. (2016) examined 17 porphyritic chondrules in EH3 chondrites and also suggested that sulfidation occurs when a S-rich reservoir gas interacted with the melted chondrule.

There were two processes, that could cause the sulfidation and formation of niningerite and the silicification that decreased the Mg/Si ratio and formation of silica, in the enstatite-chondrite-chondrule-formation region. Lehner et al. (2013) tried to lower the bulk Mg/Si ratios of enstatite chondrules by removal of Mg instead of addition of Si through sulfidation. They demonstrated that sulfidation drastically increases Mg volatility, resulting in evaporative loss of Mg. Thus, their model does not require independent sulfidation and silicification processes.

As demonstrated in the previous subsection, we observed enstatite and olivine in chondrules D3g, J5l, C5b, and K4-1. Olivine is one of the reactants and enstatite is one of the products of the latest chondrule formation event. Therefore, not only silica, but also enstatite is considered to be a product of silicification. Reactions that could modify olivine to form enstatite with either addition of Si (from gas or melt) or removal of Mg are expressed below.



If the latter is the case, the newly formed enstatite should be in nearly equal molar proportions to and associated with niningerite. The chondrules with major olivine (I6p,

D3g, J5l, C5b, and K4-1) are shown in Figures 3.2c,d,e,f, and it is clear that only minor niningerite is present. Nevertheless, it is possible that spinning of the chondrules expelled immiscible niningerite away from the chondrules (Lehner et al., 2013; Jacquet et al., 2015). However, we observe significant abundances of other immiscible phases, such as troilite, Fe,Ni-metal, and oldhamite within these chondrules. Thus, we conclude that neither evaporation of Mg during sulfidation, nor the loss of immiscible opaques are the major processes responsible for silicification.

D6a is an aggregate of two chondrule fragments in contact. D6a-0 and D6a-1 are with and without niningerite, respectively, although their chronological relationship is not clear (Figure 3.2b). Therefore, there are at least two environments in the Solar nebula that vary in their S-fugacity. K4 is a rounded aggregate with two lithologies. K4-1 includes K4-0 (Figure 3.2f). On K4-0, we observe olivine grains turning into enstatite grains by silicification. And a part of the enstatite is replaced by niningerite, which co-existed with silica, due to sulfidation $\text{Mg}_2\text{Si}_2\text{O}_6 + 2\text{S} \rightarrow 2\text{SiO}_2 + 2\text{MgS} + \text{O}_2$ (Figures 3.10c). Thus, the silicification, which generated enstatite, predated the sulfidation. As such, both silicification and sulfidation were observed in a single chondrule, and were found to be occurring independently. K4-1 experienced silicification especially towards the periphery of the chondrule. The abundance of niningerite in K4-1 is much smaller than that in K4-0 (Figure 3.2f). In K4-1 at the 10- μm scale (Figure 3.10c), niningerite and silica were observed at the boundary between enstatite and young olivine, and in the cracks inside of the enstatite. Thus, silicification predated sulfidation on K4-1 as well. While, it is not clear if the sulfidation took place in the Solar nebula, or on asteroid, as there is little connection of the sulfides with the chondrule exterior, a parent body origin seems unlikely. Since K4-0 is enclosed by K4-1, we recognize four processes in the following sequence: silicification, sulfidation, silicification, and sulfidation. Since sulfidation and silicification are different process, it is suggested here that there were regions with gas that were either enriched in S, or Si in the early Solar nebula.

3.4.4 Trace element constraints on chondrule formation

As described in section 3.3.2, the REE patterns of the glass in the chondrules are with or without negative Eu and Yb spikes. The oldhamite bearing chondrules are indicated with the symbol † in this section. The REE pattern of glass, enstatite, and olivine in J5l and K4-1 (group F) are without negative spikes (Figure 3.5e,h). The REE pattern of glass, enstatite, and olivine are consistent with those of the same phases from carbonaceous and ordinary chondrite chondrules (e.g., Jacquet et al., 2015; Kunihiro et al., 2021). Both J5l and K4-1 lack oldhamite. Therefore, during the latest chondrule formation event, oldhamite did not play a role in the fractionation of REE among the chondrule constituents.

The REE patterns of the glass in †I6p and †C5b (group S) show negative spikes in Sm, Eu, and Yb (Figure 3.5a,g). Oldhamite occurs with FeS in both †I6p and †C5b, and the coexistence of these sulfides indicates that the system has reached a cotectic condition, which indicates a crystallization temperature of 1060°C (Pitsch et al., 2025). Glass grains in these chondrules are considered to have solidified with oldhamite, resulting in depletion of Sm and Yb. The pattern is explained by the occurrence of oldhamite during the latest chondrule formation event. The REE pattern of oldhamite in †C5b is similar to previous studies (Figure 3.5f). The oldhamite in †I6p shows a negative peak in Eu instead of positive peak. Such a pattern is shown by Gannoun et al. (2011) from an EH3 chondrite. They infer that the pattern can be explained by the oldhamite being nebular condensates. As inferred already in †I6p, oldhamite occurs facing mesostasis and enstatite (Figure 3.2a). The relationship between the Sm/Eu/Yb anomalies in silicate phases and oldhamite suggests rather such signatures, and the oldhamite, arose during chondrule formation. If the REE patterns of silicate phases and oldhamite reflect partition between chondrule constituents during the latest chondrule formation event, the depletion in Eu could be inherited from the precursor components of chondrule †I6p.

The REE pattern of glass in D6a-1 (group P) also contains negative spikes in Eu and Yb (Figure 3.5b). Unlike †I6p and †C5b, this chondrule lacks oldhamite. In order to explain such negative Eu and Yb peaks in glass, Jacquet et al. (2015) proposed to remove oldhamite, with high REE abundances and peaks in Eu and Yb, during chondrule formation. Although the REE pattern of glass in D6a-1 is consistent with their scenario, no remnants of immiscible opaque phases are observed in the periphery of the chondrule (Figure 3.2b). It also is possible that oldhamite is located outside the plane of the thin section.

Glass in D3g (group P) shows REE patterns with negative spikes in Sm, Eu, and Yb (Figure 3.5d). The pattern is similar to those of glasses in †I6p and †C5b, but the chondrule does not contain oldhamite. Olivine was analyzed from this chondrule. Not only glass and enstatite, which formed during the latest chondrule formation event, but also olivine demonstrated both negative peaks in Eu and Yb. Thus, the precursors of a melt that crystallized olivine were depleted in Eu and Yb (Hsu and Crozaz, 1998; Jacquet et al., 2015). The crystallization temperature of oldhamite without FeS is ca. 2500°C (Pitsch et al., 2025), which is significantly higher than the temperature of cotectic crystallization of olivine and enstatite (1570°C; Bowen and Andersen, 1914). Thus, oldhamite could have crystallized first in D3g, then olivine and enstatite crystallized from the residual melt with Eu and Yb depletions. Similarly to D6a-1, oldhamite should have been removed from chondrule, or it is located outside the plane of the thin section. In the early stage of chondrule formation, oldhamite was crystallized from melt with the assistance of sulfidation, followed by the formation of olivine. Then enstatite formed from the melt with the assistance of silicification.

It is inferred here that during enstatite-chondrite-chondrule formation, the chondrule

precursors did not necessarily interact with a reservoir both enriched in S and Si. In Figure 3.13, the history of an enstatite-chondrite chondrule that begins with precursor material enriched in olivine, and which interacted with both a S-rich reservoir and a Si-rich reservoir is illustrated.

The REE $melt_{lpx}$ concentrations in I6p is consistent with the removal of Eu and Yb by CaS. The drop in the LREE concentrations of the $melt_{lpx}$ against the glass and low-Ca pyroxene indicates that CaS may take LREE from the $melt_{lpx}$, or that LREE is lost from the chondrule post low-Ca pyroxene formation. The concentration of Li in the $melt_{lpx}$ compared with the Li concentration in the glass and low-Ca pyroxene support the loss of Li from the chondrule, possibly by evaporation.

The REE $melt_{lpx}$ concentrations in D6a-0 compared with the low-Ca pyroxene REE concentrations suggests that the precursor was depleted in Yb, but Eu is removed. This can be attributed to CaS which was subsequently removed from the chondrule before accretion took place. The REE $melt_{lpx}$ concentrations in D6a-1 compared with the glass, low-Ca pyroxene, and cristobalite REE concentrations suggests that the precursor was depleted in Yb, but Eu is removed during the last melting event. This can be attributed to CaS which was removed from the chondrule prior to accretion. Based on the variation of Li concentration of the $melt_{lpx}$, glass, and low-Ca pyroxene, Li was brought into the chondrule during silicification. The Li was likely lost from the chondrule via evaporation post low-Ca pyroxene formation.

In D3g, the depleted Yb in both the $melt_{ol}$ and $melt_{lpx}$. This correlates with the glass, olivine and low-Ca pyroxene indicating that the precursor chondrule was likely depleted in Yb. As the $melt_{ol}$ and olivine are also depleted in Eu, CaS was likely present in the precursor chondrule. This suggests that sulphidation occurred on the precursor chondrule prior to silicification. The $melt_{lpx}$ is not depleted or enriched in Eu but the low-Ca pyroxene is depleted in Eu. This suggests that sulphidation occurred, producing CaS prior to the solidification of the low-Ca pyroxene and removed Eu and additional Yb from the chondrule $melt_{lpx}$. Li concentrations of the $melt_{ol}$, $melt_{lpx}$, glass and low-Ca pyroxene suggest that Li was introduced into the chondrule by silicification and then subsequently lost via evaporation post low-Ca pyroxene formation.

The $melt_{ol}$ and $melt_{lpx}$ in J5l are enriched Eu but depleted in Yb. This does not correlate with the olivine and low-Ca pyroxene which are enriched in Eu but not enriched or depleted in Yb. The glass is not enriched or depleted in Eu and depleted in Yb. The REE patterns in this chondrule indicate that the precursor was already enriched in Eu and depleted in Yb. The Yb was likely redistributed in the olivine, with the $melt_{lpx}$ reflecting its precursor. Based on the estimated REE of the $melt_{lpx}$ and the chondrule components, CaS is unlikely to have played a role in the last melting event. The $melt_{lpx}$ has a larger Li concentration compared to the $melt_{ol}$ and olivine. This suggests that Li was brought into the chondrule during silicification. The Li concentration of the $melt_{lpx}$, glass and low-Ca pyroxene suggests that some Li was lost from the chondrule post low-Ca pyroxene

formation.

In C5b the $melt_{ol}$ is slightly enriched in Eu and neither enriched or depleted in Yb. Whereas the $melt_{lpx}$ is not enriched or depleted in Eu or Yb. The olivine is not enriched or depleted in Eu or Yb indicating that CaS did not play a role in the precursor chondrule. The glass and low-Ca pyroxene are both depleted in Eu. The glass is depleted in Yb and the low-Ca pyroxene is not enriched or depleted in Yb. Indicates that the CaS removed Eu and Yb from the $melt_{lpx}$. Eu was removed first, and the low-Ca pyroxene crystallised before Yb was removed. Li is brought into the chondrule through gas-melt interactions during silicification and is lost via evaporation before the $melt_{lpx}$ solidifies to the glass.

The $melt_{lpx}$ in K4-0 is enriched in Eu and depleted in Yb. This correlates with the K-rich glass and the low-Ca pyroxene. The K-rich glass is relict and has similar REE concentrations to the low-Ca pyroxene, this indicates that the precursor was enriched in Eu and depleted in Yb. It is unlikely that CaS plays a role during the last melting event. In K4-1 the $melt_{ol}$ is not enriched or depleted in Eu and depleted in Yb. The $melt_{euhedral-ol}$ and $melt_{lpx}$ are enriched in Eu and depleted in Yb. The anhedral olivine pattern matches that of the $melt_{ol}$. The euhedral olivine and low-Ca pyroxene are not enriched or depleted in Eu or Yb. This indicates that the precursor chondrule was depleted in Yb but not in Eu. Eu is redistributed into the $melt_{euhedral-ol}$ and $melt_{lpx}$, indicating that CaS may have been present in the precursor chondrule but did not play a role in the last melting event. Variation in Li between the three melts supports the addition of Li during silicification. The glass has a larger Li concentration than the low-Ca pyroxene making it difficult to say for certain that some Li is lost from the chondrule.

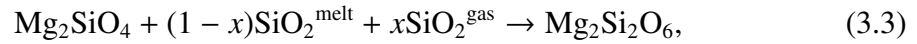
3.4.5 O-isotope composition of Si-rich reservoir

In this study, most chondrules with major olivine are with silica (D3g, J5l, C5b, K4-0, but K4-1). They are under chemical disequilibrium and the O-isotope compositions of enstatite and olivine are not necessarily identical. Meanwhile, I6p, D6a-1, and D6a-0 lack major olivine. The O-isotope composition of enstatite and the melt could be identical during formation of enstatite, as inferred for carbonaceous-chondrite chondrules (e.g., Ushikubo et al., 2012; Tenner et al., 2018). Thus, the O-isotope composition of such enstatite could correspond to that of the surrounding gas, because of mutual exchange (Marrocchi et al., 2019), notwithstanding some mass-dependent fractionation. If so, there could be two gaseous reservoirs with different $\Delta^{17}\text{O}$. One is a reservoir on the TF line inferred from enstatite grains in I6p, D6a-1, D6a-0, D3g, C5b, K4-1, and K4-0, and the other is a reservoir represented by the second trend line (Weisberg et al., 2021) inferred from enstatite grains in J5l.

Chaussidon et al. (2008) proposed that most of the olivine in carbonaceous-chondrite chondrules is relict and that pyroxene was formed by interaction in an open system be-

tween the melt of a precursor dominated by olivine and gas. Here it is demonstrated that during the latest chondrule formation event, enstatite grains formed by interaction between olivine and additional SiO_2 (Equation 3.1 instead of 3.2). Enstatite grains in chondrules without major olivine (I6p, D6a-1, and D6a-0; Figures 3.7a,b,c) show a consistent or narrower range in O-isotope compositions relative to those with major olivine (D3g, J5l, C5b, and K4-1; Figures 3.7d,e,g,h). The difference of the variation in O-isotope composition, suggests that melt in chondrules with or without major olivine contain a heterogeneous, or a homogeneous O-isotope composition. Although the number of analyses is limited, mean O-isotope compositions of olivine and enstatite differ slightly in D3g, J5l, C5b, and K4-1, suggesting the interaction of gas that differs in its O-isotope composition with the olivine.

Since enstatite in a chondrule with olivine formed by interaction between olivine and additional SiO_2 , the contribution of oxygen in enstatite from olivine and SiO_2 is 2:1 (Equation 3.1). Enstatite did not necessarily form only from SiO_2 provided by the gas. Thus, Equation 3.1 is rewritten as



where $\text{SiO}_2^{\text{melt}}$ and $\text{SiO}_2^{\text{gas}}$ are SiO_2 provided from melt and gas to form enstatite, and x corresponds to the relative molar fraction of $\text{SiO}_2^{\text{gas}}$. The O-isotope composition of the additional SiO_2 from gas is calculated by mass balance from three chondrules without an elevation in $\Delta^{17}\text{O}$ (D3g, C5b, and K4-1) by varying x . Case $x = 1$ corresponds to all SiO_2 provided by gas. We assume that the O-isotope composition of $\text{SiO}_2^{\text{melt}}$ is identical to that of olivine.

The O-isotope composition of additional SiO_2 with varying x is shown in Figures 3.7d,g,h. The averages of the three chondrules with $x = 1.0$ and $x = 0.5$ are estimated to be $(\delta^{18}\text{O}, \delta^{17}\text{O}, \Delta^{17}\text{O}) = (5.5\text{‰}, 3.5\text{‰}, 0.6\text{‰})$ and $(4.4\text{‰}, 3.8\text{‰}, 1.6\text{‰})$, respectively. Tanaka and Nakamura (2017) estimated the formation temperature of the enstatite-chondrite-chondrules to be $>1960\text{K}$. At 1960K , the mass fractionation between enstatite-rich melt and Si-rich gas is 0.254‰ for $\delta^{18}\text{O}$ (Javoy et al., 2012). Thus, the O-isotope compositions of Si-rich gas during chondrule formation with $x = 1.0$ and $x = 0.5$ are estimated to be $(\delta^{18}\text{O}, \delta^{17}\text{O}, \Delta^{17}\text{O}) = (5.2\text{‰}, 3.4\text{‰}, 0.6\text{‰})$ and $(4.1\text{‰}, 3.7\text{‰}, 1.6\text{‰})$, respectively. The SiO_2 could have been provided to the chondrules in enstatite-chondrite-chondrule forming-region by the following reaction: $\text{SiO} + \text{CO} \rightarrow \text{SiO}_2 + \text{C}$ (Tanaka and Nakamura, 2017). The O-isotope composition of CO is heavier in $\delta^{18}\text{O}$ by 2.171‰ compared to that of SiO (Javoy et al., 2012). However, because of limited resolution in the determination of the O-isotope compositions, we can only conclude that there was a Si-rich gas with elevated $\Delta^{17}\text{O}$ similar to or more than the second trend line suggested by Weisberg et al. (2021) during chondrule formation. Further examinations focusing on the difference between enstatite and olivine are necessarily.

Glass solidified after the formation of enstatite. The $\Delta^{17}\text{O}$ of glass in chondrules J5l, C5b, K4-1, and K4-0 is identical to that of enstatite with little variation along slope 0.5. The variation observed on slope 0.5 could be obtained during chondrule formation through evaporation and condensation processes, or during low temperature parent-body heating through diffusion processes, because of its fast oxygen isotope diffusion rate compared to olivine and pyroxene (e.g., Cole and Chakraborty, 2001). However, the $\Delta^{17}\text{O}$ of glass in chondrules I6p, D6a-1, and D3g, and the K-rich glass in K4-0 is significantly higher than that of enstatite. Kinetic processes do not enhance the difference between the $\Delta^{17}\text{O}$ of glass and that of enstatite. The variations preserved in glass among the chondrules implies that they are the result of chondrule formation. It is possible that the O-isotope composition of the melt evolved after the formation of enstatite. The smaller variation of the O-isotope composition in enstatite relative to glass could be the result of these phases forming at different times. No correlation was observed between $\Delta^{17}\text{O}$ and the concentration of alkali elements (Figure 3.11). During O-isotope evolution of the melt, no net transfer of volatiles between melt and gas was recognized.

3.4.6 Li-isotope composition of Si-rich reservoir

Variation in the Li-isotope composition of enstatite and olivine from the EH3 chondrules is significantly smaller than that from the CV3 chondrules (Figure 3.9f). The smaller variation in Li-isotope composition in EH3 (this work) chondrules relative to that of CV3 (Kunihiro et al., 2019b) chondrules is similar to the difference in variation observed for the O-isotope composition of EH3 (Weisberg et al., 2011, 2021, this work) chondrules relative to CV3 (Rudraswami et al., 2011; Kunihiro et al., 2019b) chondrules.

The mean and the variation of the Li-isotope composition of enstatite within the chondrules analysed here, varies from $\delta^7\text{Li} = -3.0\text{‰}$ to 2.5‰ and from 0.7‰ to 3.2‰ (1σ), respectively. Chondrule I6p has the smallest variation in $\delta^7\text{Li}$ (Figure 3.9a). It lacks major olivine and is with the smallest variation in O-isotope composition as well (Figure 3.7a). Enstatite in I6p formed from melt that was well mixed in its major elements, oxygen, and lithium. Although enstatite in I6p should be representative of such a well mixed melt, its $\delta^7\text{Li}$ and $[\text{Li}]$ are inconsistent with those of whole EH3 chondrites ($\delta^7\text{Li} = 2.9$, $[\text{Li}] = 1.5 \mu\text{g} \cdot \text{g}^{-1}$) determined by Seitz et al. (2007). A phase that could make up for such a discrepancy, is the glass that has a wide distribution of both $\delta^7\text{Li}$ and $[\text{Li}]$ values.

Li-isotope heterogeneity is maintained in chondrule olivine from enstatite chondrites, as well as in carbonaceous and ordinary chondrites (Chaussidon and Robert, 1998; Nakamura et al., 2019; Maruyama et al., 2009; Kunihiro et al., 2019b; Liu et al., 2023). Young euhedral olivines in K4-1 show a weak anticorrelation between their Li isotope-composition and concentration (Figure 3.9h). The trend is explained by

evaporation of lithium during chondrule formation. Evaporation of lithium from melt raises the $\delta^7\text{Li}$ of the melt and olivine (Kunihiro et al., 2019b). Although the O-isotope composition of enstatite is elevated relative to young euhedral olivine slightly, the O-isotope composition of young euhedral olivine is identical to that of anhedral olivine (Figure 3.7h). Young euhedral olivine formed from melt, or overgrew upon existing olivine, without the addition of SiO_2 or Li. Therefore, the growth of young euhedral olivine should have predated delivery of the additional SiO_2 .

The Li isotope-composition and concentration of the glass are controversial. Based on the partition coefficient between enstatite and melt ($D_{\text{opx/melt}}=0.211$; Ottolini et al., 2008), one expects [Li] in the glass to be consistent to or larger than that of enstatite. After formation of enstatite, lithium could be depleted by evaporation resulting in an increase in $\delta^7\text{Li}$ as inferred already. This trend is observed in C5b and K4-1, but not in the other chondrules. Li in the glass of I6p is depleted, but its isotope composition is similar to that of whole EH3 chondrite. Note that glass in I6p shows evolution in its $\Delta^{17}\text{O}$ (Figure 3.7a). Maruyama et al. (2009) demonstrated that Li was leached away from chondrule glass due to asteroidal processes, since glass is susceptible to the influence of fluid. Kunihiro et al. (2021) analyzed plagioclase in CV3 chondrules and found that it is depleted in Li with a $\delta^7\text{Li}$ similar to the whole CV3 chondrite, as observed in glass in I6p. No correlation was observed between $\delta^7\text{Li}$ and the concentration of alkali elements (Figure 3.11), this was even the case when plotting against individual alkali elements. It is not clear if asteroidal processes could have modified the isotope-composition and concentrations of the glass in EH3 chondrites, since EH are dry meteorites. As inferred already, the metamorphism of Sahara 97096 (paired with Sahara 97103 surveyed in this work) is lower than Qingzhen (Quirico et al., 2011) and any other chondrites examined by their study. We note that a significant variation in both the isotope-composition and concentration is still maintained in the glass, even though heating on the asteroid would cause the isotope compositions and concentrations of phases to move towards homogeneity. In order to discuss Li modification on asteroids in detail, more studies for other EH meteorites are necessary.

Enstatite may merely inherit the Li-isotope composition of the melt, upon formation of enstatite, which differed from that of olivine (because the melt evolved and/or because some of these olivines are relict). Li concentrations of enstatite in D3g, J51, C5b, and K4-1 (except K4-0) are 5 times more than those of olivine. The relative partition coefficient between enstatite and olivine is 0.49 ($D_{\text{opx/melt}}=0.211, D_{\text{ol/melt}}=0.427$; Ottolini et al., 2008). Thus, the Li concentration of the melt where enstatite formed should be one order of magnitude higher than that of the melt where olivine formed.

As discussed in the previous section, olivine reacted with additional SiO_2 to form enstatite following Equation 3.3. The difference in the Li-isotope composition between olivine and enstatite suggests that the Li-isotope composition of the additional SiO_2 differs from that of olivine. Since the Li isotope-composition ($\delta^7\text{Li}$) of olivine is sig-

nificantly lower than those of enstatite in each chondrule, the additional SiO_2 should be accompanied with heavier lithium.

Based on Equation 3.1, the $\delta^7\text{Li}$ and $[\text{Li}]$ of the SiO_2 from enstatite and olivine were estimated for each chondrule (Table 3.3). We calculated and estimated the Li-isotope composition and concentration of the SiO_2 that was the immediate reactant in the formation of enstatite, by mass-balance calculation. The ($\delta^7\text{Li}$ and $[\text{Li}]$) of the SiO_2 that formed enstatite in D3g, J5l, C5b, K4-1, and K4-0 were estimated to be (D3g: -1.5‰ , $13.6 \mu\text{g} \cdot \text{g}^{-1}$), (J5l: 1.8‰ , $12.6 \mu\text{g} \cdot \text{g}^{-1}$), (C5b: 2.0‰ , $13.3 \mu\text{g} \cdot \text{g}^{-1}$), (K4-1: 2.5‰ , $8.5 \mu\text{g} \cdot \text{g}^{-1}$), and (K4-0: 8.4‰ , $0.8 \mu\text{g} \cdot \text{g}^{-1}$), respectively (Figure 3.12). K4-0 is a chondrule that predates K4-1 and the Li isotope-composition and concentration of the reactant SiO_2 estimated from K4-0 does not necessarily result from the Si-rich gas from the latest chondrule formation event. Thus, we do not include K4-0 in the estimation of the Li-isotope composition of the Si-rich gas that was present during the latest chondrule formation event. The means of the Li isotope-composition and concentration for the reactant SiO_2 among D3g, J5l, C5b, and K4-1 are estimated to be ($\delta^7\text{Li}$, $[\text{Li}]$)=(1.2‰ , $12.0 \mu\text{g} \cdot \text{g}^{-1}$).

The reactant consists of SiO_2 from melt and SiO_2 from gas (Equation 3.3). The Li concentration of the melt estimated from olivine (melt_0) is one order of magnitude lower than that estimated from enstatite. Taking into account that a contribution of Li from melt_0 was neglected, the Li concentration of the reactant SiO_2 gives a lower limit for the Li concentration of SiO_2 provided from the Si-rich gas. At the same time, the Li isotope-composition of the reactant SiO_2 gives the value for the SiO_2 provided from the Si-rich gas. By assuming the Li-isotope composition of SiO_2 is not fractionated relative to that of the gas, we infer the Li-isotope composition of the Si-rich gas during the latest chondrule formation is $\delta^7\text{Li}=1.2\text{‰}$, that is close to the value of whole EH3 chondrites ($\delta^7\text{Li}=2.9\text{‰}$).

Maruyama et al. (2009) and Liu et al. (2023) determined the Li-isotope compositions of olivine, but not enstatite, in chondrules from carbonaceous chondrites. Kunihiro et al. (2019b) determined the Li- and O-isotope compositions of chondrule constituents including both olivine and enstatite from the Allende CV3 chondrite. Two occurrences are observed for enstatite. An enstatite formed from melt during chondrule formation together with olivine, and another enstatite that formed during igneous rim formation. The igneous rims may also be droplets that coagulated with the cooling chondrule and formed during the later stages of the same heating event (Jacquet et al., 2013). Previous studies suggest that the igneous rims around chondrules formed by incomplete melting of solid precursors and gas-melt interaction. During the gas-melt reaction, Si and Na condense into the chondrule melt and generate a silica- and alkaline-enriched chondrule rim (Krot et al., 2004a). Anhedral olivines in the igneous rim have an O-isotope composition similar to euhedral olivine in the main chondrule, and are poikilitically enclosed by enstatite. Thus, during the igneous rim formation, precursor olivine interacted with

additional SiO₂ to form enstatite (Kunihiro et al., 2021). There is a potential risk of the diffusion-driven Li isotopic disturbance (e.g. Dohmen et al., 2010; Tomascak et al., 2016). Kunihiro et al. (2019b) discussed the possible modification of the Li distribution by igneous and asteroidal processes. It was concluded that the enstatites with different origins form a trend with two end components (one with ($\delta^7\text{Li}$ and $[\text{Li}]$)=(30‰, 0.5 $\mu\text{g} \cdot \text{g}^{-1}$) and another with ($\delta^7\text{Li}$ and $[\text{Li}]$)=(-20‰, 10 $\mu\text{g} \cdot \text{g}^{-1}$), with the Li-isotope composition of the Si-rich gas being $\delta^7\text{Li}=-11\text{‰}$.

The Li-isotope composition of the Si-rich gas that interacted with enstatite chondrules is $\delta^7\text{Li}=1\text{‰}$. It is in the range of the Li-isotope compositions of chondrite, achondrite, lunar, and Martian meteorites obtained by whole-rock analyses ranging from $\delta^7\text{Li}=-2\text{‰}$ to 6‰ (Tomascak et al., 2016). Relative to the Li-isotope composition of the gas in the enstatite-chondrite-chondrule forming-region ($\delta^7\text{Li}=1\text{‰}$), that in carbonaceous-chondrite-chondrule forming-region is significantly small ($\delta^7\text{Li}=-11\text{‰}$). The Li-isotope composition of the Si-rich gas in the enstatite-chondrite-chondrule forming-region is more homogenized than that of the carbonaceous-chondrite-chondrule forming-region (Figure 3.13). It is possible that the smaller $\delta^7\text{Li}$ of the gas reflects the heterogeneity inherited from galactic-cosmic-ray components with ($^7\text{Li}/^6\text{Li}$)=1.5 that corresponds to $\delta^7\text{Li} \approx -900\text{‰}$ (Meneguzzi et al., 1971). If so, a correlation is expected for the B-isotope composition as well. The theoretical production ratio for B-isotopes is ($^{11}\text{B}/^{10}\text{B}$)=2.5, which was expected from the cross sections for spallation reactions of $^{12}\text{C}(p,\chi)^{10,11}\text{B}$, $^{14}\text{N}(p,\chi)^{10,11}\text{B}$, and $^{16}\text{O}(p,\chi)^{10,11}\text{B}$ by galactic cosmic-ray (Meneguzzi et al., 1971). Liu et al. (2023) determined both Li- and B-isotope composition of olivine grains in chondrules from the least altered chondrites but did not successfully identify a mixing trend in Li- and B-isotope compositions. Further analyses both of Li and B on the surface of enstatite from the igneous rims of chondrules from the least altered carbonaceous chondrites will reveal whether ‘lighter’ lithium and boron are implanted onto the surface of Solar System materials.

3.5 Conclusions

In situ O- and Li-isotope analyses for enstatite, FeO-rich pyroxene, olivine, glass, and cristobalite in chondrules from the Sahara 97103 EH3 chondrite were carried out.

The O-isotope composition of enstatite scatters around the intersection between the PCM and TF lines on oxygen three-isotope diagrams, similar to what was observed for Weisberg et al. (2011) and Weisberg et al. (2021). Almost all olivine grains in chondrules are anhedral in shape and poikilitically enclosed by enstatite. The O-isotope composition of olivine shows variation along PCM line. On combining the petrographic and O-isotope information, it was concluded that at least some olivines are relict.

The O-isotope composition of cristobalite was similar to or higher in $\delta^{18}\text{O}$ relative to that of enstatite in each chondrule, and without an elevation in $\Delta^{17}\text{O}$. O-isotope

thermometry reveals that cristobalite formed at a temperature ranging from 380°C to 1800°C or above. The O-isotope composition of some cristobalite grains are those of chondrule formation and some are of asteroidal origin. The $\Delta^{17}\text{O}$ of the glass is similar to that of enstatite. However, in some chondrules, the $\Delta^{17}\text{O}$ of the glass is higher than that of enstatite. It is possible that there the O-isotope composition of the melt evolved after the formation of enstatite.

The dependency between sulfidation (a process to form niningerite MgS in a chondrule) and silicification (a process that decreases the Mg/Si ratio in a chondrule) proposed by Lehner et al. (2013) was investigated with respect to the mineralogy. In chondrules with olivine, a significant abundance of niningerite was observed, supporting that sulfidation and silicification are independent processes. The addition of SiO_2 is necessary to form enstatite from olivine.

Olivine was found to be depleted in Eu and Yb. Here it is suggested that the chondrule melt was already depleted in Eu and Yb by the occurrence of oldhamite during the early stage of chondrule formation. Following such sulfidation to form oldhamite, olivine was crystallized. During the later stage of chondrule formation, silicification formed enstatite from olivine. Therefore, here it is proposed that a given chondrule did not necessarily interact with a reservoir that was enriched in both S and Si.

The equation $\text{Mg}_2\text{SiO}_4 + \text{SiO}_2 \rightarrow \text{Mg}_2\text{Si}_2\text{O}_6$ was used to understand how the O-isotope compositions of enstatite and olivine would change during silicification. It was then possible to estimate the O-isotope composition of the Si-rich gas. After estimating the O-isotope composition of the Si rich gas interacting with each chondrule, it was concluded that there could be a Si-rich gas with elevated $\Delta^{17}\text{O}$ similar to, or higher than the second trend line suggested by Weisberg et al. (2021).

In the same manner, the Li-isotope composition of the Si-rich gas was estimated to be $\delta^7\text{Li}=1\text{‰}$. The value is similar to that of whole EH3 chondrites, but significantly differs from that of the Si-rich gas in the carbonaceous-chondrite-chondrule forming-region ($\delta^7\text{Li}=-11\text{‰}$) inferred by Kunihiro et al. (2019b). The current study speculates that the Si-rich gas maintained Li-isotope heterogeneity across the Solar nebula, which was possibly inherited from light lithium synthesized by galactic cosmic-rays in the interstellar medium.

Supplementary Material

All Li- and O-isotope analyses are shown in Table 3.4. Trace-element compositions of chondrule constituents are shown in Table 3.5 and Figure 3.15 (all trace elements). All individual O-isotope analyses within individual chondrule is shown in Figure 3.18.

Table 3.1: The representative major-element compositions (wt%) of chondrule constituents in the Sahara 97103 EH3 chondrite: The analyses by EDS are indicated by an asterisk. A column with ‘–’ indicates that the measurement was below the detection limit.

chondrule	phase	[SiO ₂]	[TiO ₂]	[Al ₂ O ₃]	[Cr ₂ O ₃]	[FeO]	[MnO]	[MgO]	[CaO]	[Na ₂ O]	[K ₂ O]	[NiO]	total	remark
I6p	enstatite	58.47	0.11	0.46	0.27	0.46	0.19	38.30	0.35	–	–	–	98.6	En _{98.7} Fs _{0.7} Wo _{0.7}
	glass	76.28	–	16.84	–	0.14	–	0.10	0.17	7.50	0.55	–	101.6	An _{1.2} Ab _{94.3} Or _{4.5}
D6a-1	enstatite	58.68	–	0.13	0.67	1.93	0.20	36.26	0.18	–	–	–	98.1	En _{96.8} Fs _{2.9} Wo _{0.3}
	*glass	68.75	–	19.89	–	0.28	–	–	0.36	9.91	0.81	–	(≡100)	An _{1.9} Ab _{93.1} Or _{5.0}
D6a-0	enstatite	58.38	–	0.16	0.32	1.17	0.05	37.17	0.12	–	–	–	97.4	En ₉₈ Fs _{1.7} Wo _{0.2}
	*pyroxene (FeO-rich)	57.53	–	–	0.86	4.66	0.34	36.09	0.25	–	–	–	(≡100)	En _{92.8} Fs _{6.7} Wo _{0.5}
D3g	enstatite	58.21	0.19	0.87	0.35	0.47	0.29	37.00	0.46	–	–	–	97.9	En _{98.4} Fs _{0.7} Wo _{0.9}
	olivine	42.74	–	–	0.21	0.33	0.22	55.45	0.11	–	–	–	99.1	Fo _{99.3} Fa _{0.3}
	glass	69.71	0.06	18.89	–	0.16	–	0.67	2.92	6.05	0.39	–	98.9	An _{20.4} Ab _{76.4} Or _{3.3}
J5l	enstatite	59.01	0.09	1.55	0.43	0.61	0.33	36.78	0.38	–	–	–	99.2	En _{98.4} Fs _{0.9} Wo _{0.7}
	olivine	42.02	–	0.07	0.17	0.74	–	54.58	0.12	–	–	–	97.7	Fo _{99.3} Fa _{0.8}
	glass	61.50	0.09	21.62	0.07	0.08	–	3.20	5.66	5.83	0.45	0.06	98.6	An _{33.5} Ab _{63.3} Or _{3.2}
C5b	enstatite	59.07	0.06	0.16	0.38	0.55	0.13	37.60	0.21	–	–	–	98.2	En _{98.8} Fs _{0.8} Wo _{0.4}
	olivine	41.92	–	–	0.24	0.68	0.16	55.61	0.07	–	–	–	98.7	Fo _{99.3} Fa _{0.7}
	glass	75.77	–	16.42	–	0.11	–	1.07	0.15	6.56	0.56	–	100.7	An _{1.2} Ab _{93.5} Or _{5.2}
K4-1	enstatite	59.05	0.23	1.28	0.62	0.52	0.09	37.26	0.54	–	–	–	99.6	En _{98.2} Fs _{0.8} Wo _{1.0}
	olivine	41.21	–	–	0.33	0.89	0.08	54.53	0.14	–	–	–	97.2	Fo _{99.1} Fa _{0.9}
	olivine (young)	43.32	–	–	0.38	1.06	0.11	55.24	0.11	–	–	–	100.3	Fo _{98.9} Fa _{1.1}
	*glass	55.61	0.22	23.76	0.42	–	–	5.23	10.15	4.43	0.17	–	(≡100)	An _{55.3} Ab _{43.6} Or _{1.1}
K4-0	*enstatite	59.06	–	0.57	0.43	0.60	–	39.03	0.31	–	–	–	(≡100)	En _{98.6} Fs _{0.8} Wo _{0.6}
	olivine	41.55	–	–	0.24	0.51	0.14	54.54	0.17	–	–	–	97.2	Fo _{99.5} Fa _{0.5}
	*glass	54.75	–	26.65	–	–	–	3.77	8.68	5.92	0.24	–	(≡100)	An _{44.1} Ab _{54.4} Or _{1.5}
	glass (K-rich)	72.43	–	0.38	–	0.06	–	19.37	–	4.81	3.50	–	100.6	An _{0.1} Ab _{67.6} Or _{32.3}

Table 3.2: The O-isotope compositions of chondrule constituents in the Sahara 97103 EH3 chondrite: The averages were calculated from n spots. The standard deviations of $\delta^{18}\text{O}$, $\delta^{17}\text{O}$, and $\Delta^{17}\text{O}$ for a phase are shown as σ_{18} , σ_{17} , and σ_{Δ} . The covariance between $\delta^{18}\text{O}$ and $\delta^{17}\text{O}$ is shown as $\sigma_{17,18}$.

chondrule	phase	n	$\delta^{18}\text{O}$	σ_{18}	$\delta^{17}\text{O}$	σ_{17}	$\Delta^{17}\text{O}$	σ_{Δ}	$\sigma_{17,18}$
I6p	enstatite	6	5.56	0.19	3.41	0.33	0.52	0.31	0.03
	glass	6	7.54	1.08	4.93	0.77	1.01	0.33	0.77
	cristobalite	5	8.14	1.76	4.40	0.98	0.17	0.38	1.59
D6a-1	enstatite	5	5.70	0.29	3.00	0.52	0.04	0.51	0.03
	glass	5	6.47	0.83	3.75	0.92	0.38	0.60	0.66
	cristobalite	4	6.61	1.20	3.57	0.92	0.14	0.35	1.06
D6a-0	enstatite	4	6.21	0.58	3.45	0.28	0.22	0.35	0.04
	pyroxene (FeO-rich)	2	5.64	0.18	3.41	0.14	0.48	0.06	0.03
	cristobalite	1	10.80	—	5.16	—	-0.45	—	—
D3g	enstatite	12	6.12	0.63	3.03	0.42	-0.13	0.58	-0.10
	olivine	8	6.27	0.88	2.83	0.82	-0.43	0.43	0.68
	glass	6	7.05	0.71	4.73	0.45	1.06	0.21	0.28
J5l	enstatite	11	5.80	0.57	4.23	0.36	1.21	0.47	-0.01
	olivine	11	6.42	1.79	3.97	1.68	0.63	0.78	2.97
	glass	5	5.93	1.11	4.17	0.56	1.07	0.39	0.48
C5b	enstatite	11	6.64	0.71	3.28	0.64	-0.17	0.39	0.38
	olivine	17	7.34	0.81	3.53	0.97	-0.29	0.73	0.56
	glass	7	6.57	0.72	3.52	0.61	0.10	0.36	0.37
	cristobalite	3	8.25	0.53	4.01	0.48	-0.27	0.27	0.22
K4-1	enstatite	10	5.91	0.55	3.43	0.54	0.35	0.43	0.18
	olivine	5	6.18	0.39	3.02	0.48	-0.19	0.33	0.16
	olivine (young)	11	6.14	0.64	2.94	0.42	-0.25	0.29	0.19
	glass	8	5.37	0.93	3.11	0.64	0.32	0.27	0.55
K4-0	enstatite	6	6.37	0.65	3.01	0.33	-0.31	0.59	-0.12
	glass	2	5.82	0.19	3.17	0.37	0.15	0.27	0.07
	glass (K-rich)	5	8.29	1.24	5.30	0.69	0.99	0.28	0.78

Table 3.3: The Li-isotope compositions of chondrule constituents in the Sahara 97103 EH3 chondrite: The averages were calculated from n spots. The standard deviations of $\delta^7\text{Li}$ and $[\text{Li}]$ for a phase are shown as σ_δ and σ_{ab} . The covariance between $\delta^7\text{Li}$ and $[\text{Li}]$ is also shown as $\sigma_{\delta,\text{ab}}$.

chondrule	phase	n	$\delta^7\text{Li}$	σ_δ	$[\text{Li}]$	σ_{ab}	$\sigma_{\delta,\text{ab}}$
I6p	enstatite	7	0.18	0.67	4.01	1.77	0.31
	glass	2	-1.10	3.11	1.23	0.93	-2.88
D6a-1	enstatite	6	-3.01	2.03	1.04	0.42	-0.22
D6a-0	enstatite	5	-1.60	2.18	1.75	1.30	-0.25
D3g	enstatite	8	-1.79	2.61	4.38	5.93	12.33
	olivine	4	-5.45	2.40	0.43	0.09	-0.19
	glass	3	2.33	0.67	3.39	3.25	-1.32
J5l	enstatite	10	1.53	1.76	4.02	1.87	0.86
	olivine	5	-3.04	4.80	0.37	0.13	0.49
	glass	4	3.33	3.32	0.81	0.22	-0.47
C5b	enstatite	10	1.70	1.90	4.31	1.35	-0.50
	olivine	7	-2.19	2.10	0.48	0.15	0.20
	glass	3	18.23	4.97	1.72	1.10	-4.47
K4-1	enstatite	11	2.46	2.81	2.98	1.90	3.34
	olivine	1	2.50	—	0.64	—	—
	olivine (young)	6	1.18	5.86	0.57	0.29	-0.84
	glass	4	10.52	4.84	13.50	13.65	-55.94
K4-0	enstatite	3	2.50	3.15	0.45	0.10	-0.12
	olivine	1	-5.00	—	0.28	—	—
	glass (K-rich)	2	6.45	11.81	0.60	0.13	1.50

Table 3.4: The Li- and O-isotope compositions of chondrule constituents in the Sahara 97103 EH3 chondrite. Error is 1σ .

chd	phase	compo	Li spot	$\delta^7\text{Li}$	σ_δ	[Li]	σ_{ab}	O spot	$\delta^{18}\text{O}$	σ_{18}	$\delta^{17}\text{O}$	σ_{17}	$\Delta^{17}\text{O}$	σ_Δ
I6p	enstatite	En _{98.8} Fs _{0.9} Wo _{0.2}	liso-en-I6p@4779	0.60	0.56	4.79	0.40	oxy-opx-I6p@8714	5.49	0.2	3.43	0.4	0.56	0.2
		En _{98.7} Fs _{1.0} Wo _{0.3}	liso-en-I6p@4780	0.28	0.49	6.26	0.24	oxy-opx-I6p@8715	5.48	0.2	3.22	0.3	0.37	0.2
		En _{98.8} Fs _{0.9} Wo _{0.4}	liso-en-I6p@4781	1.25	0.44	3.75	0.12	oxy-opx-I6p@8716	5.81	0.2	4.01	0.4	1.00	0.2
		En _{98.8} Fs _{0.7} Wo _{0.4}	liso-en-I6p@4782	0.05	0.45	6.07	0.21	oxy-opx-I6p@8717	5.44	0.1	3.08	0.4	0.25	0.2
		En _{98.5} Fs _{1.0} Wo _{0.5}	liso-en-I6p@4783	-0.77	0.48	3.24	0.12	oxy-opx-I6p@8718	5.34	0.1	3.53	0.3	0.75	0.2
		En _{98.9} Fs _{0.7} Wo _{0.4}	liso-en-I6p@4784	-0.47	0.52	1.81	0.23	oxy-opx-I6p@8713	5.78	0.2	3.21	0.4	0.20	0.3
		En _{98.7} Fs _{0.7} Wo _{0.7}	liso-en-I6p@4785	0.35	0.68	2.17	0.10	-	-	-	-	-	-	-
	glass	An _{1.2} Ab _{94.3} Or _{4.5}	liso-gl-I6p@4900	1.10	3.00	0.57	0.03	oxy-gl-I6p@9160	7.92	0.1	5.54	0.3	1.42	0.2
		An _{0.3} Ab _{97.4} Or _{2.3}	liso-gl-I6p@4901	-3.30	3.20	1.88	0.21	oxy-gl-I6p@9159	8.81	0.1	5.95	0.3	1.37	0.2
		An ₀ Ab _{92.7} Or _{7.3}	-	-	-	-	-	oxy-gl-I6p@9161	8.00	0.1	5.15	0.3	0.99	0.2
		An _{1.9} Ab ₉₂ Or _{6.1}	-	-	-	-	-	oxy-gl-I6p@9162	7.25	0.2	4.49	0.3	0.73	0.2
		An _{1.1} Ab _{91.7} Or _{7.1}	-	-	-	-	-	oxy-gl-I6p@9163	5.60	0.2	3.84	0.3	0.92	0.2
		An _{1.3} Ab _{90.4} Or _{8.3}	-	-	-	-	-	oxy-gl-I6p@9164	7.65	0.2	4.60	0.3	0.62	0.2
		-	-	-	-	-	-	oxy-SiO ₂ -I6p@9234	8.83	0.1	4.94	0.4	0.35	0.2
	cristobalite	-	-	-	-	-	-	oxy-SiO ₂ -I6p@9230	5.69	0.2	3.40	0.3	0.45	0.2
		-	-	-	-	-	-	oxy-SiO ₂ -I6p@9231	8.24	0.2	4.64	0.3	0.37	0.2
		-	-	-	-	-	-	oxy-SiO ₂ -I6p@9232	10.49	0.1	5.61	0.3	0.17	0.2
		-	-	-	-	-	-	oxy-SiO ₂ -I6p@9233	7.47	0.2	3.39	0.3	-0.49	0.2
		-	-	-	-	-	-	-	-	-	-	-	-	-
D6a-1	enstatite	En _{96.6} Fs _{3.2} Wo _{0.2}	liso-en-D6a@4717	-2.50	1.10	1.36	0.06	-	-	-	-	-	-	-
		En _{96.7} Fs ₃ Wo _{0.3}	liso-en-D6a@4718	-0.30	1.10	0.70	0.07	oxy-opx-D6a@8721	5.32	0.2	3.15	0.4	0.38	0.3
		En _{96.8} Fs _{2.9} Wo _{0.3}	liso-en-D6a@4719	-1.20	1.10	0.72	0.05	oxy-opx-D6a@8733	5.97	0.2	3.24	0.4	0.14	0.3
		En _{96.7} Fs _{2.9} Wo _{0.4}	liso-en-D6a@4720	-3.79	0.87	1.73	0.11	oxy-opx-D6a@8722	5.64	0.2	2.08	0.5	-0.85	0.3
		En _{96.9} Fs _{2.7} Wo _{0.4}	liso-en-D6a@4721	-5.07	0.88	0.94	0.06	oxy-opx-D6a@8734	6.01	0.2	3.27	0.3	0.15	0.2
		En _{96.8} Fs _{2.9} Wo _{0.3}	liso-en-D6a@4722	-5.20	1.10	0.77	0.05	oxy-opx-D6a@8735	5.54	0.2	3.28	0.4	0.40	0.2
	glass	An ₀ Ab _{94.3} Or _{5.7}	-	-	-	-	-	oxy-gl-D6a@9165	7.32	0.2	4.03	0.4	0.22	0.2
		An _{2.7} Ab _{94.0} Or _{3.3}	-	-	-	-	-	oxy-gl-D6a@9166	5.58	0.2	3.31	0.4	0.40	0.3
		An _{4.2} Ab _{93.5} Or _{2.3}	-	-	-	-	-	oxy-gl-D6a@9167	5.87	0.1	2.87	0.4	-0.18	0.2
		An ₀ Ab _{98.5} Or _{1.5}	-	-	-	-	-	oxy-gl-D6a@9168	7.38	0.1	5.23	0.3	1.39	0.2
		An _{1.9} Ab _{93.1} Or _{5.0}	-	-	-	-	-	oxy-gl-D6a@9169	6.20	0.2	3.32	0.3	0.09	0.2
	cristobalite	-	-	-	-	-	-	oxy-SiO ₂ -D6a@9238	6.39	0.1	3.43	0.4	0.11	0.2
		-	-	-	-	-	-	oxy-SiO ₂ -D6a@9236	8.13	0.2	4.86	0.3	0.64	0.2

Table 3.4: Continued

chd	phase	compo	Li spot	$\delta^7\text{Li}$	σ_δ	[Li]	σ_{ab}	O spot	$\delta^{18}\text{O}$	σ_{18}	$\delta^{17}\text{O}$	σ_{17}	$\Delta^{17}\text{O}$	σ_Δ
		-	-	-	-	-	-	oxy-SiO2-D6a@9237	5.22	0.2	2.69	0.3	-0.03	0.3
		-	-	-	-	-	-	oxy-SiO2-D6a@9239	6.70	0.2	3.31	0.4	-0.17	0.2
D6a-0	enstatite	En _{96.3} Fs _{3.3} Wo _{0.5}	liso-en-D6a@4723	1.20	1.00	0.83	0.11	oxy-opx-D6a@8736	5.64	0.1	3.22	0.4	0.29	0.3
		En _{96.6} Fs _{3.1} Wo _{0.3}	liso-en-D6a@4724	-3.71	0.81	0.51	0.05	-	-	-	-	-	-	-
		En _{98.2} Fs _{1.5} Wo _{0.3}	liso-en-D6a@4725	-1.01	0.68	3.66	0.27	oxy-opx-D6a@8738	6.10	0.2	3.27	0.5	0.09	0.4
		En _{98.2} Fs _{0.8} Wo ₁	liso-en-D6a@4726	-3.90	0.86	2.48	0.17	oxy-opx-D6a@8741	7.01	0.2	3.49	0.3	-0.16	0.3
		En ₉₈ Fs _{1.7} Wo _{0.2}	liso-en-D6a@4727	-0.60	1.00	1.26	0.07	oxy-opx-D6a@8739	6.08	0.2	3.83	0.3	0.67	0.2
	pyroxene (FeO-rich)	En _{92.8} Fs _{6.7} Wo _{0.5}	-	-	-	-	-	oxy-opx-D6a@8743	5.76	0.2	3.51	0.4	0.52	0.3
		En _{90.6} Fs _{7.3} Wo _{2.1}	-	-	-	-	-	oxy-opx-D6a@8744	5.51	0.2	3.31	0.3	0.44	0.3
	cristobalite	-	-	-	-	-	-	oxy-SiO2-D6a@9235	10.80	0.1	5.16	0.3	-0.45	0.2
D3g	enstatite	En _{98.7} Fs _{1.1} Wo _{0.2}	liso-en-D3g@4761	-1.00	0.67	2.79	0.07	oxy-opx-D3g@8782	5.97	0.2	3.03	0.4	-0.07	0.3
		En _{98.9} Fs _{0.8} Wo _{0.4}	liso-en-D3g@4762	-3.77	0.72	1.96	0.18	oxy-opx-D3g@8778	5.86	0.2	3.56	0.3	0.51	0.3
		En _{98.8} Fs _{0.8} Wo _{0.4}	liso-en-D3g@4763	-2.08	0.54	2.91	0.39	oxy-opx-D3g@8777	5.30	0.2	3.01	0.4	0.25	0.3
		En _{98.7} Fs _{0.9} Wo _{0.4}	liso-en-D3g@4764	-2.25	0.55	2.52	0.20	oxy-opx-D3g@8776	6.35	0.2	2.26	0.4	-0.68	0.2
		En _{98.9} Fs _{0.7} Wo _{0.4}	liso-en-D3g@4765	-0.44	0.59	1.76	0.12	oxy-opx-D3g@8775	5.75	0.2	3.06	0.3	0.07	0.3
		En _{98.7} Fs _{0.7} Wo _{0.5}	liso-en-D3g@4766	-5.70	0.76	1.71	0.12	oxy-opx-D3g@8779	5.47	0.2	2.76	0.4	-0.09	0.3
		En _{98.4} Fs _{0.7} Wo _{0.9}	liso-en-D3g@4767	3.24	0.64	19.00	5.82	oxy-opx-D3g@9341	7.42	0.1	2.30	0.3	-1.56	0.2
		En _{98.7} Fs _{0.8} Wo _{0.4}	liso-en-D3g@4768	-2.30	1.10	2.38	0.18	-	-	-	-	-	-	-
		En _{98.8} Fs _{0.9} Wo _{0.3}	-	-	-	-	-	oxy-opx-D3g@8780	6.02	0.2	3.33	0.3	0.20	0.3
		En _{98.9} Fs _{0.7} Wo _{0.4}	-	-	-	-	-	oxy-opx-D3g@8783	6.01	0.2	3.03	0.3	-0.10	0.2
		En ₉₉ Fs ₁ Wo ₀	-	-	-	-	-	oxy-opx-D3g@9342	7.23	0.1	3.08	0.3	-0.68	0.3
		En _{97.5} Fs _{1.7} Wo _{0.8}	-	-	-	-	-	oxy-opx-D3g@8781	6.1	0.20	3.5	0.40	0.3	0.2
		En _{97.3} Fs _{1.9} Wo _{0.8}	-	-	-	-	-	oxy-opx-D3g@8784	5.98	0.2	3.39	0.3	0.28	0.3
	olivine	Fo _{99.6} Fa _{0.4}	liso-ol-D3g@4854	-7.90	2.00	0.53	0.08	oxy-ol-D3g@8795	6.97	0.2	3.51	0.4	-0.11	0.2
		Fo _{99.5} Fa _{0.5}	liso-ol-D3g@4855	-3.60	1.80	0.33	0.04	oxy-ol-D3g@8623	7.57	0.2	3.80	0.4	-0.14	0.3
		Fo _{99.3} Fa _{0.3}	liso-ol-D3g@4856	-3.20	1.30	0.40	0.05	oxy-ol-D3g@8797	7.08	0.2	3.61	0.3	-0.07	0.3
		Fo _{99.5} Fa _{0.5}	liso-ol-D3g@4857	-7.10	1.50	0.47	0.05	oxy-ol-D3g@8796	5.61	0.2	2.49	0.4	-0.43	0.3
		Fo _{99.7} Fa _{0.3}	-	-	-	-	-	oxy-ol-D3g@8627	5.18	0.2	1.74	0.4	-0.95	0.3
		Fo _{98.4} Fa _{1.6}	-	-	-	-	-	oxy-ol-D3g@8798	6.18	0.2	3.29	0.5	0.07	0.3
		Fo _{99.7} Fa _{0.3}	-	-	-	-	-	oxy-ol-D3g@9321	6.30	0.1	2.39	0.3	-0.88	0.2
		Fo _{99.3} Fa _{0.7}	-	-	-	-	-	oxy-ol-D3g@9322	5.28	0.1	1.82	0.3	-0.93	0.2
	glass	An _{35.9} Ab _{63.5} Or _{0.5}	liso-gl-D3g@4894	3.10	3.20	0.89	0.03	oxy-gl-D3g@9187	6.40	0.1	4.62	0.3	1.29	0.2

Table 3.4: Continued

chd	phase	compo	Li spot	$\delta^7\text{Li}$	σ_δ	[Li]	σ_{ab}	O spot	$\delta^{18}\text{O}$	σ_{18}	$\delta^{17}\text{O}$	σ_{17}	$\Delta^{17}\text{O}$	σ_Δ
		An _{46.2} Ab _{53.8} Or _{0.0}	liso-gl-D3g@4895	2.00	1.20	7.07	0.44	-	-	-	-	-	-	-
		An _{20.4} Ab _{76.4} Or _{3.3}	liso-gl-D3g@4896	1.90	3.30	2.21	0.27	oxy-gl-D3g@9186	6.23	0.1	4.11	0.4	0.88	0.2
		An ₀ Ab _{97.7} Or _{2.3}	-	-	-	-	-	oxy-gl-D3g@9188	7.57	0.1	4.73	0.4	0.79	0.2
		An _{2.2} Ab _{93.2} Or _{4.6}	-	-	-	-	-	oxy-gl-D3g@9189	6.64	0.1	4.42	0.3	0.97	0.2
		An _{1.1} Ab _{95.1} Or _{3.8}	-	-	-	-	-	oxy-gl-D3g@9190	7.83	0.1	5.31	0.4	1.24	0.2
		An ₁ Ab _{94.3} Or _{4.7}	-	-	-	-	-	oxy-gl-D3g@9191	7.64	0.1	5.18	0.4	1.20	0.2
J51	enstatite	En _{98.8} Fs _{0.8} Wo _{0.4}	liso-en-J51@4797	-0.15	0.60	5.56	0.20	oxy-opx-J51@8698	5.89	0.2	4.38	0.4	1.32	0.3
		En _{98.7} Fs _{0.7} Wo _{0.6}	liso-en-J51@4798	2.15	0.39	7.50	0.22	oxy-opx-J51@8699	5.60	0.2	3.99	0.4	1.08	0.3
		En _{98.8} Fs _{0.6} Wo _{0.6}	liso-en-J51@4799	3.19	0.51	2.73	0.16	-	-	-	-	-	-	-
		En _{98.9} Fs _{0.6} Wo _{0.5}	liso-en-J51@4800	2.38	0.42	4.27	0.40	oxy-opx-J51@8696	5.41	0.1	4.35	0.4	1.53	0.2
		En _{98.9} Fs _{0.8} Wo _{0.4}	liso-en-J51@4801	3.30	0.54	2.64	0.15	oxy-opx-J51@8695	5.37	0.1	3.94	0.4	1.15	0.2
		En _{98.3} Fs _{0.8} Wo _{0.9}	liso-en-J51@4802	2.25	0.57	3.24	0.21	oxy-opx-J51@8702	5.81	0.2	4.50	0.4	1.48	0.2
		En _{98.9} Fs _{0.6} Wo _{0.5}	liso-en-J51@4803	0.92	0.55	3.92	0.50	oxy-opx-J51@8693	5.83	0.2	4.14	0.4	1.11	0.3
		En _{98.9} Fs _{0.7} Wo _{0.5}	liso-en-J51@4804	0.24	0.55	2.08	0.16	oxy-opx-J51@8692	5.72	0.1	5.10	0.4	2.12	0.2
		En _{98.9} Fs _{0.7} Wo _{0.4}	liso-en-J51@4805	-2.08	0.59	2.04	0.19	oxy-opx-J51@8700	4.90	0.1	3.89	0.5	1.34	0.3
		En _{98.4} Fs _{0.9} Wo _{0.7}	liso-en-J51@4806	3.06	0.65	6.25	0.69	oxy-opx-J51@8701	5.76	0.1	4.18	0.4	1.18	0.2
		En _{98.7} Fs ₁ Wo _{0.3}	-	-	-	-	-	oxy-opx-J51@9337	7.01	0.2	3.86	0.4	0.22	0.3
		En _{98.9} Fs _{0.6} Wo _{0.5}	-	-	-	-	-	oxy-opx-J51@9338	6.53	0.2	4.17	0.4	0.78	0.3
	olivine	Fo _{99.4} Fa _{0.6}	liso-ol-J51@4869	-7.70	2.20	0.18	0.02	oxy-ol-J51@8599	6.90	0.2	4.46	0.4	0.87	0.2
		Fo _{99.3} Fa _{0.7}	liso-ol-J51@4870	-1.00	1.30	0.53	0.05	oxy-ol-J51@8597	7.04	0.2	4.70	0.3	1.04	0.2
		Fo _{99.3} Fa _{0.8}	liso-ol-J51@4871	3.00	1.70	0.41	0.05	oxy-ol-J51@8598	7.12	0.2	4.65	0.4	0.94	0.3
		Fo _{99.1} Fa _{0.9}	liso-ol-J51@4872	-8.20	1.60	0.29	0.02	-	-	-	-	-	-	-
		Fo _{99.4} Fa _{0.6}	liso-ol-J51@4873	-1.30	2.00	0.42	0.07	oxy-ol-J51@8600	7.18	0.1	4.27	0.4	0.54	0.2
		Fo _{99.3} Fa _{0.7}	-	-	-	-	-	oxy-ol-J51@8601	8.13	0.2	5.59	0.3	1.36	0.2
		Fo ₉₉ Fa ₁	-	-	-	-	-	oxy-ol-J51@9314	1.52	0.1	-0.72	0.3	-1.51	0.2
		Fo _{99.4} Fa _{0.6}	-	-	-	-	-	oxy-ol-J51@9315	6.58	0.1	3.60	0.3	0.18	0.2
		Fo _{99.1} Fa _{0.9}	-	-	-	-	-	oxy-ol-J51@9316	4.94	0.1	3.17	0.2	0.61	0.2
		Fo _{99.3} Fa _{0.7}	-	-	-	-	-	oxy-ol-J51@8602	7.20	0.2	4.66	0.3	0.91	0.3
		Fo _{99.3} Fa _{0.7}	-	-	-	-	-	oxy-ol-J51@8802	6.75	0.2	4.41	0.3	0.90	0.2
		Fo _{99.3} Fa _{0.7}	-	-	-	-	-	oxy-ol-J51@8596	7.23	0.2	4.89	0.4	1.13	0.3
	glass	An _{33.7} Ab _{65.4} Or _{0.9}	liso-gl-J51@4902	6.10	4.00	0.53	0.08	oxy-gl-J51@9147	5.66	0.1	3.88	0.3	0.94	0.2
		An _{41.3} Ab _{57.5} Or _{1.2}	liso-gl-J51@4903	4.40	2.40	0.73	0.08	oxy-gl-J51@9146	5.42	0.1	3.50	0.3	0.68	0.2

Table 3.4: Continued

chd	phase	compo	Li spot	$\delta^7\text{Li}$	σ_δ	[Li]	σ_{ab}	O spot	$\delta^{18}\text{O}$	σ_{18}	$\delta^{17}\text{O}$	σ_{17}	$\Delta^{17}\text{O}$	σ_Δ
		An _{33.5} Ab _{63.3} Or _{3.2}	liso-gl-J51@4904	-1.50	4.80	0.96	0.03	oxy-gl-J51@9145	4.97	0.1	3.99	0.3	1.40	0.3
		An _{18.2} Ab _{76.3} Or _{5.5}	liso-gl-J51@4905	4.30	3.00	1.00	0.18	oxy-gl-J51@9144	5.78	0.2	4.56	0.3	1.56	0.2
		An _{1.1} Ab _{93.9} Or _{5.0}	-	-	-	-	-	oxy-gl-J51@9148	7.84	0.1	4.9	0.3	0.79	0.2
C5b	enstatite	En _{99.8} Fs _{0.2} Wo ₀	liso-en-C5b@4740	3.95	0.47	4.33	0.35	oxy-opx-C5b@8756	7.75	0.1	3.99	0.4	-0.04	0.3
		En _{98.6} Fs _{1.1} Wo _{0.3}	liso-en-C5b@4741	2.32	0.48	3.64	0.21	oxy-opx-C5b@8764	6.23	0.2	3.04	0.4	-0.20	0.2
		En _{98.7} Fs _{0.9} Wo _{0.4}	liso-en-C5b@4742	4.88	0.39	2.49	0.10	oxy-opx-C5b@8757	7.19	0.2	3.95	0.3	0.21	0.3
		En _{98.6} Fs ₁ Wo _{0.4}	liso-en-C5b@4743	0.37	0.65	7.30	0.32	oxy-opx-C5b@8758	7.46	0.2	4.19	0.4	0.31	0.3
		En _{99.9} Fs ₀ Wo ₀	liso-en-C5b@4744	2.16	0.58	4.39	0.31	oxy-opx-C5b@8759	6.74	0.2	3.83	0.4	0.33	0.3
		En _{98.1} Fs _{1.5} Wo _{0.4}	liso-en-C5b@4745	0.96	0.60	4.66	0.43	oxy-opx-C5b@8760	6.51	0.2	3.15	0.4	-0.24	0.3
		En _{98.3} Fs _{1.4} Wo _{0.3}	liso-en-C5b@4746	1.47	0.65	4.57	0.48	oxy-opx-C5b@8761	5.98	0.2	2.83	0.3	-0.28	0.3
		En _{98.8} Fs ₁ Wo _{0.3}	liso-en-C5b@4747	-0.47	0.45	4.21	0.51	oxy-opx-C5b@8762	5.48	0.2	2.63	0.4	-0.22	0.3
		En _{98.8} Fs _{0.8} Wo _{0.4}	liso-en-C5b@4748	2.63	0.53	4.96	0.18	oxy-opx-C5b@8763	6.29	0.1	3.07	0.4	-0.20	0.3
		En _{98.7} Fs _{0.8} Wo _{0.5}	liso-en-C5b@4749	-1.25	0.74	2.59	0.26	-	-	-	-	-	-	-
		En _{98.5} Fs _{1.0} Wo _{0.5}	-	-	-	-	-	oxy-opx-C5b@9339	6.10	0.1	2.17	0.3	-1.00	0.2
		En _{98.6} Fs _{1.1} Wo _{0.3}	-	-	-	-	-	oxy-opx-C5b@9340	7.27	0.2	3.23	0.3	-0.55	0.2
	olivine	Fo _{98.8} Fa _{1.2}	liso-ol-C5b@4847	-2.50	1.70	0.43	0.05	oxy-ol-C5b@8615	7.62	0.2	3.40	0.4	-0.56	0.3
		Fo _{98.8} Fa _{1.3}	liso-ol-C5b@4847	-2.50	1.70	0.43	0.05	oxy-ol-C5b@8799	7.22	0.2	4.02	0.4	0.26	0.2
		Fo _{99.1} Fa _{0.9}	liso-ol-C5b@4848	0.40	1.80	0.50	0.06	oxy-ol-C5b@8616	7.29	0.2	4.21	0.3	0.42	0.3
		Fo _{99.1} Fa _{0.10}	liso-ol-C5b@4848	0.40	1.80	0.50	0.06	oxy-ol-C5b@8800	7.54	0.3	4.46	0.4	0.54	0.3
		Fo ₉₉ Fa ₁	liso-ol-C5b@4849	-1.00	1.70	0.47	0.08	oxy-ol-C5b@8614	7.21	0.2	3.46	0.4	-0.29	0.3
		Fo ₉₉ Fa ₁	liso-ol-C5b@4850	-5.50	2.10	0.38	0.06	oxy-ol-C5b@8613	7.08	0.2	3.98	0.5	0.30	0.3
		Fo _{99.2} Fa _{0.8}	liso-ol-C5b@4851	-1.50	2.50	0.49	0.08	oxy-ol-C5b@8617	7.17	0.1	3.23	0.5	-0.50	0.2
		Fo ₉₉ Fa ₁	liso-ol-C5b@4852	-0.80	1.20	0.79	0.09	oxy-ol-C5b@8619	10.21	0.2	5.54	0.4	0.23	0.3
		Fo _{99.3} Fa _{0.7}	liso-ol-C5b@4853	-4.4	1.7	0.31	0.08	oxy-ol-C5b@8801	6.76	0.2	3.16	0.4	-0.36	0.3
		Fo _{99.3} Fa _{0.7}	liso-ol-C5b@4853	-4.4	1.7	0.31	0.08	oxy-ol-C5b@8618	7.38	0.2	3.79	0.4	-0.05	0.2
		Fo _{99.3} Fa _{0.7}	-	-	-	-	-	oxy-ol-C5b@8620	7.49	0.2	4.25	0.4	0.35	0.3
		Fo _{99.1} Fa _{0.9}	-	-	-	-	-	oxy-ol-C5b@8621	7.64	0.2	4.16	0.4	0.19	0.3
		En _{98.6} Fs _{0.9} Wo _{0.5}	-	-	-	-	-	oxy-ol-C5b@8622	7.01	0.2	3.71	0.4	0.06	0.3
		Fo _{99.1} Fa _{0.9}	-	-	-	-	-	oxy-ol-C5b@9317	6.65	0.1	2.41	0.3	-1.04	0.2
		Fo _{99.7} Fa _{0.3}	-	-	-	-	-	oxy-ol-C5b@9318	7.15	0.2	2.07	0.3	-1.65	0.3
		Fo _{99.1} Fa _{0.9}	-	-	-	-	-	oxy-ol-C5b@9319	6.95	0.1	1.65	0.3	-1.96	0.2
		Fo _{99.3} Fa _{0.7}	-	-	-	-	-	oxy-ol-C5b@9320	6.41	0.1	2.46	0.3	-0.87	0.2

Table 3.4: Continued

chd	phase	compo	Li spot	$\delta^7\text{Li}$	σ_δ	[Li]	σ_{ab}	O spot	$\delta^{18}\text{O}$	σ_{18}	$\delta^{17}\text{O}$	σ_{17}	$\Delta^{17}\text{O}$	σ_Δ
	glass	An ₃₉ Ab _{59.1} Or _{1.9}	liso-gl-C5b@4897	12.50	2.00	2.77	0.27	oxy-gl-C5b@9172	5.84	0.2	3.17	0.3	0.13	0.2
		An _{1.2} Ab _{93.5} Or _{5.2}	liso-gl-C5b@4898	21.00	4.20	0.57	0.09	oxy-gl-C5b@9171	6.41	0.2	3.56	0.3	0.22	0.2
		An _{0.3} Ab _{98.6} Or _{1.1}	liso-gl-C5b@4899	21.20	3.60	1.81	0.11	oxy-gl-C5b@9170	7.87	0.2	4.78	0.3	0.68	0.2
		An _{0.0} Ab _{97.0} Or _{3.0}	-	-	-	-	-	oxy-gl-C5b@9173	6.87	0.1	3.49	0.3	-0.09	0.2
		An ₀ Ab _{96.1} Or _{3.9}	-	-	-	-	-	oxy-gl-C5b@9174	6.40	0.1	2.84	0.3	-0.49	0.2
		An ₀ Ab _{98.5} Or _{1.5}	-	-	-	-	-	oxy-gl-C5b@9175	5.76	0.1	3.24	0.3	0.25	0.2
		An ₀ Ab _{96.2} Or _{3.8}	-	-	-	-	-	oxy-gl-C5b@9176	6.87	0.2	3.58	0.3	0.01	0.3
	cristobalite	-	-	-	-	-	-	oxy-SiO2-C5b@9255	7.94	0.2	3.99	0.3	-0.13	0.2
		-	-	-	-	-	-	oxy-SiO2-C5b@9254	8.86	0.2	4.49	0.4	-0.11	0.3
		-	-	-	-	-	-	oxy-SiO2-C5b@9256	7.95	0.2	3.54	0.3	-0.58	0.2
K4-1	enstatite	En _{98.3} Fs _{1.4} Wo _{0.4}	liso-en-k4@4819	0.71	0.70	3.14	0.12	oxy-opx-K4@8677	5.82	0.2	3.34	0.4	0.31	0.3
		En _{98.4} Fs _{1.2} Wo _{0.5}	liso-en-k4@4820	4.43	0.48	6.29	0.29	oxy-opx-K4@8678	5.52	0.2	3.34	0.4	0.47	0.2
		En _{98.2} Fs _{1.0} Wo _{0.8}	liso-en-k4@4821	3.74	0.47	5.89	0.44	oxy-opx-K4@8689	5.89	0.2	3.97	0.4	0.90	0.3
		En _{98.1} Fs _{1.5} Wo _{0.4}	liso-en-K4@4822	0.90	0.90	1.52	0.09	oxy-opx-K4@8676	5.75	0.1	3.63	0.4	0.64	0.2
		En _{98.4} Fs _{0.9} Wo _{0.7}	liso-en-K4@4824	-2.90	1.00	0.54	0.07	oxy-opx-K4@8691	4.76	0.2	2.57	0.3	0.09	0.3
		En _{97.7} Fs _{2.3} Wo _{0.5}	liso-en-K4@4827	7.20	1.10	2.78	0.21	oxy-opx-K4@8673	6.29	0.1	3.50	0.4	0.23	0.3
		En _{98.4} Fs _{1.2} Wo _{0.4}	liso-en-K4@4828	3.70	0.54	2.78	0.21	oxy-opx-K4@8672	6.65	0.2	3.54	0.3	0.08	0.2
		En _{98.3} Fs _{1.2} Wo _{0.5}	liso-en-K4@4829	1.27	0.82	1.29	0.05	oxy-opx-K4@8670	5.67	0.2	2.93	0.4	-0.02	0.2
		En _{98.3} Fs _{1.2} Wo _{0.6}	liso-en-K4@4830	1.80	0.75	1.41	0.07	-	-	-	-	-	-	-
		En _{98.3} Fs _{0.9} Wo _{0.8}	liso-en-K4@4831	5.61	0.38	4.67	0.59	oxy-opx-K4@8669	6.43	0.2	4.46	0.5	1.12	0.3
		En _{98.2} Fs _{0.8} Wo _{1.0}	liso-en-K4@4832	0.59	0.71	2.50	0.26	oxy-opx-K4@8668	6.32	0.2	3.01	0.4	-0.28	0.3
	olivine	Fo _{99.1} Fa _{0.9}	liso-ol-K4@4875	2.50	1.90	0.64	0.07	oxy-ol-K4@8592	6.45	0.1	3.33	0.4	-0.02	0.2
		Fo _{98.7} Fa _{1.3}	-	-	-	-	-	oxy-ol-K4@8591	5.61	0.2	2.46	0.3	-0.46	0.2
		Fo _{98.6} Fa _{1.4}	-	-	-	-	-	oxy-ol-K4@8595	6.55	0.2	3.11	0.4	-0.29	0.3
		Fo _{99.1} Fa _{0.9}	-	-	-	-	-	oxy-ol-K4@8804	6.35	0.2	3.59	0.4	0.29	0.3
		Fo _{99.2} Fa _{0.8}	-	-	-	-	-	oxy-ol-K4@9313	5.94	0.1	2.61	0.3	-0.48	0.2
	olivine (young)	Fo _{98.7} Fa _{1.3}	liso-ol-K4@4876	-5.70	1.10	1.05	0.12	oxy-ol-K4@8576	4.87	0.1	2.58	0.3	0.05	0.2
		Fo _{98.7} Fa _{1.3}	liso-ol-K4@4876	-5.70	1.10	1.05	0.12	oxy-ol-K4@8594	6.06	0.1	3.36	0.3	0.21	0.2
		Fo _{98.9} Fa _{1.1}	liso-ol-K4@4877	-2.40	1.50	0.38	0.06	oxy-ol-K4@8577	7.05	0.2	3.25	0.4	-0.41	0.2
		Fo _{98.9} Fa _{1.1}	liso-ol-K4@4877	-2.40	1.50	0.38	0.06	oxy-ol-K4@8803	6.43	0.2	2.99	0.4	-0.36	0.3
		Fo _{98.6} Fa _{1.4}	liso-ol-K4@4878	-0.10	1.60	0.25	0.03	oxy-ol-K4@8579	5.84	0.2	2.68	0.3	-0.36	0.2
		Fo _{98.8} Fa _{1.2}	liso-ol-K4@4879	-0.10	1.20	0.74	0.03	oxy-ol-K4@8578	6.53	0.2	3.07	0.4	-0.32	0.3

Table 3.4: Continued

chd	phase	compo	Li spot	$\delta^7\text{Li}$	σ_δ	[Li]	σ_{ab}	O spot	$\delta^{18}\text{O}$	σ_{18}	$\delta^{17}\text{O}$	σ_{17}	$\Delta^{17}\text{O}$	σ_Δ
	glass	Fo _{98.3} Fa _{1.7}	liso-ol-K4@4880	11.10	1.80	0.39	0.06	oxy-ol-K4@8573	6.60	0.2	3.01	0.5	-0.42	0.3
		Fo _{99.0} Fa _{1.0}	liso-ol-K4@4881	4.30	2.00	0.58	0.03	oxy-ol-K4@8574	6.76	0.2	3.46	0.5	-0.05	0.3
		Fo _{99.0} Fa _{1.1}	liso-ol-K4@4881	4.30	2.00	0.58	0.03	oxy-ol-K4@8575	6.10	0.2	3.32	0.4	0.15	0.4
		Fo _{98.7} Fa _{1.3}	-	-	-	-	-	oxy-ol-K4@9311	5.33	0.1	2.12	0.3	-0.65	0.2
		Fo _{99.3} Fa _{0.7}	-	-	-	-	-	oxy-ol-K4@9312	5.94	0.1	2.5	0.3	-0.59	0.2
		An _{61.1} Ab _{38.2} Or _{0.7}	liso-gl-K4@4906	11.00	2.80	1.77	0.86	oxy-gl-K4@9135	4.35	0.1	2.72	0.3	0.46	0.2
		An _{48.6} Ab _{50.4} Or _{0.9}	liso-gl-K4@4909	17.10	2.50	1.57	0.07	oxy-gl-K4@9132	6.22	0.1	3.56	0.3	0.33	0.3
		An ₆₅ Ab _{34.5} Or _{0.5}	liso-gl-K4@4910	7.86	0.94	25.32	4.57	oxy-gl-K4@9134	4.19	0.2	2.00	0.3	-0.17	0.2
		An _{60.1} Ab _{38.7} Or _{1.1}	liso-gl-K4@4911	6.10	0.92	25.32	4.71	oxy-gl-K4@9133	5.27	0.2	3.17	0.3	0.43	0.3
		An _{52.7} Ab _{46.5} Or _{0.7}	-	-	-	-	-	oxy-gl-K4@9141	5.46	0.2	3.11	0.3	0.27	0.2
		An _{50.8} Ab _{46.8} Or _{2.5}	-	-	-	-	-	oxy-gl-K4@9142	5.58	0.1	2.95	0.4	0.05	0.2
		An _{55.3} Ab _{43.6} Or _{1.1}	-	-	-	-	-	oxy-gl-K4@9193	4.89	0.1	3.16	0.4	0.62	0.2
		An _{8.9} Ab _{86.5} Or _{4.6}	-	-	-	-	-	oxy-gl-K4@9194	7.00	0.1	4.23	0.4	0.60	0.2
K4-0	enstatite	En _{99.7} Fs _{0.2} Wo _{0.1}	liso-en-K4@4823	-0.60	1.70	0.54	0.07	oxy-opx-K4@8690	5.42	0.2	3.19	0.4	0.37	0.3
		En _{99.9} Fs _{0.0} Wo _{0.1}	liso-en-K4@4825	5.70	1.20	0.46	0.06	-	-	-	-	-	-	-
		En _{99.7} Fs _{1.2} Wo _{0.1}	liso-en-K4@4826	2.40	1.30	0.35	0.02	oxy-opx-K4@8675	5.86	0.2	3.42	0.5	0.37	0.3
		En _{98.3} Fs _{1.2} Wo _{0.5}	-	-	-	-	-	oxy-opx-K4@9333	6.66	0.1	2.93	0.3	-0.53	0.2
		En _{98.6} Fs _{0.8} Wo _{0.6}	-	-	-	-	-	oxy-opx-K4@9334	6.66	0.1	3.22	0.3	-0.24	0.2
		En _{98.2} Fs _{1.0} Wo _{0.8}	-	-	-	-	-	oxy-opx-K4@9335	7.25	0.1	2.75	0.3	-1.02	0.2
		En ₁₀₀ Fs ₀ Wo ₀	-	-	-	-	-	oxy-opx-K4@9336	6.38	0.1	2.53	0.3	-0.79	0.2
	olivine	Fo _{99.5} Fa _{0.5}	liso-ol-K4@4874	-5.00	1.70	0.28	0.03	-	-	-	-	-	-	-
	glass	An _{48.6} Ab _{49.0} Or _{2.4}	-	-	-	-	-	oxy-gl-K4@9143	5.68	0.1	2.91	0.3	-0.04	0.2
		An _{44.1} Ab _{54.4} Or _{1.5}	-	-	-	-	-	oxy-gl-K4@9192	5.95	0.2	3.43	0.4	0.34	0.3
	glass (K-rich)	An _{0.1} Ab _{67.6} Or _{32.3}	liso-gl-K4@4907	-1.90	4.00	0.51	0.08	oxy-gl-K4@9136	9.03	0.2	5.82	0.3	1.12	0.2
		An ₀ Ab _{66.8} Or _{33.2}	liso-gl-K4@4908	14.80	4.30	0.69	0.05	oxy-gl-K4@9137	9.77	0.2	5.73	0.3	0.66	0.2
		An ₀ Ab _{37.2} Or _{62.8}	-	-	-	-	-	oxy-gl-K4@9138	6.48	0.1	4.11	0.3	0.74	0.3
		An ₀ Ab _{54.3} Or _{45.7}	-	-	-	-	-	oxy-gl-K4@9139	7.90	0.2	5.43	0.3	1.32	0.3
		An ₀ Ab _{68.9} Or _{31.1}	-	-	-	-	-	oxy-gl-K4@9140	8.25	0.1	5.42	0.3	1.13	0.2

Table 3.5: Trace-element compositions of chondrule constituents in the Sahara 97103 EH3 chondrite. The concentration is expressed in $\mu\text{g} \cdot \text{g}^{-1}$. Averages are calculated from n spots. Standard deviations of $[Z]$ in a phase are shown as σ_Z .

chondrule	phase	n	[Li]	σ_{Li}	[Sr]	σ_{Sr}	[Y]	σ_{Y}	[Zr]	σ_{Zr}	[Nb]	σ_{Nb}	[Ba]	σ_{Ba}	[La]	σ_{La}	[Ce]	σ_{Ce}	[Pr]	σ_{Pr}	[Nd]	σ_{Nd}	[Sm]	σ_{Sm}
I6p	glass	5	1.1	0.5	8	6	8	5	19	14	0.3	0.4	5	3	0.3	0.3	0.9	0.9	0.2	0.2	1.1	0.8	0.13	0.07
	enstatite	7	4	2	0.9	0.9	0.3	0.4	1	2	0.02	0.02	2	3	0.05	0.09	0.2	0.3	0.02	0.03	0.1	0.2	0.1	0.1
	CaS	1	5	1	58.0	0.5	76	2	24.1	0.9	0.06	0.02	5.8	0.7	14.9	0.3	40	1	6.6	0.3	35	1	15.7	0.8
D6a-1	cristobalite	5	0.4	0.2	2	2	0.9	0.9	1	1	0.02	0.01	2	2	0.3	0.5	1	1	0.1	0.1	0.5	0.6	0.3	0.4
	glass	2	3	3	31	37	13	7	26	14	2	2	11	10	0.5	0.5	2	1	0.3	0.2	2	1	0.7	0.9
	enstatite	9	1.0	0.4	1	2	0.3	0.5	0.6	0.6	0.04	0.02	1	1	0.02	0.02	0.1	0.2	0.02	0.03	0.1	0.2	0.02	0.01
D6a-0	enstatite	3	2	1	2	3	0.2	0.1	0.9	0.7	0.019	0.003	1.4	0.7	0.011	0.006	0.03	0.02	0.006	0.004	0.02	0.01	0.02	0.03
	MgS	1	0.23	0.06	6.33	0.09	1.38	0.04	9	1	0.066	0.009	0.4	0.1	0.005	0.002	0.007	0.005	0.002	0.001	0.08	0.02	0.04	0.02
	glass	5	2.1	0.7	37	56	13	17	12	10	0.3	0.5	9	10	0.5	0.7	3	4	1	1	5	7	0.5	0.8
D3g	olivine	4	0.4	0.1	0.9	0.2	0.2	0.1	0.3	0.4	0.029	0.009	1.2	0.4	0.025	0.005	0.08	0.02	0.015	0.004	0.11	0.04	0.04	0.01
	enstatite	11	3	2	1.3	0.9	0.6	0.5	1.2	0.8	0.03	0.03	1.3	0.6	0.01	0.01	0.06	0.05	0.02	0.01	0.11	0.07	0.03	0.02
	glass	5	3	5	149	61	11	14	36	34	0.7	0.8	31	20	2	1	4	4	0.6	0.8	4	4	1	2
J51	olivine	4	0.46	0.05	0.7	0.8	0.14	0.06	0.1	0.2	0.03	0.03	0.5	0.2	0.007	0.005	0.01	0.02	0.004	0.002	0.03	0.02	0.01	0.01
	enstatite	11	4	2	1	1	0.3	0.1	2	2	0.02	0.01	2	1	0.02	0.03	0.04	0.04	0.009	0.009	0.05	0.04	0.01	0.01
	glass	5	1.5	0.3	5	5	8	5	27	15	0.7	0.6	3	1	0.9	0.7	3	3	0.5	0.4	3	2	0.2	0.2
C5b	olivine	8	0.5	0.1	0.4	0.6	0.08	0.05	0.06	0.03	0.02	0.01	1	1	0.01	0.01	0.02	0.02	0.004	0.002	0.03	0.02	0.011	0.009
	enstatite	11	4	2	2	5	0.5	0.4	1	1	0.1	0.2	2	2	0.08	0.08	0.2	0.2	0.03	0.03	0.2	0.1	0.1	0.2
	MgS	2	1.0	0.3	12.0	0.2	1.14	0.02	5	5	0.0314	0.0002	4.7	0.8	0.02	0.01	0.022	0.009	0.005	0.003	0.050	0.002	0.03	0.01
K4-1	CaS	1	1.8	0.2	18	1	5.1	0.3	17	1	0.4	0.1	8.4	0.5	1.56	0.07	3.1	0.2	0.45	0.03	2.1	0.1	0.90	0.07
	glass	5	7	11	171	46	17	4	39	6	2	1	25	5	2	1	6	3	0.8	0.5	5	2	1.4	0.7
	olivine	4	0.53	0.09	1.3	0.9	0.3	0.3	2	3	0.04	0.03	2	2	0.02	0.02	0.1	0.1	0.03	0.03	0.1	0.1	0.02	0.02
K4-0	olivine (young)	6	0.7	0.2	1	3	0.10	0.07	0.06	0.02	0.03	0.01	2	4	0.008	0.008	0.02	0.02	0.02	0.03	0.03	0.02	0.01	0.01
	enstatite	8	3	2	3	7	0.2	0.2	0.4	0.3	0.022	0.007	2	4	0.007	0.007	0.02	0.01	0.005	0.006	0.04	0.05	0.03	0.02
	glass	5	0.5	0.2	4	4	0.2	0.3	3	6	0.05	0.08	2	2	0.01	0.01	0.01	0.01	0.003	0.002	0.02	0.01	0.03	0.02
	enstatite	4	0.8	0.7	0.8	0.6	0.07	0.03	1.8	0.5	0.012	0.007	1.4	0.9	0.004	0.002	0.007	0.004	0.004	0.002	0.02	0.01	0.010	0.008
	MgS	6	0.6	0.3	8	2	1.0	0.7	4.5	0.8	0.036	0.009	1	1	0.010	0.004	0.010	0.005	0.003	0.002	0.03	0.01	0.05	0.05
chondrule	phase	n	[Eu]	σ_{Eu}	[Tb]	σ_{Tb}	[Gd]	σ_{Gd}	[Dy]	σ_{Dy}	[Ho]	σ_{Ho}	[Er]	σ_{Er}	[Tm]	σ_{Tm}	[Yb]	σ_{Yb}	[Lu]	σ_{Lu}	[Hf]	σ_{Hf}	[Pb]	σ_{Pb}
I6p	glass	5	0.03	0.02	0.2	0.1	0.8	0.5	1.4	1.0	0.5	0.3	0.8	0.4	0.11	0.05	0.10	0.05	0.19	0.09	1.0	0.4	4	6
	enstatite	7	0.006	0.003	0.01	0.02	0.1	0.1	0.07	0.09	0.009	0.007	0.04	0.05	0.006	0.007	0.03	0.03	0.02	0.01	0.1	0.1	0.6	0.5
	CaS	1	2.8	0.2	4.0	0.1	21.5	0.5	22	1	3.8	0.2	7.2	0.5	1.03	0.04	14.3	0.4	1.1	0.1	3.7	0.3	91	7
D6a-1	cristobalite	5	0.02	0.02	0.05	0.06	0.2	0.2	0.2	0.3	0.02	0.01	0.1	0.1	0.01	0.01	0.1	0.2	0.011	0.009	0.10	0.08	0.9	0.7
	glass	2	0.15	0.09	0.4	0.2	1	1	2	2	0.7	0.3	1.4	1.0	0.2	0.1	0.6	0.5	0.28	0.08	1.0	0.3	4	5
	enstatite	9	0.006	0.003	0.02	0.03	0.05	0.09	0.1	0.1	0.03	0.05	0.05	0.07	0.01	0.01	0.02	0.01	0.02	0.02	0.09	0.08	0.4	0.2
D6a-0	enstatite	3	0.004	0.002	0.003	0.002	0.01	0.01	0.03	0.01	0.009	0.003	0.03	0.03	0.008	0.004	0.04	0.03	0.01	0.01	0.10	0.09	0.6	0.1
	MgS	1	0.017	0.004	0.017	0.006	0.04	0.02	0.13	0.04	0.051	0.009	0.16	0.02	0.033	0.005	0.29	0.04	0.054	0.008	0.08	0.03	1.6	0.4
	glass	5	0.14	0.16	0.4	0.5	2	2	2	3	0.5	0.5	1	2	0.2	0.3	0.2	0.3	0.3	0.4	0.5	0.2	2	2
D3g	olivine	4	0.006	0.007	0.009	0.003	0.04	0.01	0.06	0.03	0.013	0.004	0.04	0.02	0.005	0.002	0.029	0.009	0.009	0.003	0.007	0.004	1.0	0.3
	enstatite	11	0.006	0.002	0.02	0.02	0.08	0.07	0.1	0.1	0.03	0.02	0.09	0.08	0.01	0.01	0.05	0.04	0.02	0.01	0.08	0.05	0.7	0.3
	glass	5	0.6	0.5	0.3	0.4	1	2	2	2	0.4	0.4	1	1	0.2	0.2	1	1	0.3	0.2	1.0	0.6	1.3	0.5
J51	olivine	4	0.007	0.003	0.002	0.001	0.011	0.003	0.02	0.01	0.011	0.006	0.03	0.02	0.004	0.001	0.04	0.02	0.018	0.007	0.020	0.002	0.7	0.2
	enstatite	11	0.008	0.004	0.006	0.004	0.02	0.02	0.04	0.04	0.02	0.01	0.04	0.03	0.008	0.004	0.04	0.01	0.015	0.004	0.11	0.16	0.4	0.2
	glass	5	0.08	0.09	0.3	0.1	1.4	0.8	2	1	0.4	0.2	1.1	0.5	0.13	0.06	0.3	0.5	0.2	0.2	1.05	0.57	3	3
C5b	olivine	8	0.003	0.002	0.002	0.002	0.006	0.004	0.01	0.01	0.003	0.002	0.011	0.008	0.003	0.002	0.02	0.01	0.006	0.004	0.01	0.01	2.0	0.5
	enstatite	11	0.011	0.008	0.010	0.005	0.06	0.04	0.07	0.05	0.02	0.01	0.07	0.04	0.009	0.007	0.08	0.06	0.02	0.02	0.09	0.09	1.3	0.7
	MgS	2	0.074	0.006	0.01	0.01	0.039	0.005	0.16	0.01	0.034	0.007	0.099	0.002	0.032	0.003	0.31	0.08	0.038	0.004	0.048	0.005	2.15	0.09
K4-1	CaS	1	0.82	0.06	0.22	0.03	1.11	0.09	1.11	0.07	0.31	0.03	0.64	0.06	0.11	0.01	1.7	0.1	0.070	0.008	0.50	0.09	57	3
	glass	5	0.5	0.1	0.45	0.09	2.1	0.5	3.0	0.7	0.7	0.2	1.66	0.38	0.23	0.05	1.0	0.5	0.30	0.07	1.1	0.3	1.1	0.5
	olivine	4	0.007	0.009	0.01	0.02	0.07	0.05	0.05	0.06	0.03	0.03	0.05	0.06	0.009	0.009	0.032	0.009	0.01	0.01	0.06	0.06	0.9	0.1
K4-0	olivine (young)	6	0.006	0.004	0.003	0.003	0.006	0.004	0.02	0.01	0.007	0.006	0.02	0.01	0.005	0.003	0.03	0.03	0.01	0.01	0.02	0.02	1.1	0.4
	enstatite	8	0.01	0.02	0.01	0.01	0.03	0.04	0.06	0.09	0.03	0.04	0.04	0.05	0.008	0.009	0.04	0.02	0.02	0.02	0.04	0.02	0.4	0.2
	glass	5	0.02	0.01	0.005	0.004	0.012	0.007	0.017	0.009	0.003	0.004	0.02	0.02	0.006	0.006	0.03	0.06	0.01	0.01	0.04	0.07	1.2	0.6
	enstatite	4	0.008	0.004	0.002	0.001	0.006	0.004	0.015	0.007	0.007	0.001	0.016	0.009	0.003	0.001	0.02	0.02	0.01	0.01	0.11	0.07	0.6	0.3
	MgS	6	0.03	0.01	0.01	0.01	0.04	0.06	0.1	0.1	0.04	0.04	0.1	0.1	0.03	0.02	0.3	0.1	0.03	0.03	0.04	0.03	2.0	0.6

Table 3.6: Trace element compositions (in $\mu\text{g} \cdot \text{g}^{-1}$) of silicate melts reconstructed based on partitioning coefficients against olivine and enstatite.

chondrule	phase	[Li]	[Sr]	[Y]	[Zr]	[Nb]	[Ba]	[La]	[Ce]	[Pr]	[Nd]	[Sm]
I6p	low-Ca px	19.0	-	9.52	218	0.04	-	23.1	58.4	6.95	27.5	7.69
D6a-1	low-Ca px	4.58	-	9.70	112	0.09	-	8.11	32.1	6.03	19.3	2.27
D6a-0	low-Ca px	8.28	-	13.4	131	0.08	-	11.9	49.2	8.87	26.8	2.56
D3g	low-Ca px	14.3	-	18.1	226	0.07	-	6.71	23.0	5.20	25.1	3.60
	ol	0.90	1320	34.5	864	859	4750	917	1344	-	398	32.3
J5l	low-Ca px	18.7	-	8.21	307	0.05	-	10.6	14.9	3.01	11.1	1.64
	ol	1.07	437	15.2	186	534	1590	215	147	-	64.8	6.94
C5b	low-Ca px	18.4	-	14.1	243	0.18	-	38.5	61.2	9.27	35.6	15.6
	ol	1.10	284	8.35	86.2	489	2490	386	181	-	74.9	10.2
K4-1	low-Ca px	14.0	-	7.56	66.3	0.05	-	3.21	5.72	1.84	9.22	3.33
	ol	1.24	1770	26.3	2170	889	11000	676	656	-	201	21.1
	ol-young	1.58	94.7	9.58	87.8	520	477	208	149	-	70.2	7.64
K4-0	low-Ca px	3.86	-	2.23	327	0.03	-	2.01	2.78	1.21	3.70	1.22

chondrule	phase	[Eu]	[Tb]	[Gd]	[Dy]	[Ho]	[Er]	[Tm]	[Yb]	[Lu]	[Hf]	[Pb]
I6p	low-Ca px	1.25	0.75	6.35	3.22	0.36	1.29	0.15	0.74	0.32	9.38	-
D6a-1	low-Ca px	1.42	0.97	3.80	2.88	1.20	1.63	0.22	0.38	0.31	10.6	-
D6a-0	low-Ca px	1.08	0.98	5.30	4.00	1.30	1.94	0.31	0.67	0.42	7.96	-
D3g	low-Ca px	1.43	1.21	6.31	6.39	1.12	2.81	0.32	1.02	0.31	9.82	-
	ol	9.51	-	49.1	45.8	-	3.23	-	1.04	0.32	20.3	-
J5l	low-Ca px	1.75	0.39	1.71	1.62	0.70	0.93	0.21	0.84	0.30	13.1	-
	ol	8.82	-	9.25	11.7	-	2.08	-	1.50	0.45	17.9	-
C5b	low-Ca px	2.50	0.61	4.69	3.15	0.76	2.07	0.24	1.82	0.31	10.6	-
	ol	3.86	-	4.63	9.57	-	0.86	-	0.73	0.16	13.7	-
K4-1	low-Ca px	2.61	0.50	2.25	2.84	1.18	1.35	0.21	0.83	0.34	5.18	-
	ol	9.71	-	42.3	32.4	-	3.21	-	1.04	0.35	55.6	-
	ol-young	7.68	-	5.32	12.1	-	1.42	-	1.19	0.34	10.4	-
K4-0	low-Ca px	1.86	0.09	0.46	0.67	0.29	0.52	0.09	0.41	0.20	13.7	-

Table 3.7: Partitioning coefficients for olivine-melt and enstatite-melt.

source	phase	Li	Sr	Y	Zr	Nb	Ba	La	Ce	Pr	Nd	Sm
Kennedy et al. (1993)	ol-PO49	–	0.0015	0.0094	0.00068	0.00005	0.00032	0.00003	0.0001	–	0.00042	0.0011
Ottolini et al. (2008)	ol	0.427	–	–	–	–	–	–	–	–	–	–
	en	0.211	–	–	–	–	–	–	–	–	–	–
Cartier et al. (2014)	en (1 σ)	–	–	0.03 (1)	0.006 (3)	0.4 (8)	–	0.002 (2)	0.003 (2)	0.003 (2)	0.004 (2)	0.008 (4)

source	phase	Eu	Tb	Gd	Dy	Ho	Er	Tm	Yb	Lu	Hf	Pb
Kennedy et al. (1993)	ol-PO49	0.00075	–	0.0012	0.0014	–	0.013	–	0.03	0.039	0.0011	–
Ottolini et al. (2008)	ol	–	–	–	–	–	–	–	–	–	–	–
	en	–	–	–	–	–	–	–	–	–	–	–
Cartier et al. (2014)	en (1 σ)	0.005 (2)	0.017 (7)	0.012 (5)	0.022 (9)	0.026 (9)	0.03 (1)	0.04 (1)	0.05 (1)	0.05 (2)	0.008 (3)	–

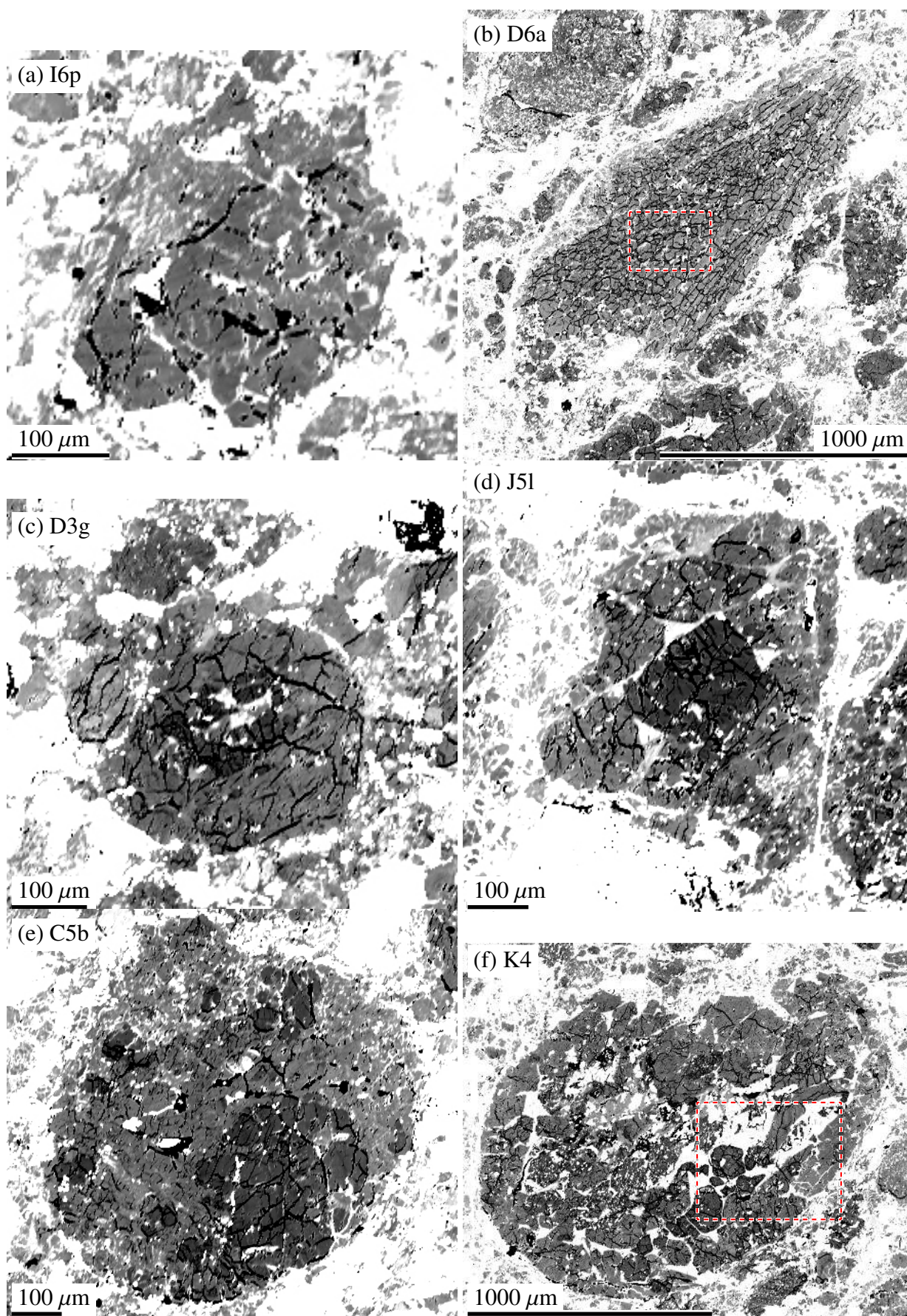


Figure 3.1: BSE images of chondrules: (a) I6p, (b) D6a, (c) D3g, (d) J5l, (e) C5b, and (f) K4.

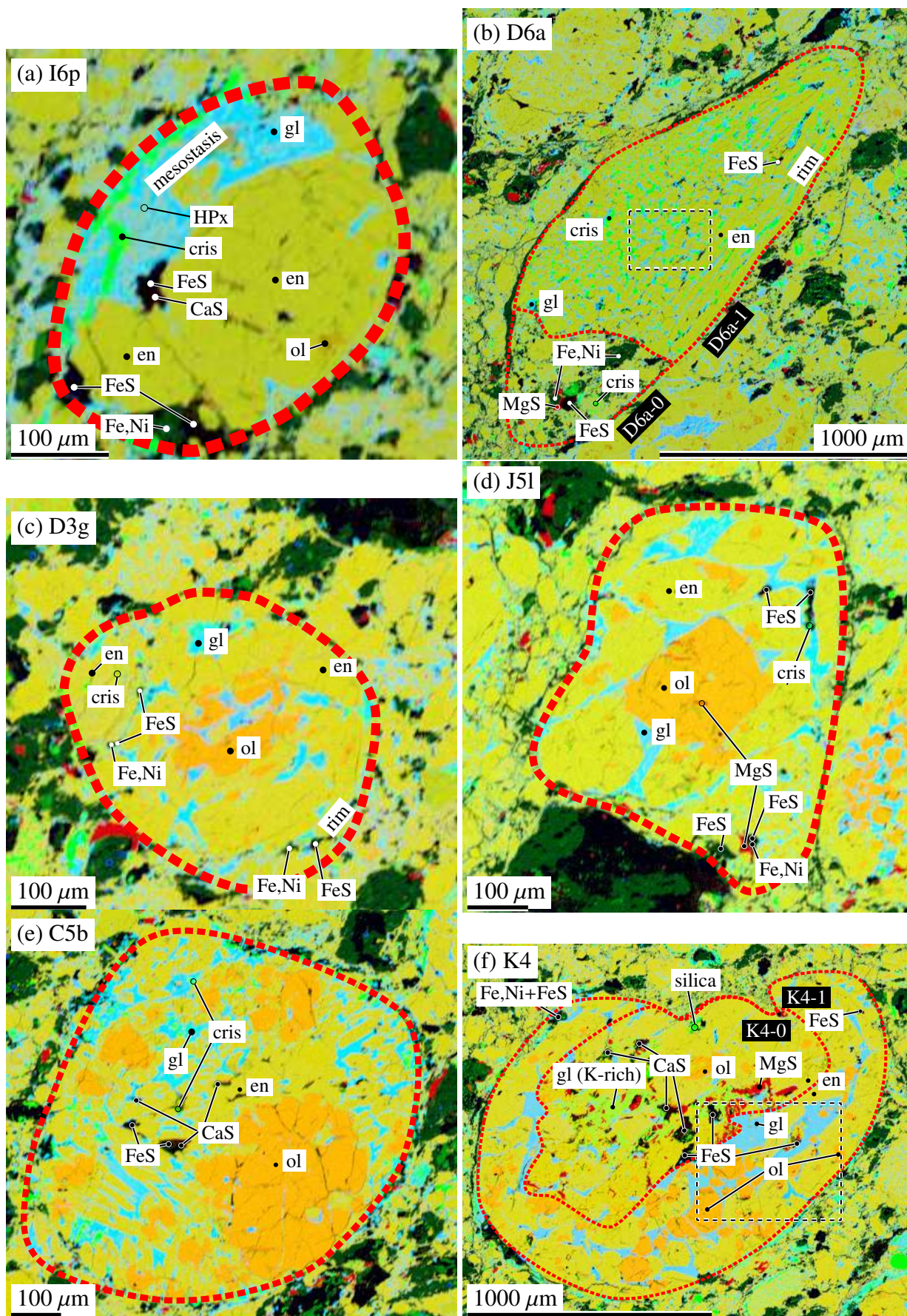


Figure 3.2: Mg-Si-Al element maps of chondrules: Mg, Si, and Al are assigned to the red, green, and blue channels, respectively. (a) I6p, (b) D6a, (c) D3g, (d) J5l, (e) C5b, and (f) K4. The area with yellow, orange, cyan, light green, and red corresponds to low-Ca pyroxene (en), olivine (ol), glass (gl), cristobalite (cris) or silica (SiO_2), and MgS , respectively. FeS , CaS , and Fe,Ni are shown as black.

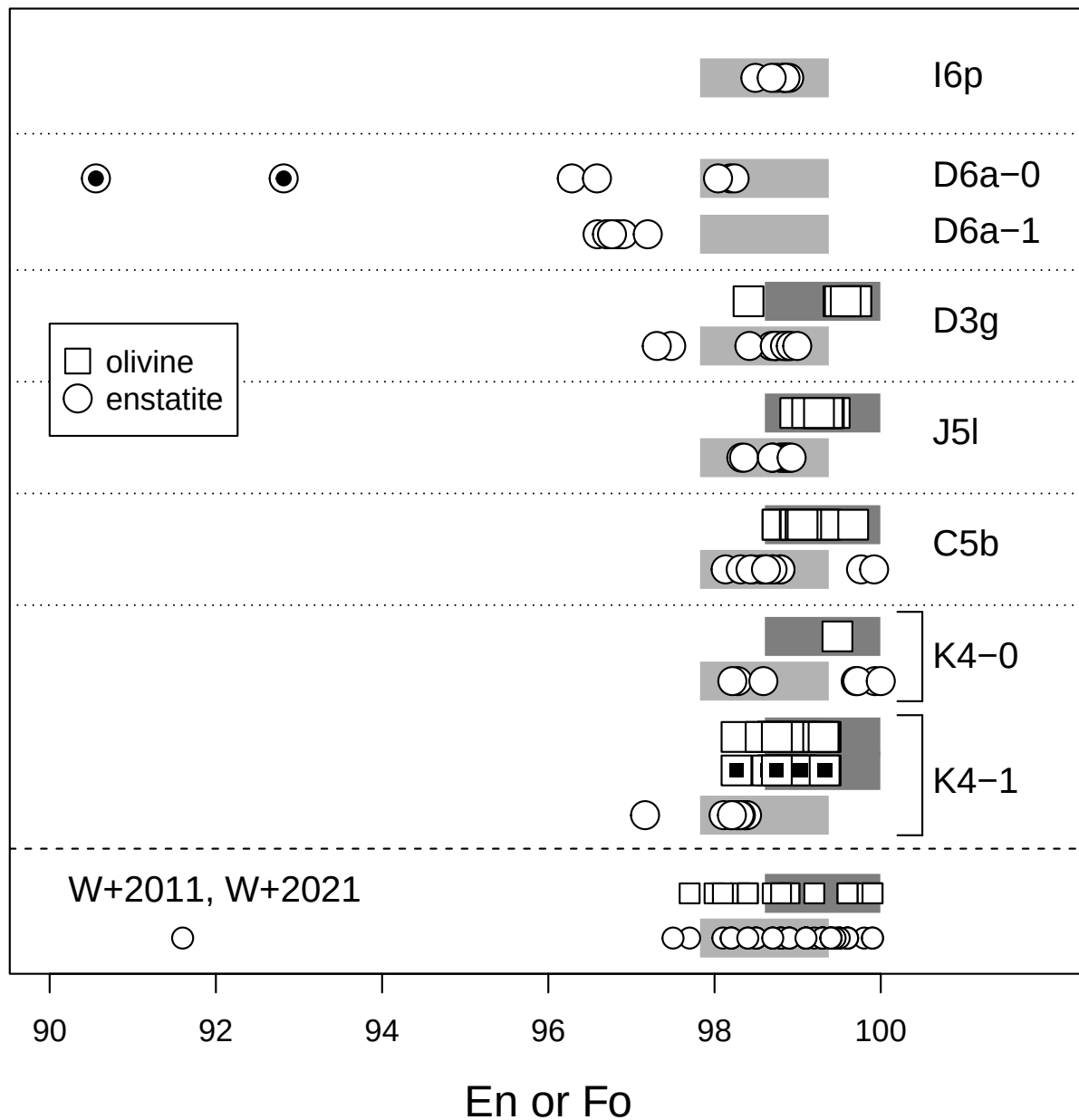


Figure 3.3: The $\frac{\text{Mg}}{\text{Mg}+\text{Fe}}$ ratio of enstatite (En) and olivine (Fo) in the chondrules studied here: En and Fo are shown by a circle and square, respectively. Values from Weisberg et al. (2011) and Weisberg et al. (2021) are shown for comparison. The gray zone indicates the 'typical range' for En and Fo, which is defined by I6p, D3g, and J5l. FeO-rich pyroxene and young olivine are shown by a black core in a symbol.

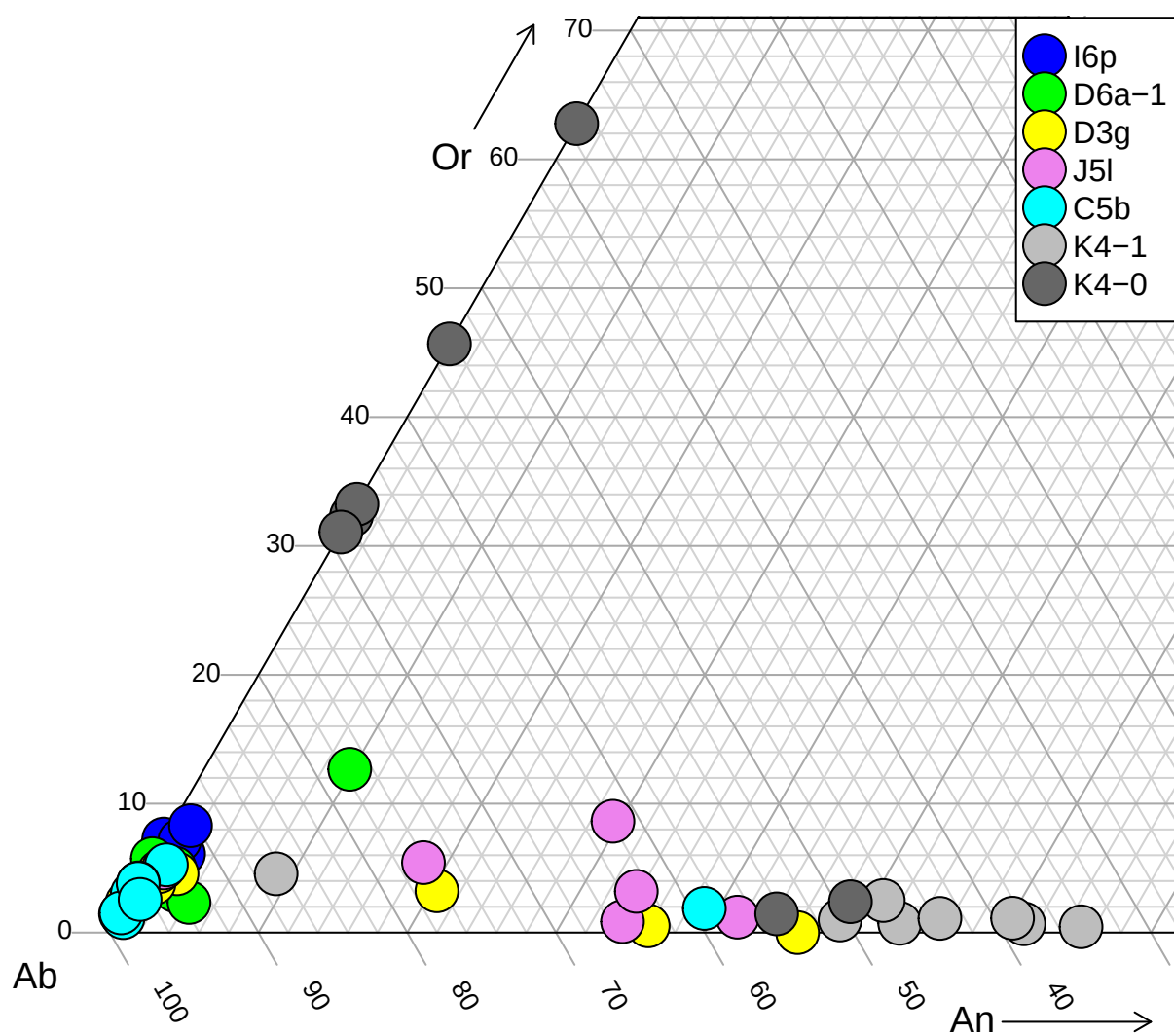


Figure 3.4: The major-element composition of glass: Or, Ab, and An are calculated as $\frac{K}{K+Na+Ca}$, $\frac{Na}{K+Na+Ca}$, and $\frac{Ca}{K+Na+Ca}$, respectively.

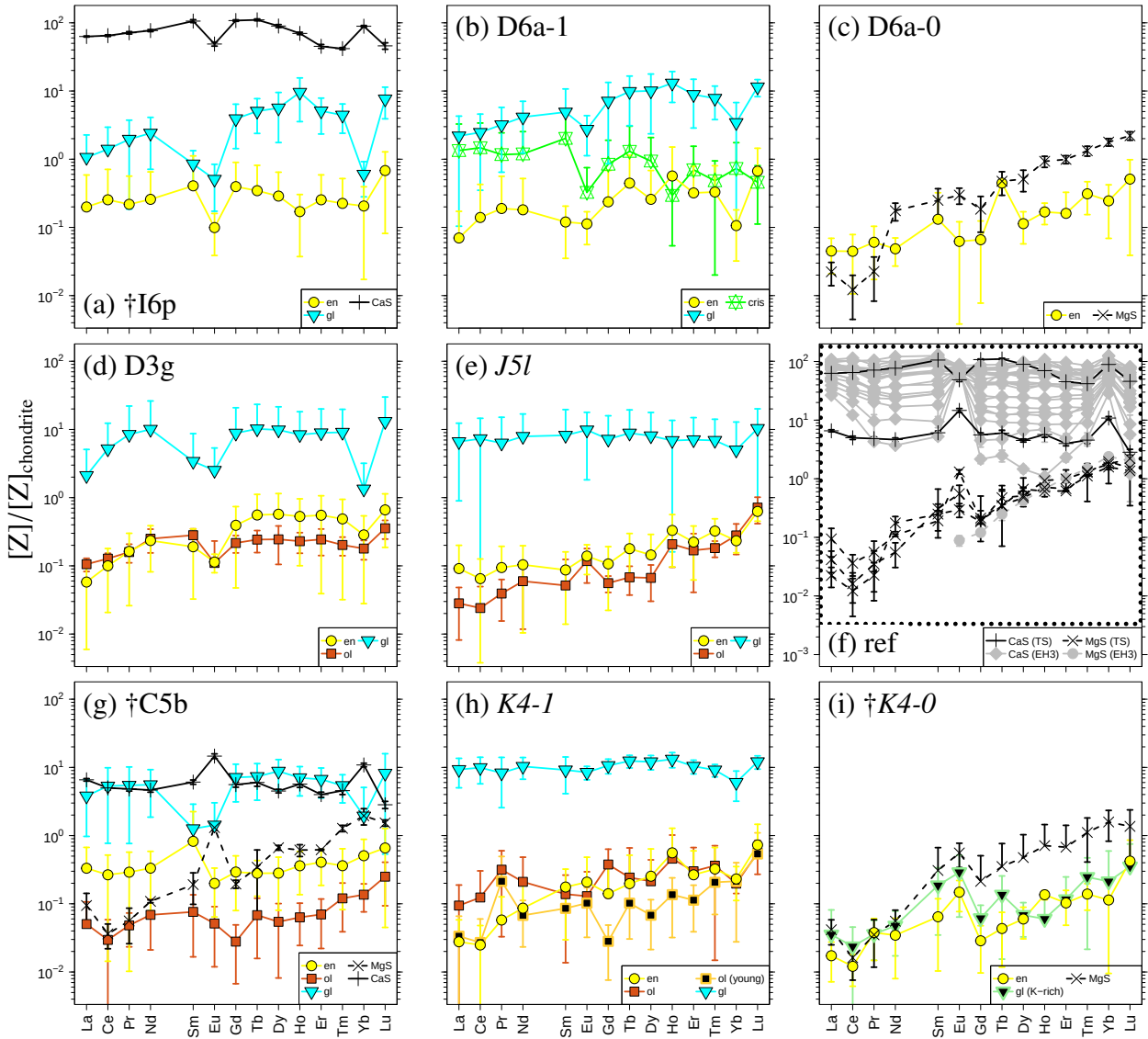


Figure 3.5: Rare-earth-element patterns of individual chondrule constituents in the Sahara 97103 EH3 chondrite: (a) †I6p, (b) D6a-1, (c) D6a-0, (d) D3g, (e) *J5l*, (f) reference, (g) †C5b, (h) *K4-1*, and (i) †K4-0. Occurrence of oldhamite within a chondrule is shown by symbol †. In reference panel, sulfides by this study (TS) and those from EH3 by Crozaz and Lundberg (1995) and Ham-mouda et al. (2022) are shown. In reference panel, range for individual panel is shown by dot rectangle. Trace-element compositions are normalized by those by Wasson and Kallemeyn (1988).

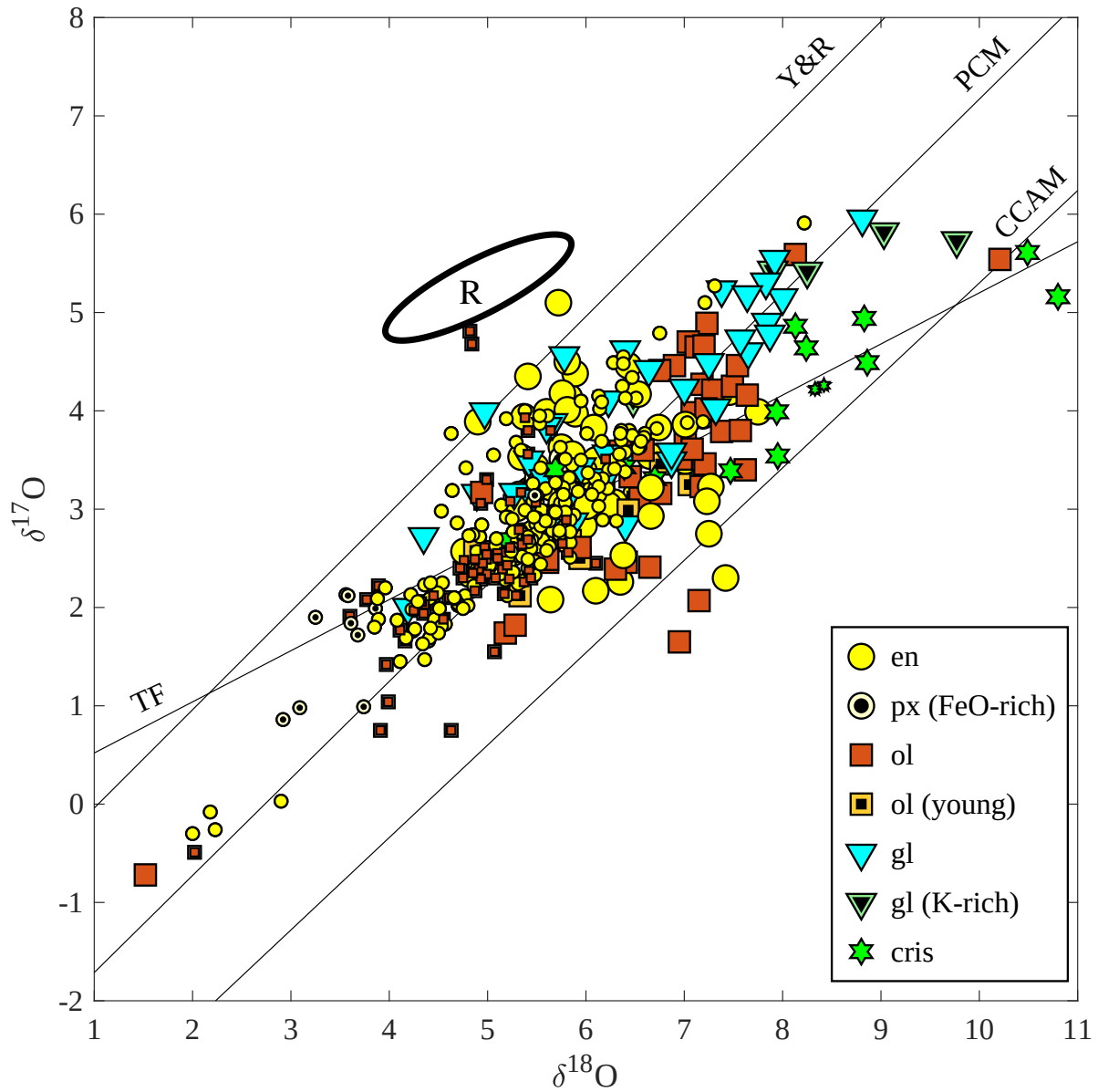


Figure 3.6: The O-isotope compositions of chondrule constituents in EH3 and EL3 chondrites. All individual spots from this study, Weisberg et al. (2011), and Weisberg et al. (2021) are shown. Enstatite, olivine, glass, and cristobalite are shown by circle (yellow), square (red), reverse triangle (cyan), and hexagon (green), respectively. FeO-rich pyroxene, young olivine, and K-rich glass are shown by circle (yellow), square (orange), and reverse triangle (green) with filled symbol, respectively. Analyses by Weisberg et al. (2011) and Weisberg et al. (2021) are shown by smaller symbols. Range of O-isotope composition for R chondrites are shown for comparison (Weisberg et al., 1991; Schulze et al., 1994).

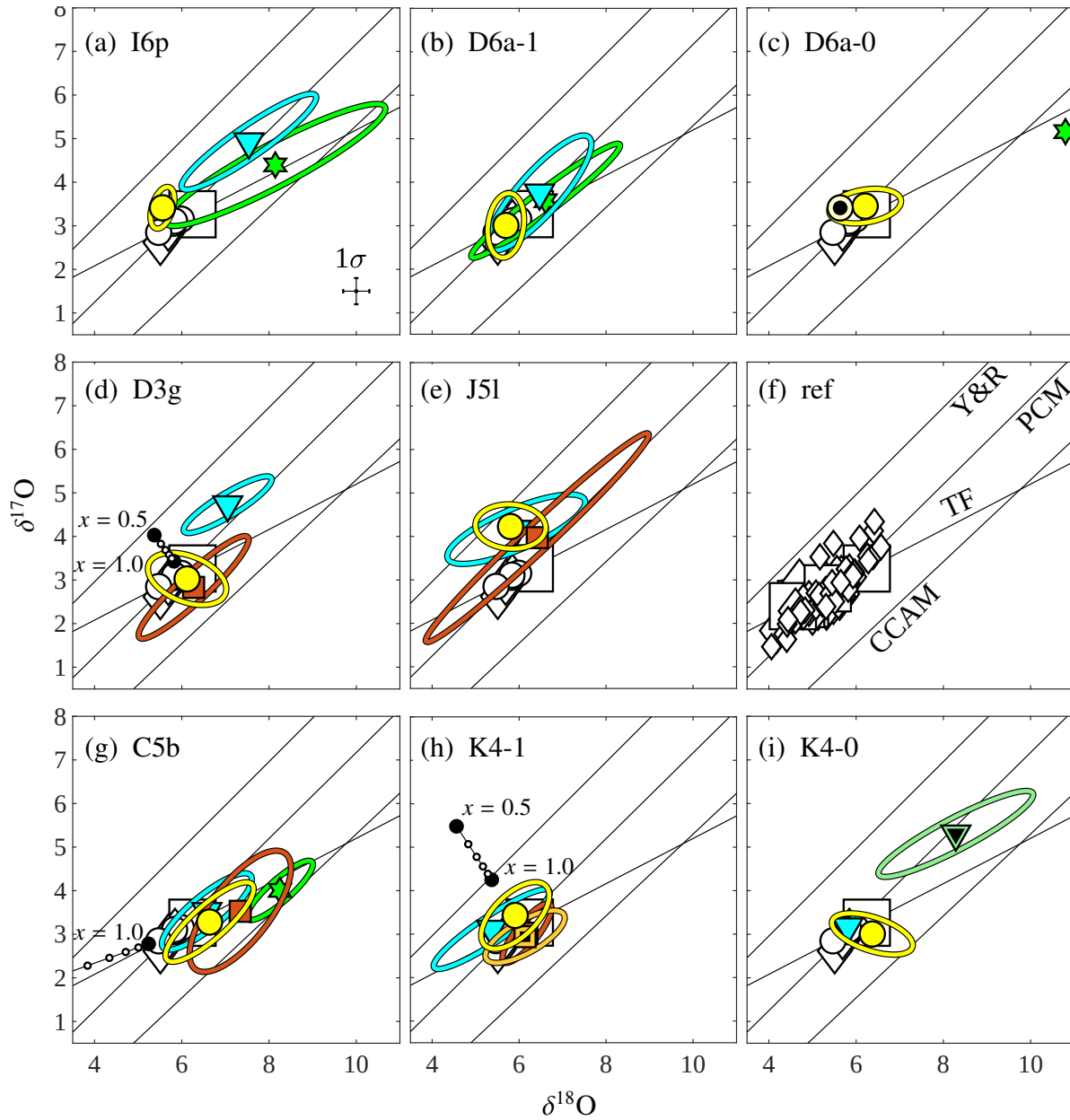


Figure 3.7: The O-isotope compositions (average and range) of individual chondrule constituents in the Sahara 97103 EH3 chondrite: (a) I6p, (b) D6a-1, (c) D6a-0, (d) D3g, (e) J5l, (f) references, (g) C5b, (h) K4-1, and (i) K4-0. See the caption for Figure 3.6 for symbol explanation. The range of compositions are shown by ovals (see Figure 3.18 for individual spots). The panel for individual chondrules, whole chondrite, whole chondrules, and aggregates of enstatite in Sahara 97103 (Tanaka and Nakamura, 2017) are shown by open square, open diamond, and open circle, respectively. In the reference panel, whole EH3 chondrites, whole EH3 chondrules (Clayton et al., 1984; Tanaka and Nakamura, 2017), and calculated whole EH3 and EL3 chondrules (Weisberg et al., 2021) are shown by open square, open diamond, and smaller open diamond, respectively.

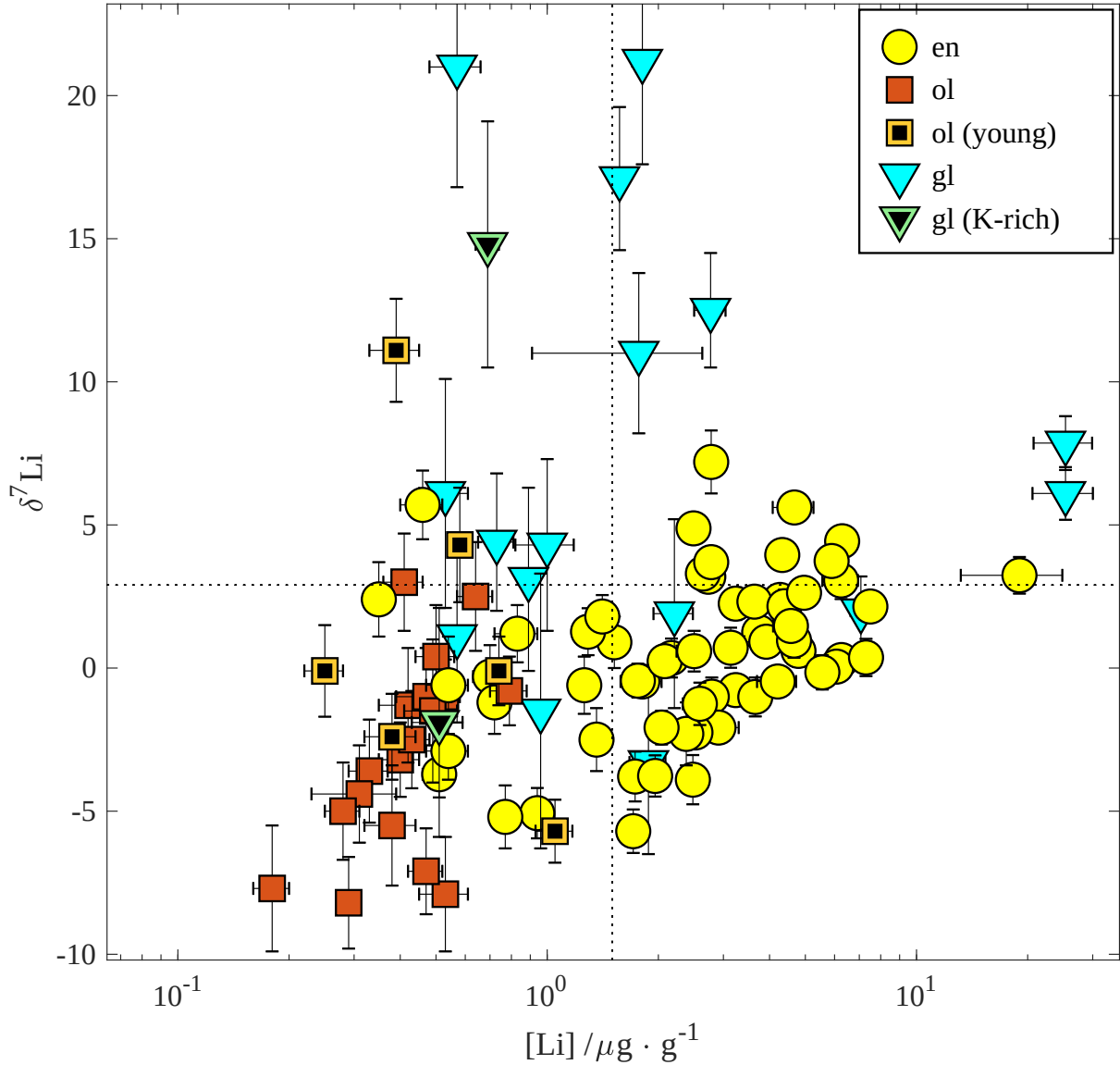


Figure 3.8: The Li isotope-composition and concentration of the six chondrules studied here: The whole EH3 chondrite value (Seitz et al., 2007) is shown by horizontal and vertical dot lines. Enstatite, olivine, and glass are shown by circle (yellow), square (red), and reverse triangle (cyan), respectively. Young olivine and K-rich glass are shown by square (orange) and reverse triangle (green) with a filled symbol, respectively. Length of error bars on some analyses are smaller than the size of the symbols.

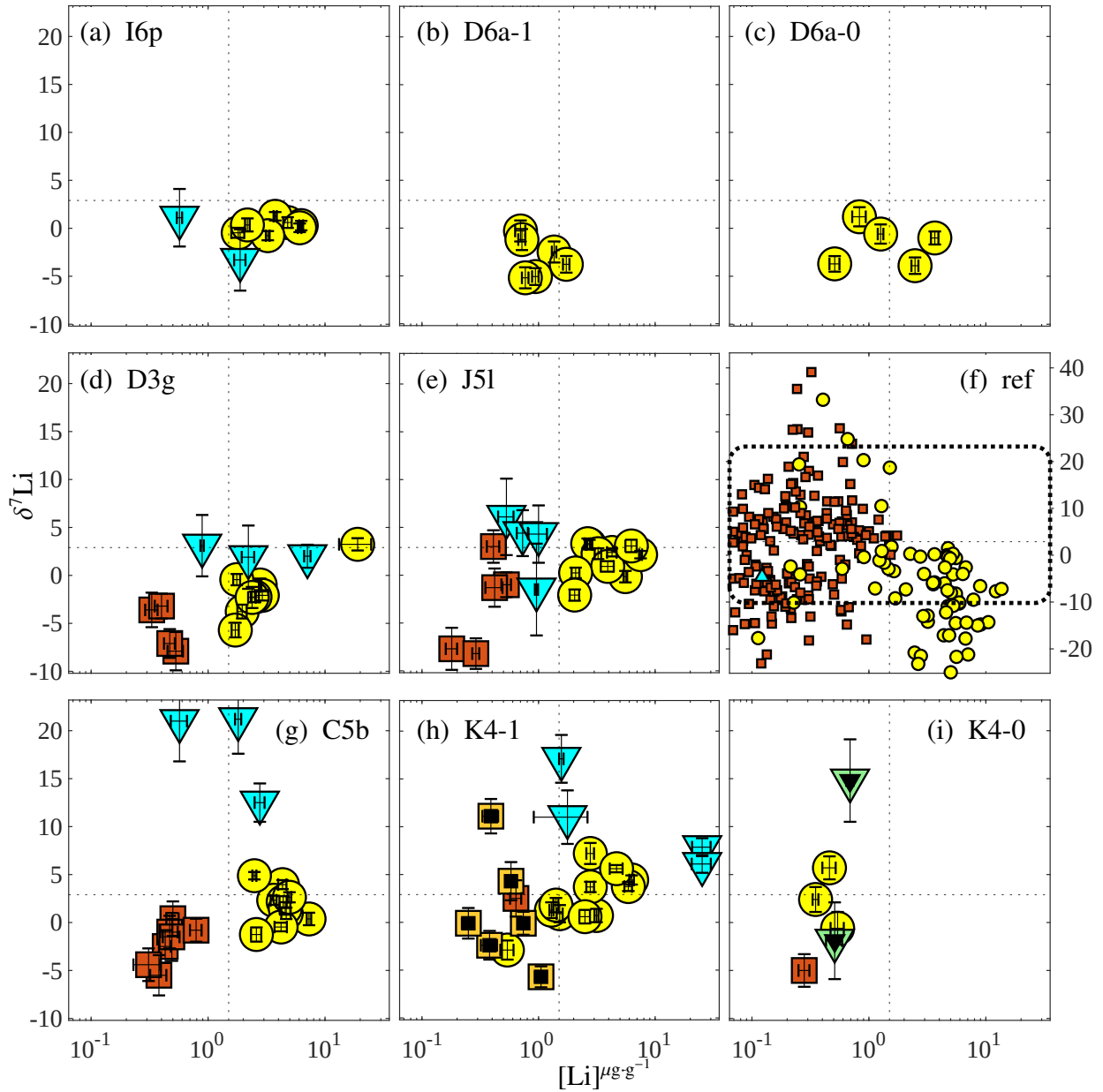


Figure 3.9: The Li isotope-compositions of individual chondrule constituents in the Sahara 97103 EH3 chondrite: (a) I6p, (b) D6a-1, (c) D6a-0, (d) D3g, (e) J51, (f) references, (g) C5b, (h) K4-1, and (i) K4-0. See the caption for Figure 3.8 for the symbol explanation. In the reference panel, enstatites, olivines, and plagioclase (triangle with cyan) from the Allende CV3 chondrules (Maruyama et al., 2009; Kunihiro et al., 2019b) are shown. In the reference panel, the range for each individual panel is shown by a dotted rectangle. Length of error bars on some analyses are smaller than the size of the symbols.

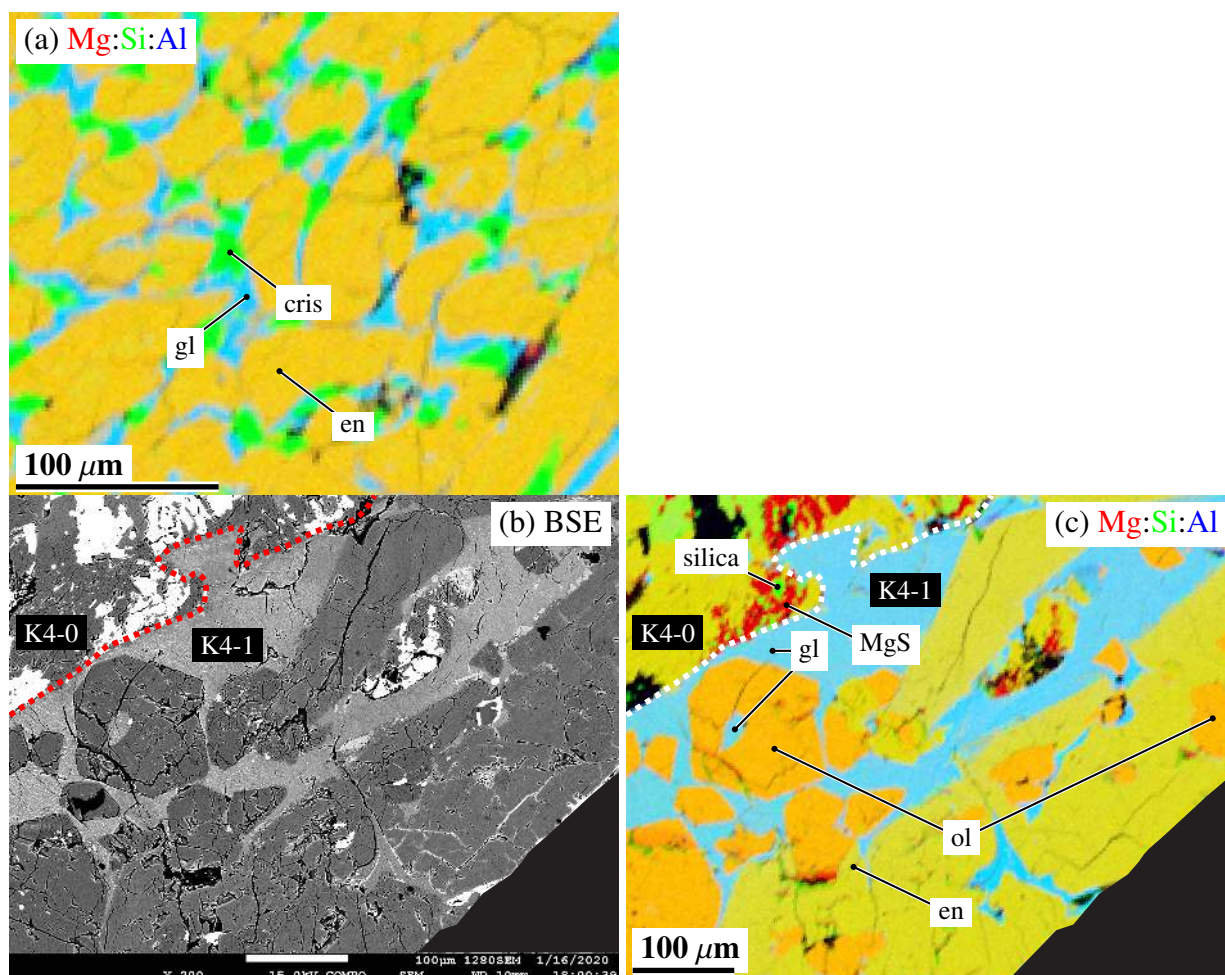


Figure 3.10: Occurrences of silica in D6a-1, euhedral and anhedral olivines in K4-1, and niningerite and silica in K4-0 are shown by BSE, or Mg-Si-Al element maps: (a) Mg-Si-Al element map of the local area in D6a-1 (Figure 3.2b). Enstatite (yellow) is inter-filled by glass (cyan) and silica (green). (b) BSE and (c) Mg-Si-Al element map of the local area in K4-1 and K4-0 (Figures 3.1f, 3.2f). In K4-1, two occurrences of olivine (orange) are observed. Anhedral olivine is politically surrounded by enstatite (yellow). The other euhedral olivine is enclosed by glass (cyan) in the mesostasis. In K4-0, niningerite (red) and silica (green) replace enstatite (yellow).

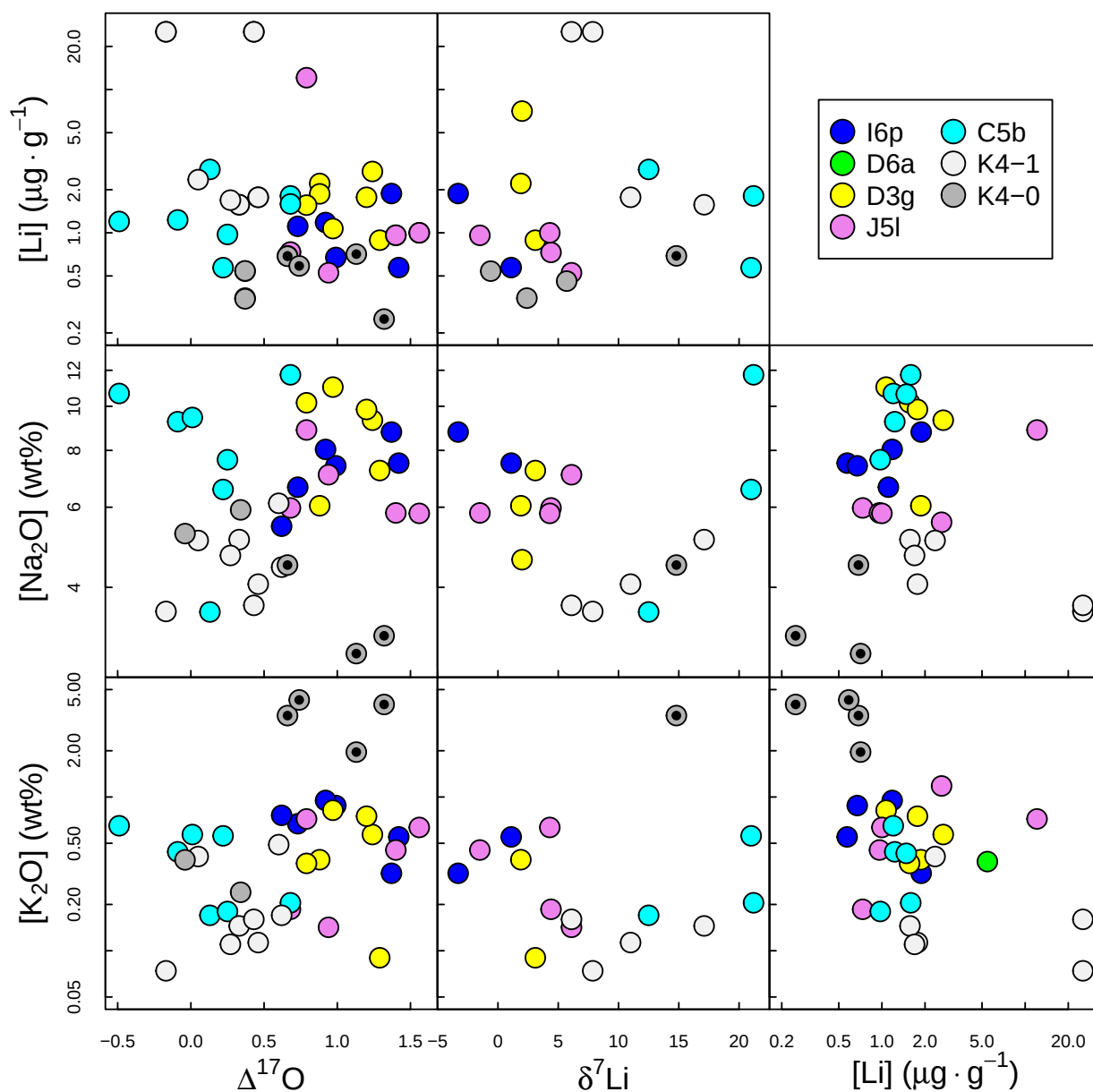


Figure 3.11: The relationship between Li- and O-isotope compositions and alkali elements in the glass. K-rich glass is shown by a filled symbol.

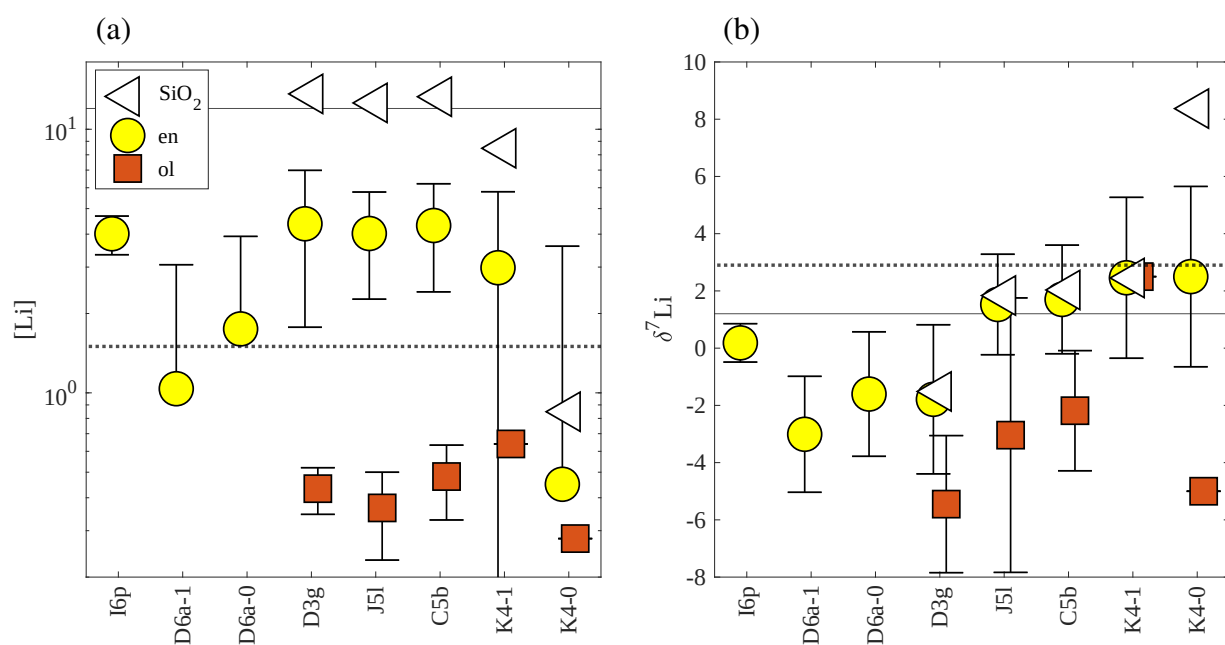


Figure 3.12: The (a) Li concentration and (b) Li isotope-composition of the additional SiO_2 . The average among the chondrules (D3g, J5l, C5b, and K4-1) is shown by a solid line. The values for the whole EH3 chondrite (Seitz et al., 2007) is shown by a dotted line.

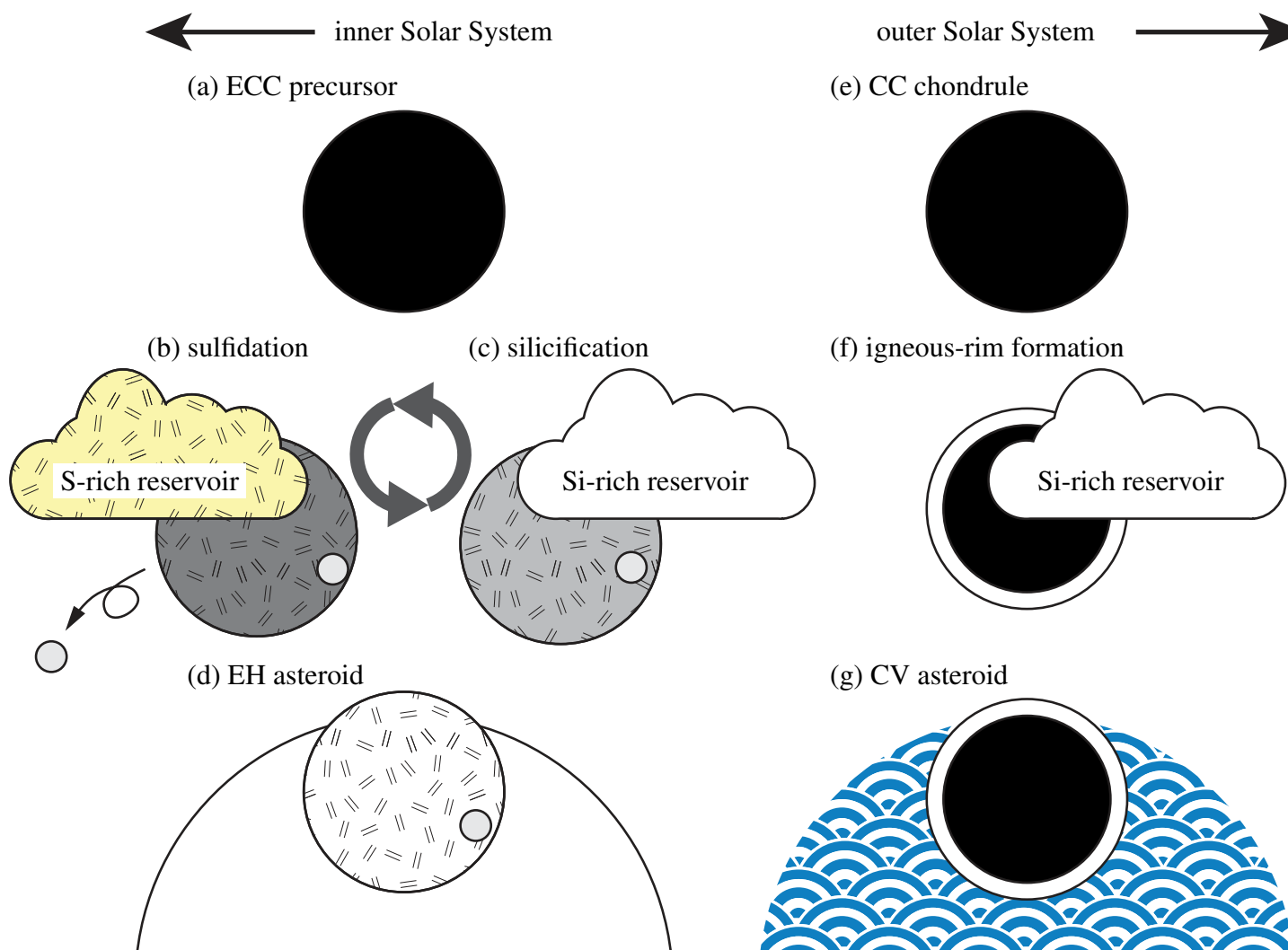


Figure 3.13: Schematic illustration that demonstrates interaction between chondrule, and S- and Si-rich reservoirs: In enstatite-chondrule forming-region, the events begin with (a) precursor for enstatite-chondrite chondrule (ECC) enriched in olivine in the Solar nebula. (b) The precursor interacted with S-rich reservoir to form sulfide including oldhamite. Some of oldhamites were expelled away. (c) The precursor interacted with Si-rich reservoir to form enstatite. These sulfidation and silicification were repeated in the Solar nebula. Sulfidation does not necessarily predate silicification. (d) At the end, chondrules were accreted within the EH asteroid. In carbonaceous-chondrule forming-region, the events begin with (e) carbonaceous chondrite (CC) chondrule enriched in olivine in the Solar nebula. (f) The chondrule interacted with Si-rich reservoir to form igneous rim. (g) At the end, chondrules were accreted within the CV asteroid.

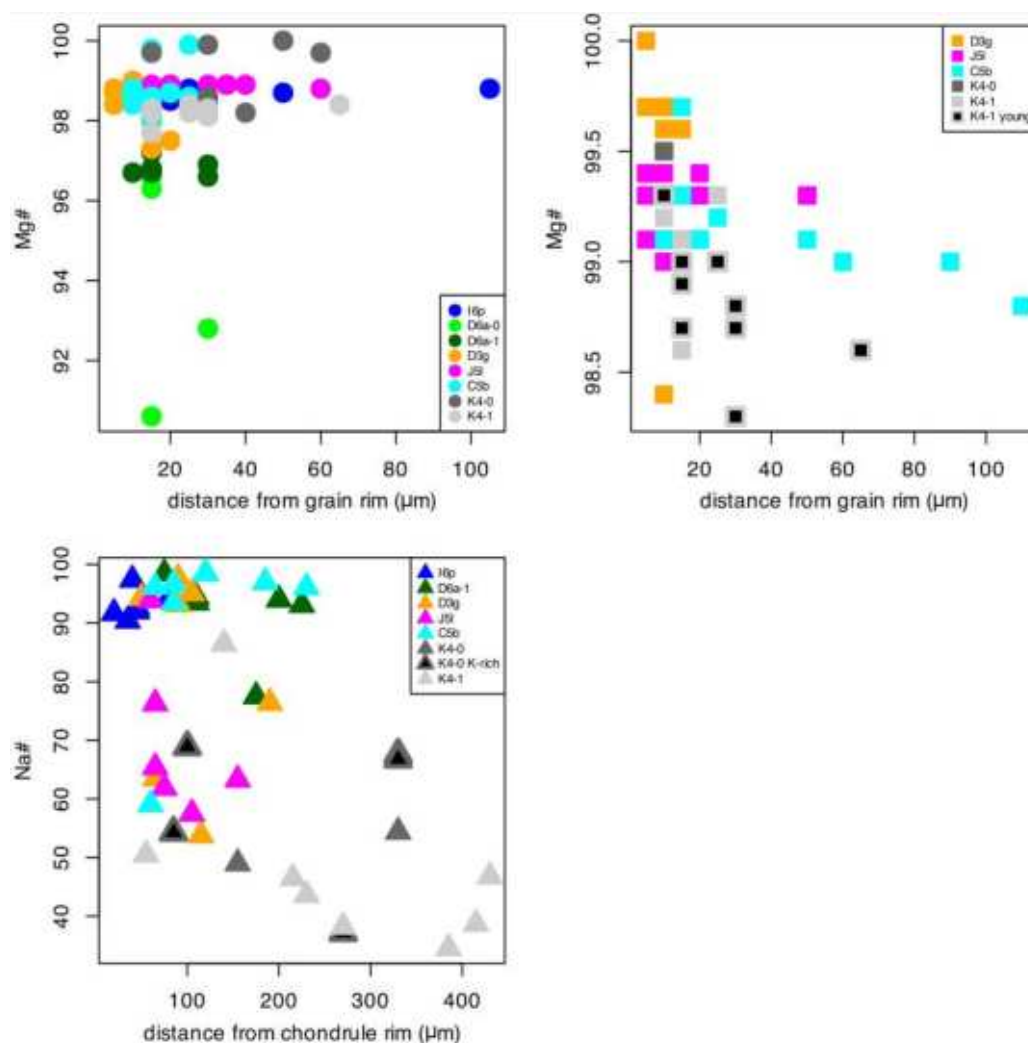


Figure 3.14: Spatial variation of the major-element compositions of the EH3 chondrule components: With the exception of the Na-rich glass, there is no significant spatial variation in the chondrule components in terms of major-element composition. This suggests that major-element diffusion does not have any significant impact on my results. The variation in the Na content of the glass is attributed to the Si-rich gas being enriched in alkali elements.

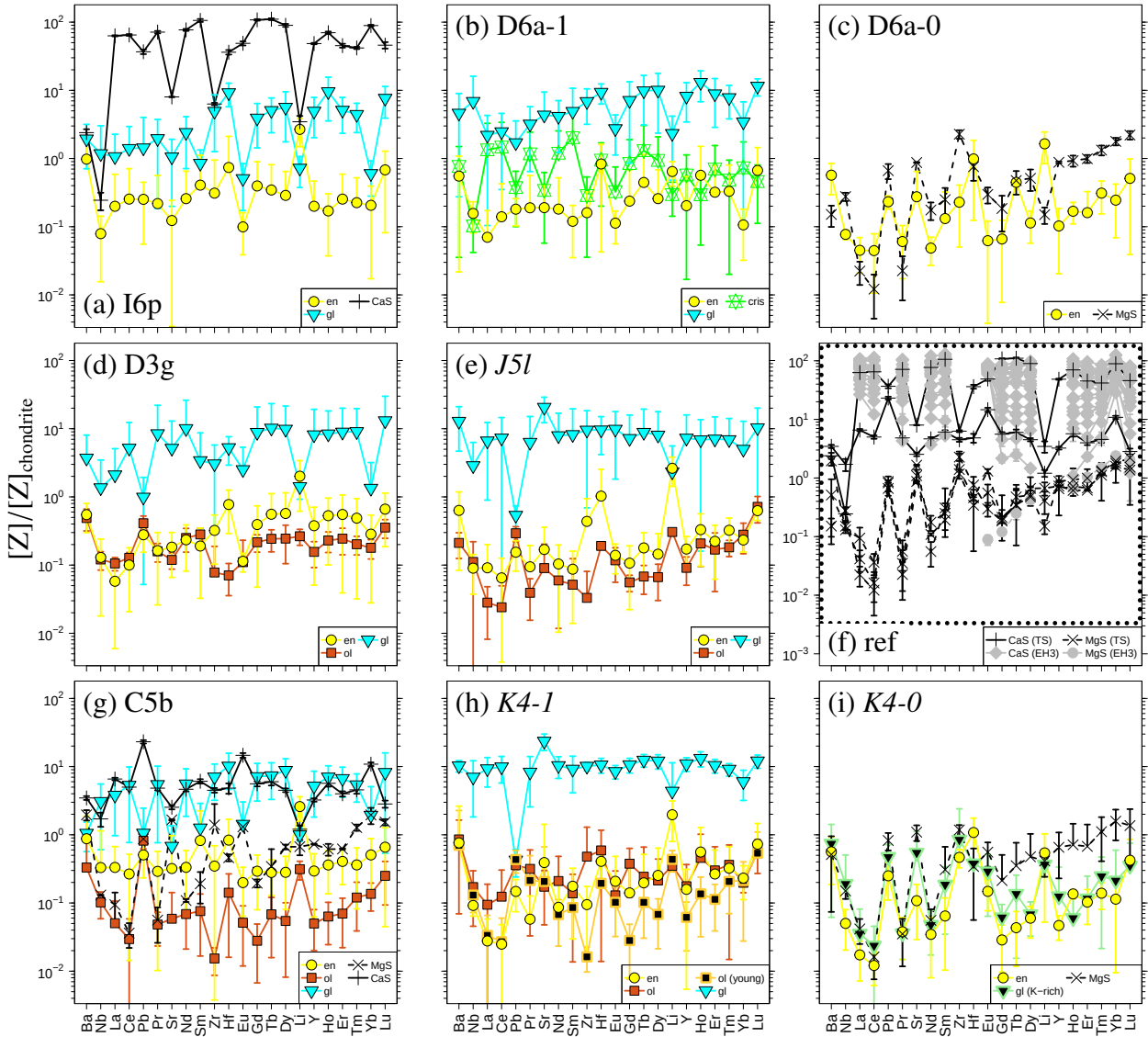


Figure 3.15: Chondrite-normalized trace-element patterns of individual chondrule constituents in the Sahara 97103 EH3 chondrite: (a) I6p, (b) D6a-1, (c) D6a-0, (d) D3g, (e) J5l, (f) reference, (g) C5b, (h) K4-1, and (i) K4-0. In (f), sulfides by this study (TS) and those from EH3 by Crozaz and Lundberg (1995) and Hammouda et al. (2022) are shown. In reference panel, range for individual panel is shown by dot rectangle.

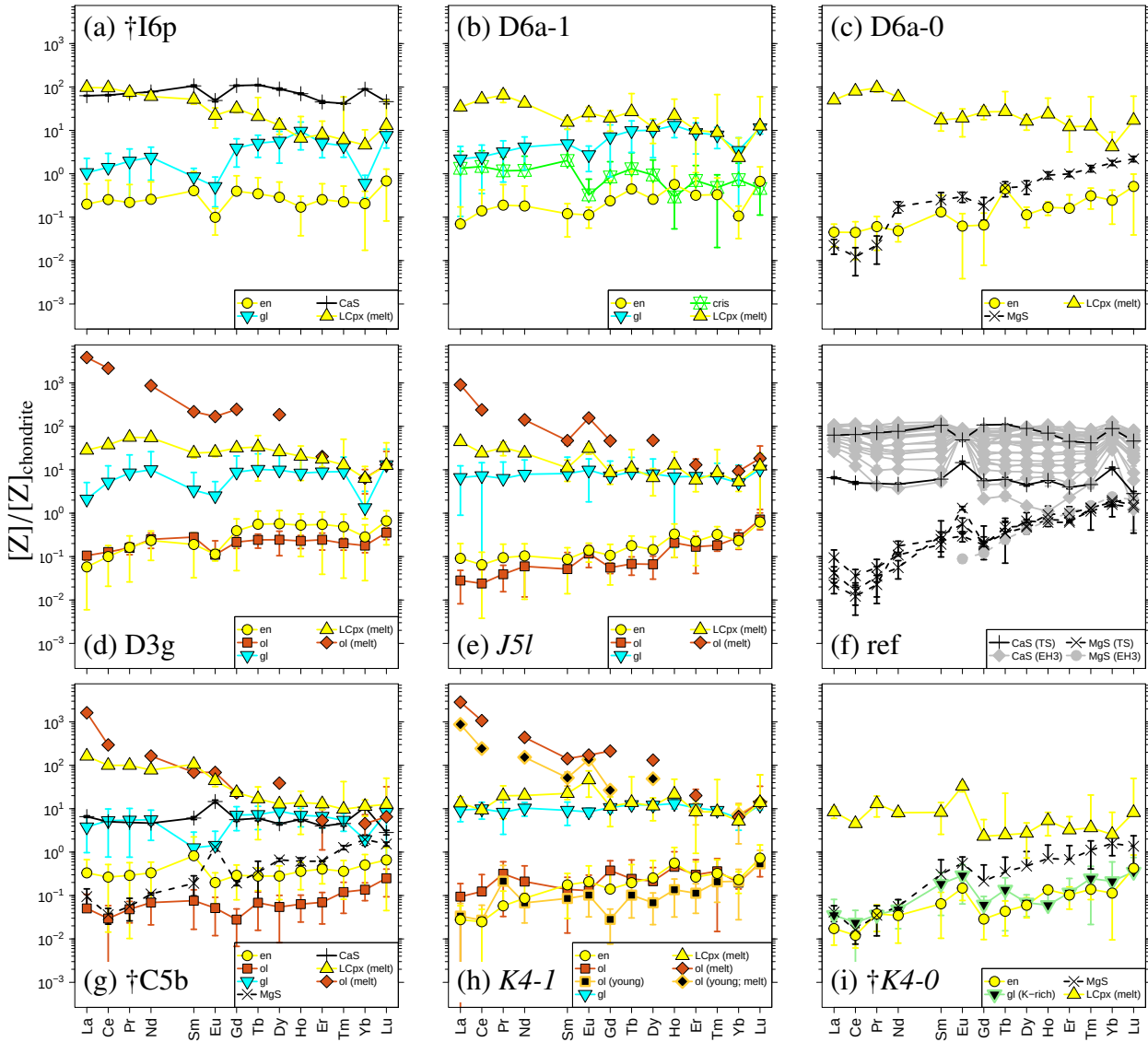
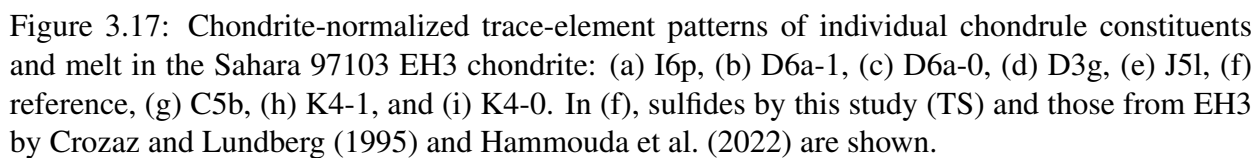


Figure 3.16: Rare-earth-element patterns of individual chondrule constituents and melt in the Sahara 97103 EH3 chondrite: (a) $\dagger$ I6p, (b) D6a-1, (c) D6a-0, (d) D3g, (e) J5l, (f) reference, (g) $\dagger$ C5b, (h) K4-1, and (i) $\dagger$ K4-0. Occurrence of oldhamite within a chondrule is shown by symbol $\dagger$. In reference panel, sulfides by this study (TS) and those from EH3 by Crozaz and Lundberg (1995) and Hammouda et al. (2022) are shown. Trace-element compositions are normalized by those by Wasson and Kallemeyn (1988).



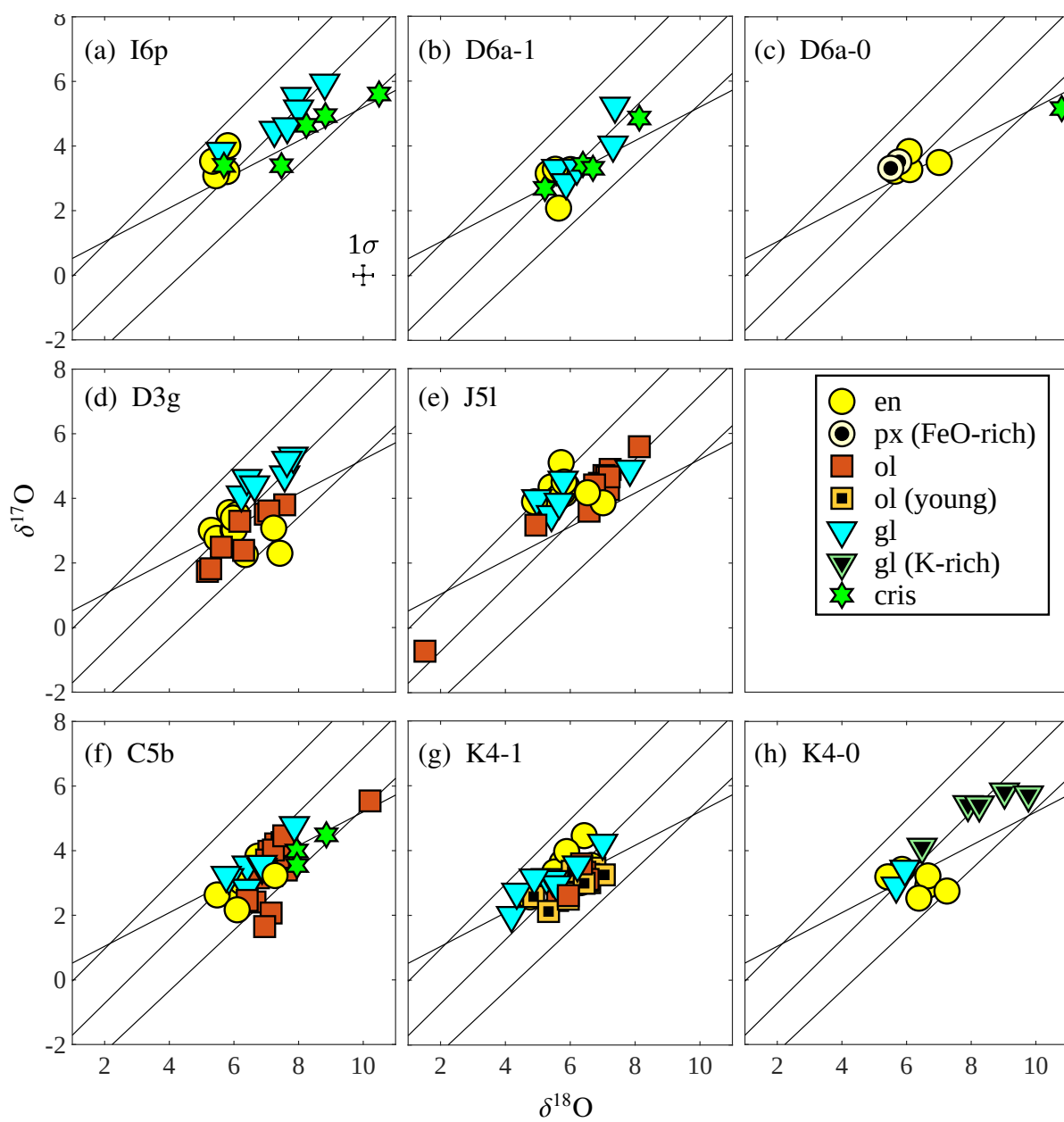


Figure 3.18: The O-isotope compositions of individual chondrule constituents in the Sahara 97103 EH3 chondrite: (a) I6p, (b) D6a-1, (c) D6a-0, (d) D3g, (e) J5l, (f) C5b, (g) K4-1, and (h) K4-0.

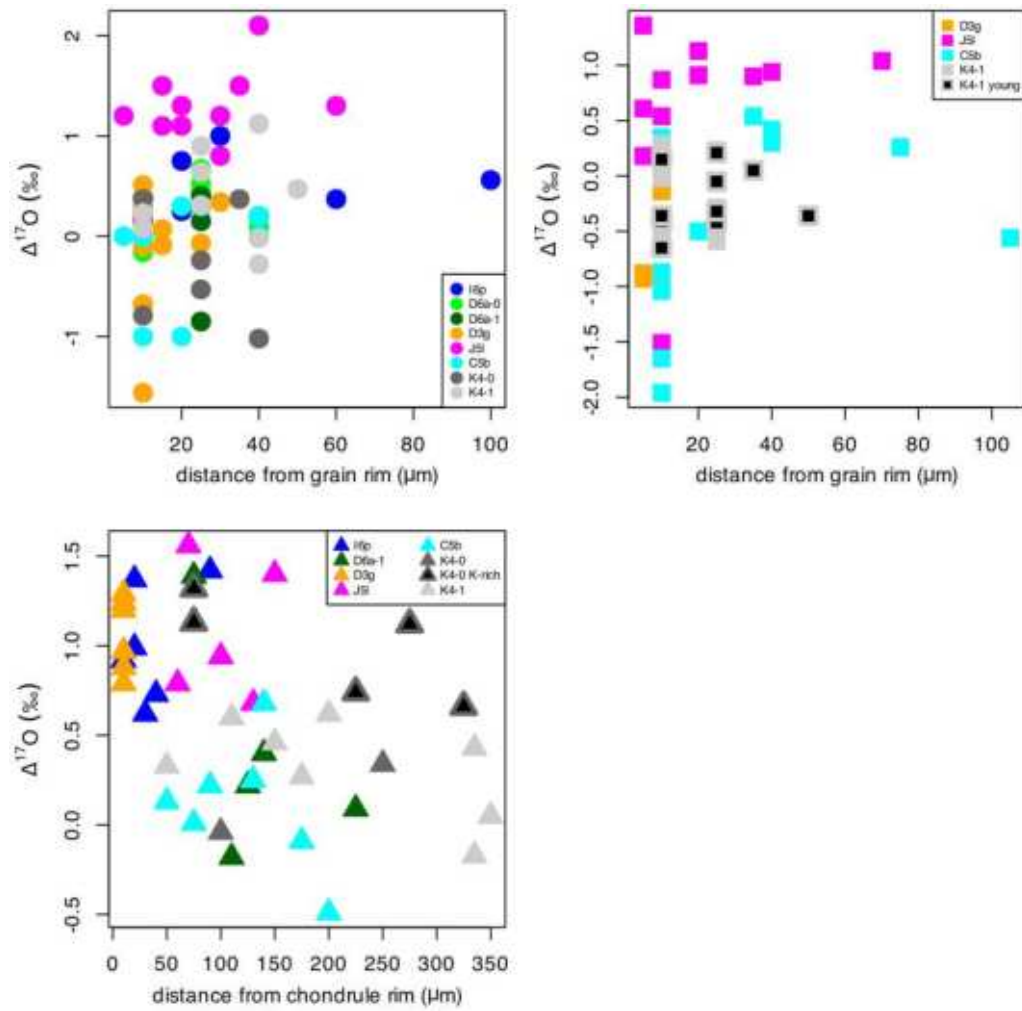


Figure 3.19: Spatial variation of O-isotope compositions of EH3 chondrule components.

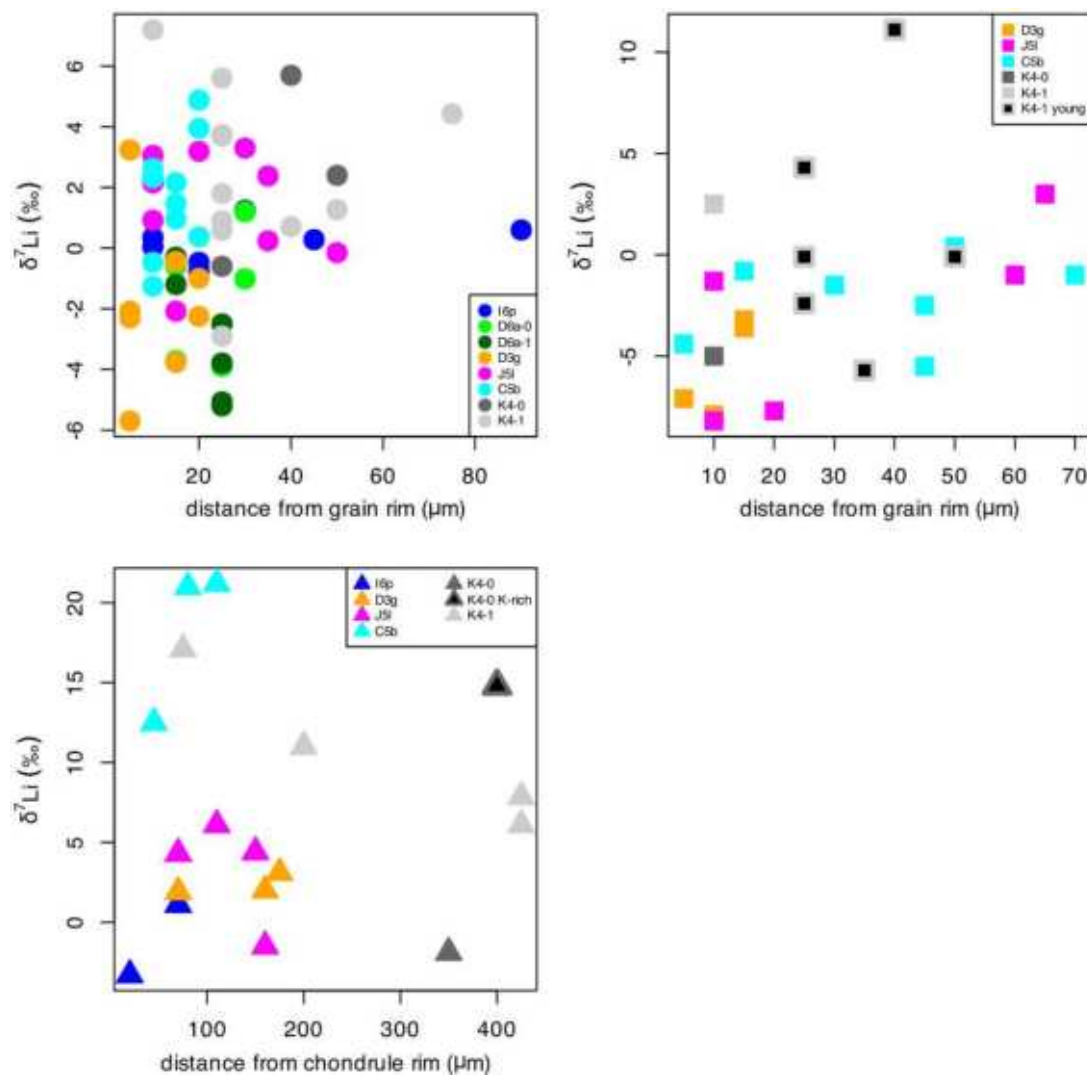


Figure 3.20: Spatial variation of Li-isotope composition of EH3 chondrule components.

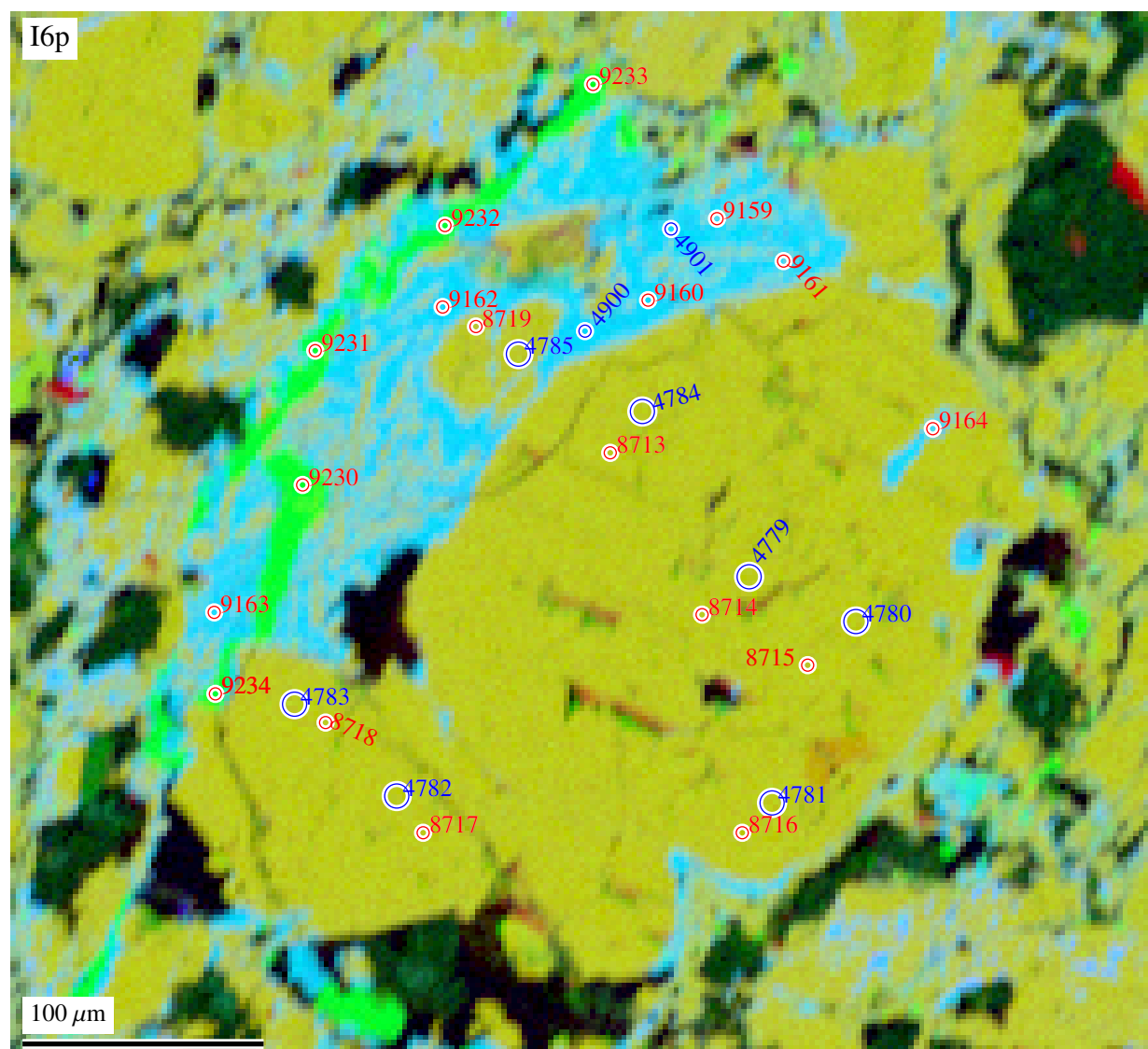


Figure 3.21: Spot location for O- and Li-isotope analyses on I6p: Spots for O and Li-isotope analyses are shown by red and blue circles, respectively. Size of the circles corresponds to size of craters by ion probe.

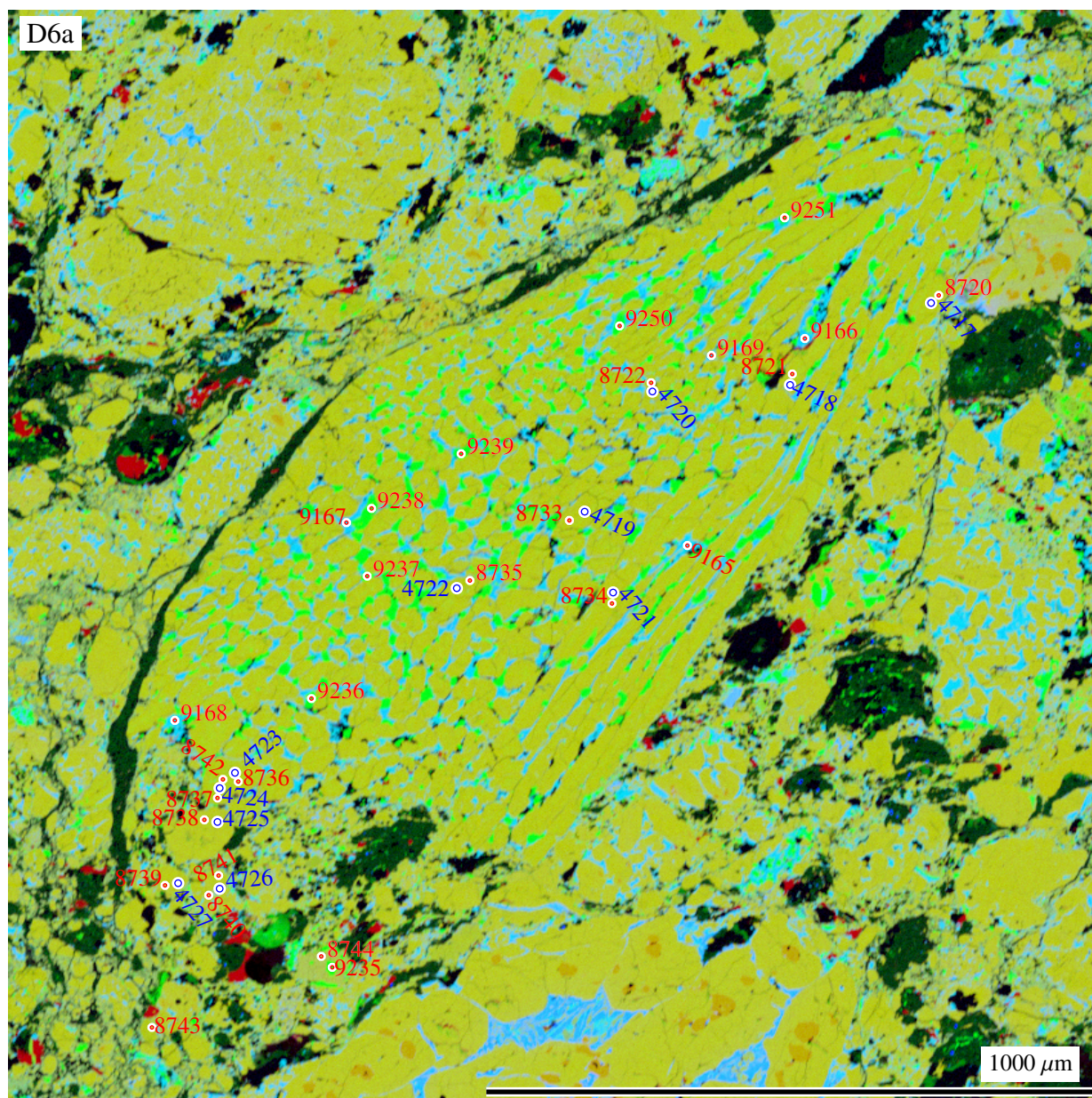


Figure 3.22: Spot location for O- and Li-isotope analyses on D6a: Spots for O and Li-isotope analyses are shown by red and blue circles, respectively. Size of the circles corresponds to size of craters by ion probe.

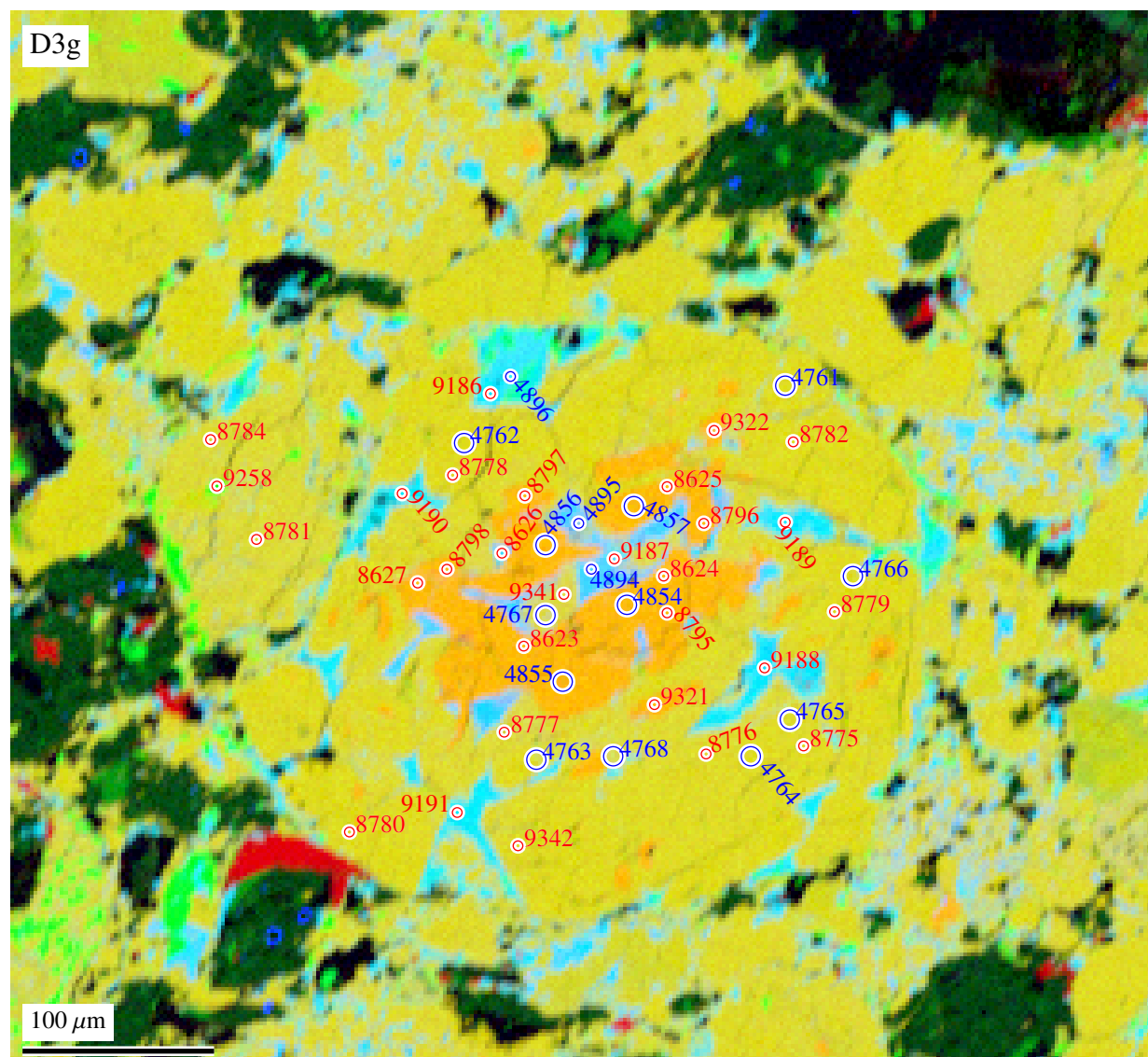


Figure 3.23: Spot location for O- and Li-isotope analyses on D3g: Spots for O and Li-isotope analyses are shown by red and blue circles, respectively. Size of the circles corresponds to size of craters by ion probe.

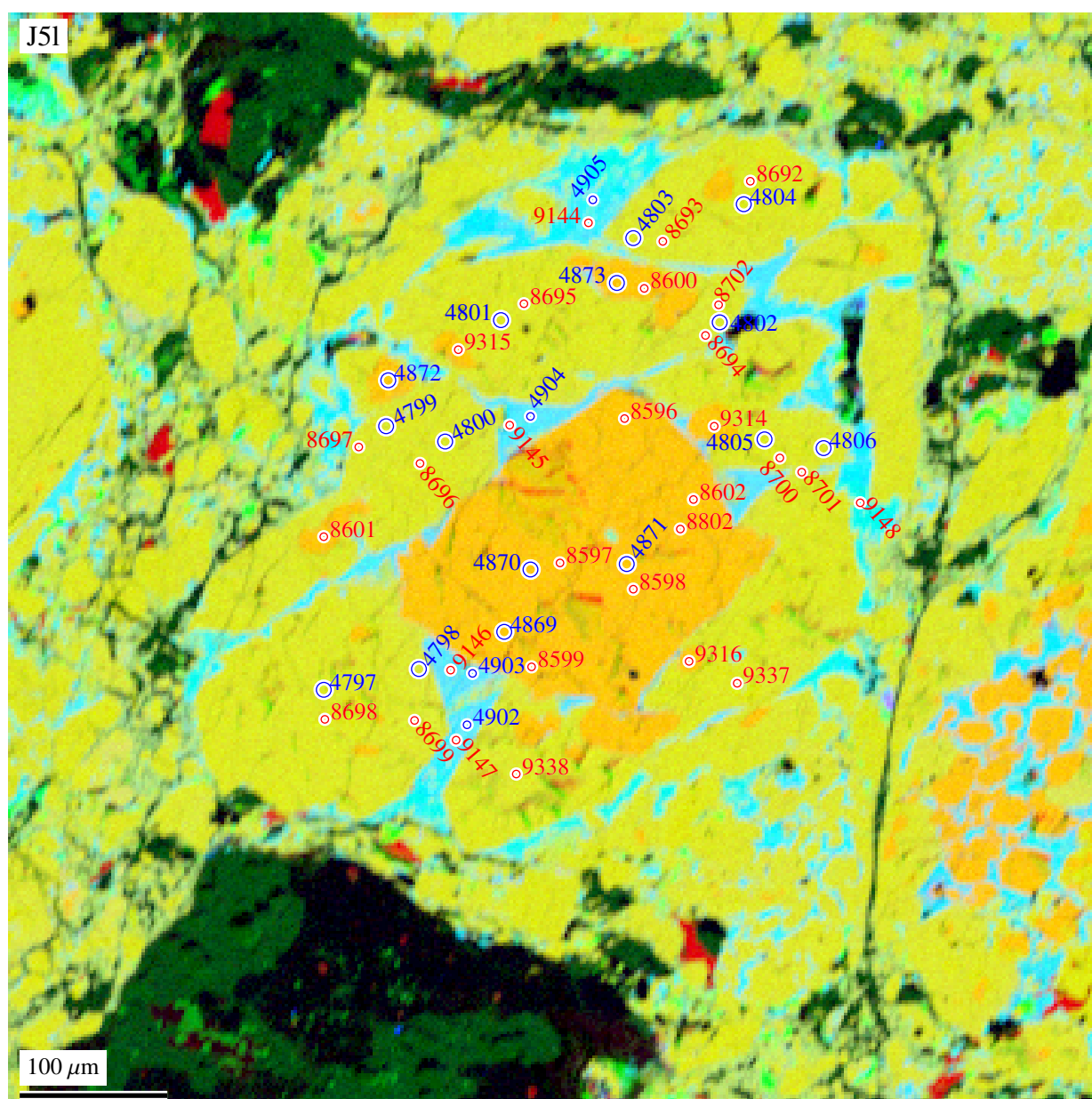


Figure 3.24: Spot location for O- and Li-isotope analyses on J51: Spots for O and Li-isotope analyses are shown by red and blue circles, respectively. Size of the circles corresponds to size of craters by ion probe.

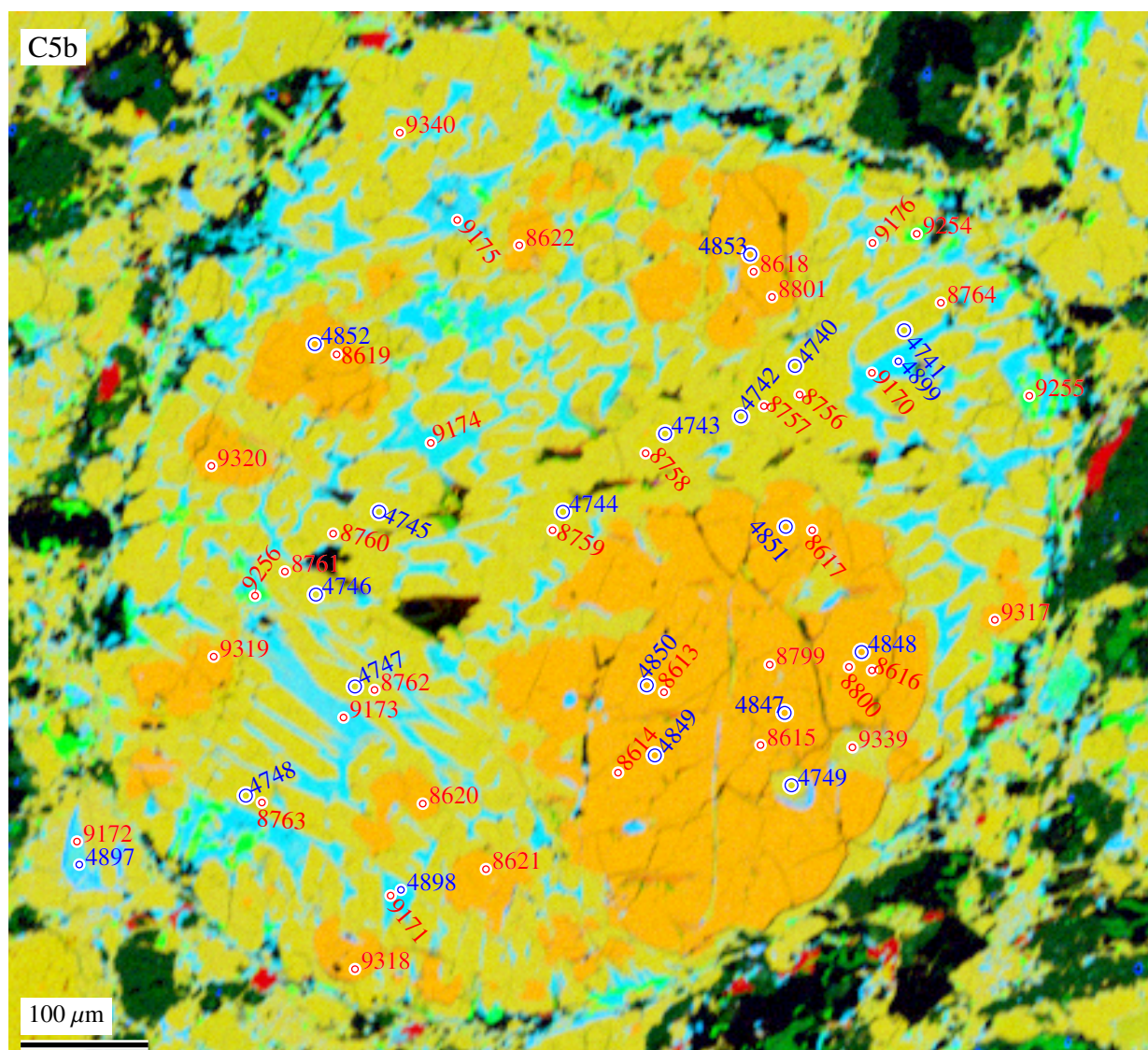


Figure 3.25: Spot location for O- and Li-isotope analyses on C5b: Spots for O and Li-isotope analyses are shown by red and blue circles, respectively. Size of the circles corresponds to size of craters by ion probe.

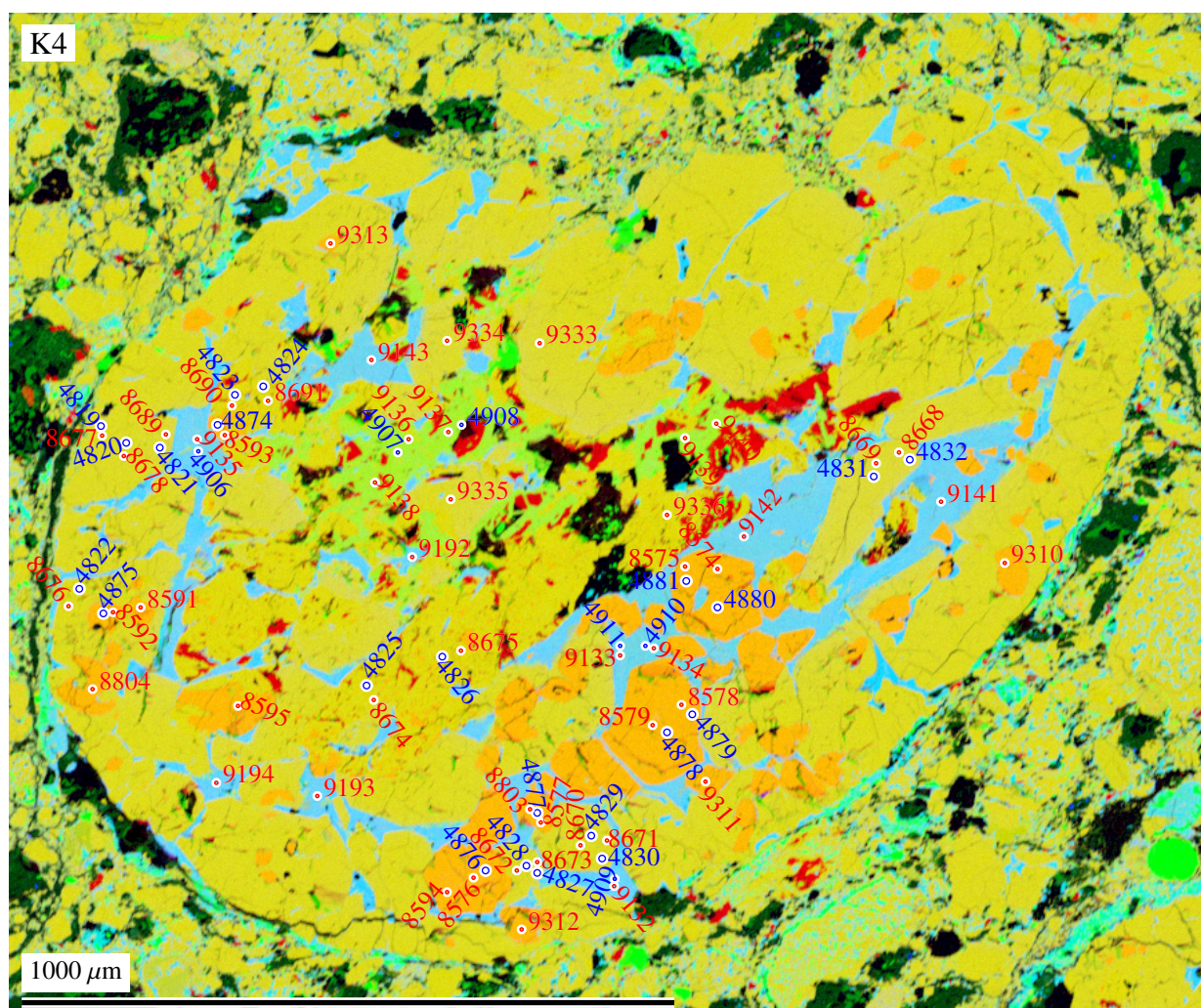


Figure 3.26: Spot location for O- and Li-isotope analyses on K4: Spots for O and Li-isotope analyses are shown by red and blue circles, respectively. Size of the circles corresponds to size of craters by ion probe.

Chapter 4

O- and Li-isotope composition of Indarch and Y73470 (EH4): Implications for the evolution of the enstatite chondrite forming region

4.1 Introduction

EH4 chondrites are an important mid-point between unequilibrated EH3 chondrites (Weisberg and Kimura, 2012) and the equilibrated EH5 chondrites (Skinner and D., 1971; Weisberg and Kimura, 2012). EH4 chondrites are more equilibrated than EH3 chondrites (Weisberg and Kimura, 2012). However, as they retain their chondrules (as observed in this study and previous studies such as McKibbin et al. (2024)), they will preserve a record of their nebula environment.

At the first order, the composition of EH4 chondrites are indistinguishable from those of EH3 chondrites (Kallemeyn and Wasson, 1986). A key difference between the two is that EH4 chondrules contain a significantly smaller abundance of olivine grains compared to the EH3 (Schneider et al., 2002; McKibbin et al., 2024), as confirmed in this study. McKibbin et al. (2024) observed that EH3 had an olivine content of 10 mol% which decreased to 0.01 mol% in the EH4. McKibbin et al. (2024) identified relict olivines in the chondrules of EH4 Y74370 with compositions close to pure forsterite. This was attributed to dissolution reactions with free silica and the extraction of minor-elements by enstatite (McKibbin et al., 2024). This implies that silicification may have occurred on the enstatite asteroid as well as during chondrule formation.

The availability of EH3 chondrites is an on going issue. EH4 chondrules are considered here as an acceptable alternative to the EH3 chondrules. In order to expand the insights gained by examining the EH3 chondrules, the major-element, O- and Li-isotope compositions of three EH4 chondrules were also determined. This will allow for further understanding of the geochemical properties of the protosolar nebula in the enstatite chondrite forming region. The three EH4 chondrules that were selected for this are Indarch-Ch1, Y47370-Ch1, and Y74370-Ch5. These three chondrules were selected as Tanaka et al. (2021) previously examined these meteorites and found a correlation between O-isotopes and silicon isotopes which showed that chondrules with larger $\Delta^{17}\text{O}$ values exhibit smaller $\delta^{30}\text{Si}$ values. Tanaka et al. (2021) sug-

gested that variations of the Si- and O-isotope compositions of enstatite chondrites is the result of gas-melt interaction event between a Si-rich gas and the melted or partially melted precursor chondrules.

Tanaka et al. (2021) observed that enstatite chondrules with $\Delta^{17}\text{O} > -0.1\text{‰}$ had $\delta^{30}\text{Si}$ values ranging from -0.43‰ to -0.54‰ , this is consistent with the values for ordinary and carbonaceous chondrites. However, chondrules with $\Delta^{17}\text{O}$ values of $< -0.2\text{‰}$ exhibited $\delta^{30}\text{Si}$ values ranging from -0.20‰ to -0.40‰ (Tanaka et al., 2021). These $\delta^{30}\text{Si}$ values are larger than the values determined for ordinary and carbonaceous chondrites (Tanaka et al., 2021). The increase in the $\delta^{30}\text{Si}$ value of the inner solar system was attributed to the production of metal and the interactions of a Si-rich gas reservoir and the olivine-rich precursors of the enstatite chondrules (Tanaka et al., 2021). Chondrules in Sahara 97103 and Indarch was found to be depleted in $\delta^{30}\text{Si}$ compared to the chondrules in Y74370 (Tanaka et al., 2021).

The examination of the EH3 chondrules in this study indicated that the Si-rich gas is enriched in alkali elements such as Na and Li. In this chapter Li-isotope composition of the EH4 will be compared with those of the EH3 to examine the Li-isotope heterogeneity in the Si-rich gas in the enstatite chondrite forming region. The EH4 chondrules will be examined to see if a similar correlation that was observed for the Si-isotope compositions exists for the Li-isotope compositions.

4.2 Experimental

The experimental procedures for determining the major-element, O-, and Li-isotope compositions are the same as those for the EH3. Thus the experimental procedures and standards are described in detail in the previous chapter. As with the enstatites and olivines in the EH3 chondrules, no matrix effect corrections were required or applied for the EH4 enstatites and olivines. The major-element compositions were primarily obtained using EPMA. However, for O-isotope spots that were acquired in areas that had not previously been targeted by EPMA, EDS was used to determine the major-element composition. The experimental procedure for this is also described in the previous chapter. The Raman experimental procedure is detailed in the previous chapter.

4.3 Results

Indarch-Ch1 is a fragment with a diameter of 1000 by 1400 μm and is divided into three domains (see Figure 4.1a). The first domain is located in the middle of the chondrule fragment and is the remains of the chondrule core. It is surrounded on two sides by the second domain and one side by third domain. The core is 520 to 580 μm and characterised by abundant Fe-bearing enstatite (Fe content of $>1\%$) of 5 to 110 μm which will be referred to as Fe-enstatite (see Table 4.1). Throughout the core, small anhedral MgS and FeS grains (<5 to 10 μm) are enclosed by the Fe-enstatite (see Figures 4.2 and 4.4a). On the left side of the core and a little into the centre, Na-rich glass (5 to 15 μm) occurs.

The second domain (250 by 380 μm) is the remains of the chondrule mantle, and it dominates the left side and the middle of the chondrule fragment above the core domain. It is characterised by abundant Fe-enstatite (5 to 140 μm) and Na-rich glass (5 to 35 μm) as shown in Figures 4.2, 4.3d, and 4.4b. The Fe-enstatites and glass enclose small anhedral enstatite grains (<5 to 15 μm) with a Fe content of $<1\%$. These enstatites will be referred to as Mg-enstatites.

The third domain is the remains of the chondrule rim. It is separated into two pieces by the

core and mantle domains located in the top right and bottom right of the chondrule fragment. The rim pieces are 360 by 440 μm and 290 by 750 μm , and characterised by abundant subhedral Fe-enstatite (5 to 40 μm) and anhedral Mg-enstatite (<5 to 130 μm), as shown in Figures 4.2, 4.3c, and 4.4d. Most of the Mg-enstatite in both rim pieces is concentrated close to the edge of the chondrule, and is enclosed by the Fe-enstatite. Small amounts of Na-rich glass (<5 to 30 μm) are observed in both pieces of the rim. The FeS (<5 to 10 μm) is most prominent in the mantle domain. Metal (<5 to 10 μm) is observed in the core domain only.

Y74370-Ch1 is a chondrule fragment with a diameter of 660 by 720 μm . It is divided into two domains (Figure 4.1b). The first domain is in the middle of the fragment and is considered to be part of the core of chondrule. It separates the second domain, the chondrule rim into two pieces located at the top and bottom of the fragment. The core is 660 by 460 μm . Its lower section is dominated by elongated Fe-enstatite grains that are 5 to 25 μm in width (Figures 4.5 and 4.6d). This gives the lower core a plate like shape. Between the Fe-enstatites, Na-rich plagioclase (albite) occurs, with being 5 to 25 μm in width. Between some of the Fe-enstatite, there is minor Mg-enstatite ranging from ≤ 5 μm . Some minor FeS is observed in this domain as inclusions in the Fe-enstatite and the plagioclase. The FeS is fine-grained being ≤ 5 μm . Along the edges of the Fe-enstatite grains, fine-grained phases (≤ 5 μm), which are enriched in Mg and Ca, cluster. The bulk of the core domain is occupied by Fe-enstatite ranging from 10 to 125 μm (Figures 4.5 and 4.6b). Between the enstatites, Na-rich plagioclase (5 to 40 μm) occurs. Fe-enstatite (5 to 15 μm) and Mg-enstatite (<5 to 10 μm) are included in the plagioclase. The Mg-enstatite inclusions are more prevalent than the Fe-enstatite inclusions.

The lower rim domain is 660 by 200 μm and the upper rim domain is 500 by 160 μm . It is characterised by anhedral Mg-enstatite (5 to 40 μm) is enclosed by Fe-enstatite (Figures 4.6a, c and 4.7). Anhedral olivine (5 to 15 μm) is enclosed by both Mg-enstatite and Fe-enstatite (Figures 4.6a, c and 4.7b, d). Between the enstatites, Na-rich plagioclase (5 to 40 μm) occurs. Fe-enstatite (5 to 15 μm) and Mg-enstatite (<5 to 10 μm) are included in the plagioclase. The Mg-enstatite inclusions are more prevalent than the Fe-enstatite inclusions. The enstatites, the olivine, and the plagioclase all contain FeS inclusions (≤ 5 μm). The FeS is less prevalent in the olivine and Mg-enstatite compared to the Fe-enstatite and plagioclase. The FeS generally occurs close to the edges of the other phases. Small grains enriched in Mg and Ca (≤ 5 μm) cluster along the edges of some of the Fe-enstatite grains.

Y74370-Ch5 is 570 by 720 μm and divided into two domains (Figure 4.1c). The first domain is the remains of the chondrule core. It is 150 by 390 μm in size, and dominated by two blocky, euhedral to subhedral Fe-enstatite grains (150 by 290 μm and 150 by 100 μm ; Figure 4.8). Na-rich plagioclase (5 to 20 μm) is observed between the enstatite grains and separates the core from the rest of the chondrule fragment (Figure 4.8 and 4.10a,b,c). Anhedral Mg-enstatite (5 to 10 μm) is enclosed by the Fe-enstatite and, in some cases, the plagioclase. It is concentrated at the edges of the domain, and very small amounts closer to the center.

The second domain is the remains of the chondrule rim. The rim is 570 by 460 μm , and is dominated by subhedral Fe-enstatite (10 to 50 μm ; Figure 4.8). Between the Fe-enstatite grains, Na-rich plagioclase (5 to 50 μm) occurs. Anhedral Mg-enstatite grains (5 to 30 μm) are concentrated around the edges of the domain, with very few close to the centre of the domain (Figures 4.9a, b, c, and 4.10d). Most of the Mg-enstatite is enclosed by Fe-enstatite and plagioclase. At the edges of the Fe-enstatites and particularly at the edges of the domain, Ca- and Mg-rich grains (<5 to 20 μm) occur. Throughout the chondrule, minor FeS (<5 to 10 μm) is observed.

4.3.1 Major-element composition

Three types of enstatite were identified. Two of these were the previously identified Fe-enstatites and Mg-enstatites. The third enstatite type was enriched in Ca (0.9 to 4.1 wt.% in CaO) compared to the other two and will be referred to as Ca-enstatites. The Fe-enstatites are defined by a relatively wide range in Fe content (0.6 to 1.6 wt.%). The Mg-enstatites are characterised by major-element compositions that are close to pure enstatite (98.7 to 100 % in enstatite component, En). They plot tightly packed compared to the other two enstatite types.

The enstatites in Indarch-Ch1 exhibit the largest range in their compositions, with Y74370-Ch1 exhibiting the smallest range of compositions. The Fe-enstatites in Indarch-Ch1 have the highest Fe content, while those in Y74370-Ch1 have the lowest Fe content. The Fe-enstatites in Y74370-Ch5 have slightly lower Fe contents compared to those in Indarch-Ch1. When compared to the enstatites in the EH3 chondrules, the Fe-enstatites in Indarch-Ch1 and Y74370-Ch5 exhibit similar compositions to most of the EH3 enstatites. At the first order, part from one exception, the three enstatite types plot close together (within 2.5 % in En and within 1.2 % in Wo; Figure 4.11).

All of the olivines show a high Mg content, close to pure forsterite ($Fo_{99.8}$ to $Fo_{99.9}$). This is consistent with the results from McKibbin et al. (2024). The EH4 olivines differ from the EH3 olivines which have a larger range of compositions ($Fo_{98.1}$ to $Fo_{99.9}$). The Ca content of the olivines in the EH4 ($Ca_{0.1}$) has a smaller range compared to those in the EH3 ($Ca_{0.0}$ to $Ca_{0.5}$).

The glass in Indarch-Ch1, and the plagioclase in Y74370-Ch1 and Y74370-Ch5 show very different compositions. The plagioclase plots with the very albite-rich glass in the EH3 chondrules. The plagioclase has a tight grouping with the Y74370-Ch1 has a slightly larger range in Na content and a slightly smaller range in K content compared to the Y74370-Ch5. The glass in Indarch-Ch1 does not contain any K and has a wide range in Na, which is similar to some of the glass from the EH3 chondrules.

4.3.2 Raman

Site maps and results by Raman spectroscopic analysis for Y74370-Ch1 are shown in Figure 4.14. Nine sites were examined in total. Three of the spectra were targeting Mg-enstatite, three were targeting Fe-enstatite, and three were targeting Ca-enstatite. The Raman spectra were compared with results from Ulmer and Stalder (2001) in order to determine what polymorphs the enstatites were. The Fe-enstatites and Ca-enstatites were all determined to have clino-enstatite structures. However, two Mg-enstatites were determined to be orthorhombic and one was determined to be clino-enstatite.

4.3.3 O-isotope composition

At the first order, there is no significant difference between the enstatites in the EH4 chondrules and the EH3 chondrules (Figure 4.15). The Fe-enstatites have a slightly smaller range compared to the Mg-enstatites ($\delta^{18}O, \delta^{17}O = 2\text{‰}, 2\text{‰}$ and $\delta^{18}O, \delta^{17}O = 2.5\text{‰}, 2.5\text{‰}$ respectively). The enstatites mostly plot between the PCM and CCAM lines, with the bulk of the spots plotting close to the TF-PCM intersection. The EH4 olivines have a significantly smaller range compared to the EH3 olivines. Unlike the EH3 olivines, the EH4 olivines do not vary along the PCM line. Rather, they plot between the PCM and CCAM lines. They exhibit a small variation in $\delta^{18}O$ of 1‰ and a $\delta^{17}O$ variation of 2‰.

Individual spots within the individual EH4 chondrules are shown in Figure 4.16. No significant difference was observed between the Mg-enstatites and the Fe-enstatites in the same chondrule. The enstatite in Indarch-Ch1 plots in two clusters varying along the PCM line with a variation of $\delta^{18}\text{O}, \delta^{17}\text{O} = 2.5\text{‰}, 2.5\text{‰}$ for Mg enstatite and $2\text{‰}, 2\text{‰}$ for Fe enstatite. Indarch-Ch1 shows the largest variation in O-isotope composition, with Y74370-Ch1 showing the smallest variation ($\delta^{18}\text{O}, \delta^{17}\text{O} = 1\text{‰}, 1.5\text{‰}$ for both Mg-enstatite and Fe-enstatite). The enstatites in Y74370-Ch5 shows a similar variation in $\delta^{18}\text{O}$ as Indarch-Ch1, but shows no significant variation in $\delta^{17}\text{O}$. The enstatites in Y74370-Ch1 show no significant variation in either $\delta^{18}\text{O}$ or $\delta^{17}\text{O}$. No significant difference was observed between the olivines and enstatites in the same chondrule.

4.3.4 Li-isotope composition

Comparison of the Li-isotope composition of the chondrule components in the EH4 and EH3 chondrules is shown in Figure 4.17. The average of the EH4 enstatites ($[\text{Li}] = 1.83 \mu\text{g} \cdot \text{g}^{-1}$ and $1.80 \mu\text{g} \cdot \text{g}^{-1}$, $\delta^7\text{Li} = -2.90\text{‰}$ and -0.19‰ for Fe-enstatite and Mg-enstatite respectively) exhibit slightly smaller Li concentrations compared to the EH3 enstatite average ($[\text{Li}]$, $\delta^7\text{Li} = 3.26 \mu\text{g} \cdot \text{g}^{-1}$, 0.46‰). The Mg-enstatite $\delta^7\text{Li}$ average is similar to that of the EH3 enstatites, but the $\delta^7\text{Li}$ average of the Fe-enstatites is slightly smaller. The EH3 enstatites exhibit a larger range in Li concentration ($18.65 \mu\text{g} \cdot \text{g}^{-1}$) but a smaller range in $\delta^7\text{Li}$ (12.90‰) compared to the range of EH4 enstatites ($[\text{Li}]$, $\delta^7\text{Li} = 3.05 \mu\text{g} \cdot \text{g}^{-1}$, 45.90‰).

The $\delta^7\text{Li}$ and Li concentration averages of the EH4 olivines ($[\text{Li}]$, $\delta^7\text{Li} = 0.82 \mu\text{g} \cdot \text{g}^{-1}$, 0.58‰) is slightly larger compared to the EH3 olivines ($[\text{Li}]$, $\delta^7\text{Li} = 0.44 \mu\text{g} \cdot \text{g}^{-1}$, -3.04‰ for anhedral olivine and ($[\text{Li}]$, $\delta^7\text{Li} = 0.57 \mu\text{g} \cdot \text{g}^{-1}$, 1.18‰ for euhedral olivine). However, there is no significant difference between the EH3 euhedral olivines and the EH4 olivines. The averages of the EH4 enstatites and olivines plot closer together compared to the EH3 enstatite and olivine averages. The EH4 olivines exhibit larger ranges in both $\delta^7\text{Li}$ (15.70‰) and Li concentration ($2.19 \mu\text{g} \cdot \text{g}^{-1}$) compared to the EH3 olivines ($[\text{Li}]$, $\delta^7\text{Li} = 0.61 \mu\text{g} \cdot \text{g}^{-1}$, 11.20‰) and euhedral olivines ($[\text{Li}]$, $\delta^7\text{Li} = 0.80 \mu\text{g} \cdot \text{g}^{-1}$, 16.80‰).

No significant difference is observed between the EH3 ($[\text{Li}]$, $\delta^7\text{Li} = 4.69 \mu\text{g} \cdot \text{g}^{-1}$, 7.18‰) and EH4 glass averages ($[\text{Li}]$, $\delta^7\text{Li} = 5.06 \mu\text{g} \cdot \text{g}^{-1}$, 5.57‰). The EH4 glass has smaller ranges ($[\text{Li}]$, $\delta^7\text{Li} = 3.47 \mu\text{g} \cdot \text{g}^{-1}$, 11.50‰) compared to the EH3 glass ($[\text{Li}]$, $\delta^7\text{Li} = 24.79 \mu\text{g} \cdot \text{g}^{-1}$, 24.50‰), likely due to a smaller number of spots. K-rich glass averages ($[\text{Li}]$, $\delta^7\text{Li} = 0.60 \mu\text{g} \cdot \text{g}^{-1}$, 6.45‰) is similar to the EH3 olivines with a similar range in $\delta^7\text{Li}$. Most of the plagioclase spots plots with lower $\delta^7\text{Li}$ values compared to the other phases. The plagioclase has a small range of Li concentrations ($1.32 \mu\text{g} \cdot \text{g}^{-1}$) with the average ($1.93 \mu\text{g} \cdot \text{g}^{-1}$) showing no significant difference compared to the EH4 enstatites.

Individual spots within individual EH4 chondrules is shown in Figure 4.18. At the first order, the Fe-enstatites are similar with consistent averages ($[\text{Li}]$, $\delta^7\text{Li} = 2.23 \mu\text{g} \cdot \text{g}^{-1}$, -1.91‰ ; $1.73 \mu\text{g} \cdot \text{g}^{-1}$, -4.65‰ ; $1.52 \mu\text{g} \cdot \text{g}^{-1}$, -2.18‰ for Indarch-Ch1, Y74370-Ch1, and Y74370-Ch5 respectively). Y74370-Ch5 has the smallest variation in both Li concentration ($0.93 \mu\text{g} \cdot \text{g}^{-1}$) and $\delta^7\text{Li}$ (8.80‰), with Indarch showing the largest variations ($[\text{Li}]$, $\delta^7\text{Li} = 2.52 \mu\text{g} \cdot \text{g}^{-1}$, 41.40‰). Y74370-Ch1 has a similar Li concentration variation ($2.38 \mu\text{g} \cdot \text{g}^{-1}$) as Indarch-Ch1 but the variation in Li-isotope composition (18.70‰) differs significantly. Indarch-Ch1 and Y74370-Ch1 both have single outliers in terms of Li concentration.

The Mg-enstatites have large variations in Li concentration and $\delta^7\text{Li}$. Y74370-Ch1 shows larger variations ($[\text{Li}]$, $\delta^7\text{Li} = 3.81 \mu\text{g} \cdot \text{g}^{-1}$, 31.60‰) compared to Indarch-Ch1 ($[\text{Li}]$, $\delta^7\text{Li} = 1.62 \mu\text{g} \cdot \text{g}^{-1}$, 11.40‰). The Y74370-Ch1 average ($[\text{Li}]$, $\delta^7\text{Li} = 1.88 \mu\text{g} \cdot \text{g}^{-1}$, 3.87‰) is larger in both

Li concentration and $\delta^7\text{Li}$ compared to the average in Indarch-Ch1 ($[\text{Li}]$, $\delta^7\text{Li}=1.68 \mu\text{g} \cdot \text{g}^{-1}$, -5.40‰).

The olivines plot fairly close to the enstatites with the average plotting with a smaller Li concentration compared to the enstatites and a $\delta^7\text{Li}$ that is larger than the averages for the enstatites in Indarch-Ch1 and Y74370-Ch5, and larger than the Fe-enstatite average in Y74370-Ch1 but smaller than the Y74370-Ch1 Mg enstatite average.

The glass shows large variations and consistently plots with larger Li concentration and $\delta^7\text{Li}$ compared to the other phases. Plagioclase in Y74370-Ch5 has a small variation ($[\text{Li}]$, $\delta^7\text{Li}=0.23 \mu\text{g} \cdot \text{g}^{-1}$, 6.20‰) compared to the Y74370-Ch1 ($[\text{Li}]$, $\delta^7\text{Li}=1.32 \mu\text{g} \cdot \text{g}^{-1}$, 14.50‰). The Y74370-Ch1 plagioclases plot with smaller $\delta^7\text{Li}$ compared to those in Y74370-Ch5. There is no significant difference in the respective Li concentrations between the plagioclases in Y74370-Ch1 and Y74370-Ch5. These concentrations are consistent with those of the Fe-enstatites.

4.4 Discussion

4.4.1 Are the Mg-enstatites older than the Fe-enstatites?

The big question from this session is the chronological order/ crystallisation sequence of the phases. At the first order, phases from oldest to youngest are olivine, Mg-enstatite, Fe-enstatite, glass, plagioclase, and Ca-enstatite. The olivine is most likely to be the oldest phase and is likely to be the precursor to the enstatite. McKibbin et al. (2024) observed a significant drop in the abundance of olivine between EH3 and EH4 meteorites. This was also observed in this study. McKibbin et al. (2024) observed that at higher petrological types the concentration of minor-elements become restricted, which results in the olivine composition getting closer to that of pure forsterite with peak metamorphic temperatures leading to reduced grain sizes. These changes reflect diffusive equilibrium with enstatite-rich groundmass and dissolution reaction with free silica (McKibbin et al., 2024). This may explain the variation between the EH3 and EH4 olivines observed in this study.

It is difficult to determine whether the Mg-enstatites or the Fe-enstatites came first. As the Fe-enstatite shares a similar composition to the enstatites in the EH3 chondrules, this indicates that it did not necessarily form after the Mg-enstatites. This is supported by some of the Mg-enstatites forming between the Fe-enstatites. The olivine is the oldest phase in the chondrules and is mostly observed enclosed by the Mg-enstatite, with only a few exceptions. Some of the olivines share contacts with both enstatite types. As most of the olivine is surrounded by the Mg-enstatite, this may indicate that the Mg-enstatite is older than the Fe-enstatite. Ortho-enstatite forms when the cooling rate is relatively slow and clino-enstatite forms due to rapid quenching (Smyth, 1974). As the Fe-enstatites are clino-enstatite, this implies that they cooled rapidly. This is consistent with them forming during the last chondrule melting event. As the Mg-enstatites are orthorombic, they would have cooled more slowly, indicating that they are from a different generation of chondrule melt and may be relict. The composition of the Mg-enstatites along with the Raman spectrum of the Mg-enstatite aggregate suggests that the Mg-enstatites may have originated on the enstatite asteroid. The prolonged heating and longer cooling period on the enstatite asteroid would have allowed the transformation of the clino-enstatite into the more stable ortho-enstatite. They would have then been broken off of the asteroid and recycled into the EH4 chondrules.

4.4.2 Silicification and sulphidation in the EH4 chondrules

The heated enstatite chondrites exhibit enstatites with a FeO content of <1% (Weisberg and Kimura, 2012). The bulk of the EH3 enstatite exhibited major-element compositions that suggested they formed under slightly more oxidised conditions compared to the enstatite asteroid. This holds true for the EH4 Fe-enstatites. The Mg-enstatites compositions more closely match what is expected for enstatites from the heated enstatite chondrites. This indicates that the Mg-enstatites initially came from an enstatite asteroid that was broken up or had pieces broken off. These pieces were then recycled during the production of the EH4 chondrules. This is supported by the Mg-enstatite aggregate with the orthorhombic crystal structure identified in Y74370-Ch1 as ortho-enstatite is formed from a slower cooling rate, while clino-enstatite forms during rapid cooling (Smyth, 1974).

The glass is older than the plagioclase as it is the result of the rapid cooling of the melt. Unlike the glass, plagioclase is a mineral and would have cooled more slowly. The glass is most likely the precursor of the plagioclase, with the plagioclase forming as a result of metamorphic processes, likely on the asteroid. The variation in the glass and plagioclase compositions indicate that there were differences in the composition of the chondrule melt. Calcium may have also been removed from the plagioclase during metamorphism. The Ca may have then been pulled into the enstatite, resulting in the production of the Ca-enstatite. FeS existed prior to the production of enstatite. The FeS (and MgS in Indarch) may have contributed to the production of the Fe-enstatite, leaving the S to take some Ca from the glass as the plagioclase formed. As CaS is present in both enstatite types and in one olivine grain, if the S did extract Ca during plagioclase formation, then there is at least two generations of CaS. The presence of sulphides in the olivines and both enstatite types indicate that sulphidation took place prior to silicification.

As the Fe- and Ca-enstatites have similar Mg contents, at the first order the Fe-enstatites are the precursor of the Ca-enstatites. However, as the Mg-enstatites contains some Ca-enstatites, it is more likely that the Ca-enstatites formed from both of the other enstatite types. The source of the Ca was the glass that was altered to plagioclase. Inclusions of Ca-enstatite are observed without any plagioclase. This indicates a second source of Ca to form Ca-enstatite, is likely to be CaS.

The Fe-enstatite in Indarch-Ch1 is observed to be more enriched in Ca in areas closer to the Mg-enstatite. This is not the case for the Y74370 chondrules. The core domains in Indarch-Ch1 is enriched in metal relative to the rest of the chondrule domains. In the core domain of Y74370-Ch5, the Fe content of Fe-enstatite varies, even within the same grain. In Indarch-Ch1, FeS is observed to be primarily in the core and mantle domains. However, in Y74370-Ch1 and Y74370-Ch5, the FeS is primarily in the rim domains, and specifically included in the plagioclase. The FeS in Indarch-Ch1 occurs between the Fe-enstatite grains. The FeS has rounded shapes indicating that they formed from a melt. This indicates that the FeS in the plagioclase is relict compared to the host plagioclase, and supports the sulphidation occurred prior to enstatite production.

Silica is only observed in the glass of Indarch-Ch1 at two sites (Figures 4.3d and 4.4d). The silica at Site4 in Indarch-Ch1 has a contact with the Mg-enstatite, containing a silica inclusion. This gives a sense of the 3D positioning of the silica. In Site8, one of the silica grains is cut in two pieces by the glass, with two of the grains sharing contacts with the Fe-enstatite. No metal is observed accompanying the silica, indicating that it was not produced by the reduction of FeO. Based on the petrography it is most likely that silicification is the dominant process in producing enstatite from olivine-rich precursors. This was expected and agrees with the observations and interpretations from the EH3 chondrules.

4.4.3 O-isotope variation between EH4 and EH3 chondrules

The enstatites in the EH4 chondrules plot in the same range as the those of the enstatites in the chondrules of the EH3 Sahara 97103 chondrite. Most of the enstatites from all three chondrules plot close to the TF-PCM intersection. The Fe-enstatites plot the closest to the EH3 enstatites. This is consistent with the Fe-enstatite major-element compositions. The EH4 olivines plot close to the K4-1 olivines and euhedral olivines without varying significantly along the PCM line. The EH4 chondrule components are more homogenised than their EH3 counterparts. This can be attributed to heating on the enstatite asteroid pulling the O-isotope composition closer to the TF-PCM intersection.

The two enstatite clusters in Indarch-Ch1 and Y74370-Ch5 suggest that there may have been two different generations of for the Mg-enstatites in both chondrules and the Fe-enstatites in Indarch-Ch1. The $\delta^{17}\text{O}$ variations observed for the enstatites in Y74370-Ch1 and Ch5 is small compared to Indarch-Ch1 and the EH3 enstatites. These smaller variations are likely the result of secondary processes on the enstatite asteroid causing the O-isotopes of the enstatites to be homogenised. Alternatively, the similar O-isotope compositions between the Mg-enstatites and Fe-enstatites in the same chondrule indicates that the O-fractionation was stable during the last chondrule melting event.

The EH4 olivines plot in a similar place to most of the EH3 olivines but exhibit a significantly smaller range. There is no significant difference between the olivines and the enstatites in the same chondrule. This indicates that these olivines are not necessarily relict. However, the olivines in the EH4 should be relict. As the EH4 precursor are enstatite chondrules from the enstatite asteroid, the olivines may have formed during the formation of the enstatite precursor chondrule. The O-isotope compositions of the EH4 olivines may reflect this.

The presence of the glass indicates that Indarch-Ch1 has undergone less heating on the asteroid compared to Y74370-Ch1 and Ch5. This will have allowed the record of the different generations of enstatite to survive. This supports the recycling of the enstatite chondrule material and may indicate that the precursor of the Mg-enstatites were older enstatite chondrites. Based on the comparison of the O-isotopes of the EH4 chondrule components and those of the EH3, the O-isotope compositions of chondrules is maintained on the enstatite asteroid.

4.4.4 Li-isotope variation between EH4 and EH3 chondrules

The Fe-enstatites are tightly grouped and are the closest to the EH3 enstatites in terms of Li-isotope composition. However, they do have smaller Li concentrations compared to most of the EH3 enstatites. The Mg-enstatites by comparison exhibit a larger range of $\delta^7\text{Li}$ values compared to the Fe-enstatites and the EH3 enstatites. This larger range supports Mg-enstatite forming from an earlier generation of melt. Comparing the enstatites in the EH4 and the EH3 indicates that the Fe-enstatites are the result of silicification producing enstatite from an olivine-rich precursor and the Mg-enstatites are recycled from chondritic material from the enstatite asteroid. The Mg-enstatites tend to plot in two groups, with Indarch-Ch1 plotting in a tighter pack compared to those in Y74370-Ch1. The variations in the Mg-enstatites suggests that they are not all from the same generation. Chondrule Y74370-Ch1 will have undergone several heating events in both the nebula (during chondrule formation) and on the asteroid. The variation in the Li-isotope composition of the Mg-enstatite in this chondrule likely reflects a previous heating event on the enstatite asteroid. During the last melting event, the Mg-enstatites are then recycled from the enstatite asteroid into the new EH4 chondrule. Loss of Li on the asteroid then results in a heavier Li-isotope composition. This would support the recycling of material

from existing enstatite chondrites.

The EH4 olivines exhibit a larger range Li concentration and a similar range of $\delta^7\text{Li}$ compared to the EH3 olivines. Although the EH4 olivines were shown to not necessarily be relict by the O-isotope compositions, the Li-isotope compositions may reflect their precursors. Weisberg et al. (1994) suggested that the precursors of enstatite chondrites may have had compositions similar to that of ordinary chondrites. This would imply that the precursor chondrules may have migrated from the ordinary-chondrite forming-region and possibly the carbonaceous-chondrite forming-region. Seitz et al. (2007) and references therein determined that carbonaceous chondrites exhibited bulk Li-isotope compositions of 1.1‰ to 4.9‰. Carbonaceous and ordinary chondrules were found to have bulk Li-isotope compositions ranging from -7.2‰ to 3.0‰ and -8.0‰ to 5.9‰ respectively (Seitz et al., 2012). Assuming that the olivine-rich precursors of the enstatite chondrules migrated from the ordinary- and carbonaceous-chondrite forming-regions to the enstatite-chondrite forming-region, then the variation in between the EH3 and EH4 enstatites may reflect the heterogeneity in the Li-isotope compositions the different chondrite forming regions. Ciesla and Cuzzi (2006) suggest that the mechanism for the migration of solid material inward was gas drag. However, they also suggest that headwinds generated by the difference in velocity between solid material and ambient gas may be responsible for the migration of solid material in the solar nebula (Ciesla and Cuzzi, 2006).

No significant difference is observed between the EH4 and EH3 glass averages. As both reflect the last chondrule melting event, at the first order this is as expected. This suggests that the Si-rich gas that interacted with the EH3 and EH4 chondrules was the same reservoir. Variations in the glass is likely the result of Li being lost from the chondrule via evaporation, post enstatite production. The difference in the Li concentrations and Li-isotope composition of the plagioclase and the glass indicates that during the production the plagioclase there was a significant drop in both [Li] and $\delta^7\text{Li}$ values. This indicates that plagioclase production during heating on the asteroid may have allowed the removal of some Li by evaporation.

The Li-isotope results indicate that there have been at least four generations of heating events. The first will have produced the original enstatites from an olivine-rich precursor during a chondrule formation event. These enstatites were then heated and processed to become the Mg-enstatites on the enstatite asteroid. This resulted in the variation observed of the Mg-enstatites in Y74370-Ch1. These enstatites were then broken off of the asteroid and recycled during a second period of chondrule formation, which resulted in the production of the Fe-enstatites and the glass. This melting event may explain why the Li-isotope compositions of Mg-enstatite in Indarch-Ch1 are consistent with the Fe-enstatites in the same chondrule. The chondrule components will have then been processed again on the enstatite asteroid, resulting the production of plagioclase from the glass. Impact events are likely responsible for breaking up or breaking pieces of from the initial enstatite asteroid prior to the recycling of the enstatite chondrite material. These events may have also been a potential source of the re-heating required to form the new chondrules.

4.5 Conclusions

Based on the isotopic similarities between the EH4 and the EH3 chondrules, it is likely that they followed a similar evolutionary path. In Indarch-Ch1, Y74370-Ch1, and Y74370-Ch5 silicification is the dominant process in producing enstatite from their respective olivine-rich precursors. This is evidenced by the lack of MgS in the Y74370 chondrules and only minor MgS in Indarch-Ch1. This indicates that sulphidation did not play a major role in the last melting event. The sulphides in these chondrules are possibly relict, with existing FeS and

possibly MgS playing a role in the production of the Fe-enstatites.

Mg-enstatite was determined to be the older of the two enstatite types. Based on the major-element composition of the two enstatites, the Mg-enstatites formed in a slightly more reduced environment compared to the Fe-enstatites. Weisberg and Kimura (2012) stated that enstatites in heated enstatite chondrites have compositions close to that of pure enstatite. The Mg-enstatites have a composition that is reminiscent of these enstatites. This indicates that the Mg-enstatites originate from an older enstatite chondrite that had accreted on the asteroid. This is supported by orthorhombic structure of the Mg-enstatites. By comparison, the Fe-enstatites exhibit compositions closer to that of the EH3 enstatites and a clino-enstatite structure. This indicates that they formed from the last melting event. From these enstatites, it implies that the EH4 chondrules precursors may have been enstatite chondrules in the enstatite asteroid, rather than olivine-rich chondrules.

Based on the O- and Li-isotope compositions of the EH4 chondrule components, the Si-rich reservoir that interacted with the EH3 and EH4 chondrule precursors is very similar. As stated earlier the EH4 chondrules precursors may have been enstatite chondrules. The similarities between the EH3 and EH4 chondrules gives an indication that the EH4 chondrule precursors were EH3 chondrules that interacted with the same or a similar Si-rich gas reservoir that the Sahara 97103 chondrules interacted with. Assuming this is the case, variations within the Si-rich gas can be attributed to either spatial or temporal variations. However, current evidence suggests that the enstatite-chondrite forming-region was well mixed and homogenised compared to the outer solar system. The O-isotope composition of the EH4 chondrule components compared to those of the EH3 chondrule components suggest that the O-isotope compositions of enstatite chondrules is maintained on the enstatite asteroid. The similarities in the Li-isotope compositions of the EH4 chondrule components makes it unlikely that there is a correlation as what was observed for Si-isotopes by Tanaka et al. (2021).

In addition the Li-isotope compositions of the EH4 chondrule components suggest that there were four generations of heating events. In the first event, the enstatite chondrules are produced from olivine-rich precursors. This is followed by heating on the enstatite asteroid. The Mg-enstatites are then broken off of the enstatite asteroid during impact events and recycled in a second chondrule forming event which produced the Fe-enstatites and glass. These are then processed on the enstatite asteroid, with the glass turning into plagioclase. The re-heating that allowed for the formation of the new chondrules was likely a short term heating event such as shock waves, jets and outflows, impacts, and lightning discharges (Alexander, 2005; Scott and Krot, 2014).

Table 4.1: Major-element composition of chondrule constituents in the chondrules Indarch-Ch1, Y74370-Ch1, and Y74370-Ch5 determined by EPMA and EDS: en-area refers to an area dominated by Fe-enstatite. en-Mg-area refers to an area dominated by Mg-enstatite.

spot	phase	en-area/ en-Mg-area	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	NiO	total	chem	domain
emp-en-ch1-indarch@1229	Fe-enstatite	en-area	59.97	0.04	0.30	0.52	1.06	0.17	38.48	0.18	0.00	0.01	0.00	100.71	$En_{98.5}Fs_{1.1}Wo_{0.4}$	mantle
emp-en-ch1-indarch@1230	Fe-enstatite	en-area	59.78	0.05	0.35	0.39	0.55	0.07	38.93	0.26	0.05	0.00	0.00	100.43	$En_{99.7}Fs_{0.1}Wo_{0.2}$	core
emp-en-ch1-indarch@1231	Fe-enstatite	en-area	58.95	0.02	0.15	0.53	1.12	0.14	37.75	0.17	0.01	0.01	0.00	98.84	$En_{98.1}Fs_{1.6}Wo_{0.3}$	mantle
emp-en-ch1-indarch@1232	Fe-enstatite	en-area	60.07	0.05	0.30	0.46	1.06	0.13	38.57	0.16	0.02	0.00	0.00	100.81	$En_{98.2}Fs_{1.2}Wo_{0.3}$	mantle
emp-en-ch1-indarch@1233	Fe-enstatite	en-area	59.06	0.05	0.16	0.52	1.25	0.13	37.75	0.19	0.00	0.00	0.02	99.12	$En_{97.8}Fs_{1.8}Wo_{0.4}$	mantle
emp-en-ch1-indarch@1234	Fe-enstatite	en-area	59.40	0.01	0.20	0.03	0.25	0.02	38.61	0.20	0.14	0.01	0.01	98.87	$En_{99.3}Fs_{0.3}Wo_{0.4}$	core
emp-en-ch1-indarch@1425	Fe-enstatite	en-area	59.74	0.07	0.41	0.40	0.74	0.16	38.49	0.26	0.08	0.01	0.00	100.36	$En_{98.5}Fs_{1.1}Wo_{0.5}$	mantle
emp-en-ch1-indarch@1426	Fe-enstatite	en-area	59.05	0.00	0.25	0.39	0.98	0.12	37.77	0.21	0.03	0.00	0.00	98.80	$En_{98.2}Fs_{1.4}Wo_{0.4}$	mantle
emp-en-ch1-indarch@1427	Fe-enstatite	en-area	60.45	0.03	0.19	0.42	1.15	0.15	38.57	0.14	0.01	0.01	0.01	101.15	$En_{98.1}Fs_{1.6}Wo_{0.3}$	mantle
emp-en-ch1-indarch@1428	Fe-enstatite	en-area	59.53	0.03	0.35	0.46	1.03	0.11	37.60	0.16	0.01	0.00	0.01	99.28	$En_{98.2}Fs_{1.5}Wo_{0.3}$	mantle
emp-en-ch1-indarch@1429	Fe-enstatite	en-area	59.70	0.05	0.42	0.43	0.77	0.12	37.49	0.26	0.13	0.00	0.00	99.34	$En_{98.2}Fs_{1.5}Wo_{0.3}$	core
emp-en-ch1-indarch@1430	Fe-enstatite	en-area	60.20	0.01	0.07	0.04	0.07	0.00	39.67	0.13	0.01	0.01	0.00	100.20	$En_{99.9}Fs_{0.1}Wo_{0.0}$	core
emp-en-ch1-indarch@1437	Fe-enstatite	en-area	59.64	0.04	0.25	0.42	1.09	0.12	38.49	0.21	0.06	0.01	0.00	100.31	$An_{61.3}Ab_{38.4}Or_{0.3}$	mantle
emp-en-ch1-indarch@1438	Fe-enstatite	en-area	59.30	0.08	0.45	0.49	1.25	0.14	37.98	0.21	0.03	0.01	0.00	99.95	$En_{99.8}Fs_{0.1}Wo_{0.1}$	rim
emp-en-ch1-indarch@1439	Fe-enstatite	en-area	59.45	0.01	0.18	0.00	0.14	0.00	39.84	0.21	0.08	0.00	0.00	99.92	$En_{99.4}Fs_{0.2}Wo_{0.4}$	rim
emp-en-ch1-indarch@1440	Fe-enstatite	en-area	59.28	0.02	0.25	0.46	1.09	0.10	38.70	0.20	0.00	0.01	0.00	100.09	$En_{98.1}Fs_{1.5}Wo_{0.4}$	rim
emp-en-ch1-indarch@1441	Fe-enstatite	en-area	59.30	0.07	0.39	0.38	1.03	0.17	38.66	0.24	0.10	0.01	0.00	100.34	$En_{98.1}Fs_{1.5}Wo_{0.4}$	core
eds-en-fe-ch1-indarch@10692	Fe-enstatite	en-area	59.88	0.00	0.05	0.59	1.12	0.07	37.98	0.18	0.00	0.00	0.14	100	$En_{98.0}Fs_{1.6}Wo_{0.3}$	mantle
eds-en-fe-ch1-indarch@10693	Fe-enstatite	en-area	60.06	0.01	0.07	0.33	1.38	0.23	37.57	0.22	0.00	0.04	0.11	100	$En_{97.6}Fs_{2.0}Wo_{0.4}$	mantle
emp-en-ch1-indarch@1431	Mg-enstatite	en-Mg-area	59.76	0.00	0.04	0.03	0.09	0.00	40.62	0.05	0.03	0.00	0.00	100.61	$En_{99.8}Fs_{0.1}Wo_{0.1}$	rim
emp-en-ch1-indarch@1432	Mg-enstatite	en-Mg-area	59.87	0.00	0.07	0.05	0.10	0.01	40.53	0.06	0.19	0.00	0.03	100.91	$En_{99.8}Fs_{0.1}Wo_{0.1}$	rim
emp-en-ch1-indarch@1433	Mg-enstatite	en-Mg-area	59.44	0.00	0.05	0.02	0.09	0.03	39.40	0.04	0.05	0.01	0.00	99.14	$En_{98.0}Fs_{1.6}Wo_{0.4}$	rim
emp-en-ch1-indarch@1434	Mg-enstatite	en-Mg-area	59.99	0.00	0.05	0.02	0.03	0.00	39.72	0.04	0.01	0.00	0.00	99.85	$En_{99.6}Fs_{0.1}Wo_{0.3}$	rim
emp-en-ch1-indarch@1435	Fe-enstatite	en-Mg-area	59.77	0.03	0.18	0.39	1.07	0.14	38.05	0.19	0.01	0.00	0.03	99.85	$En_{98.1}Fs_{1.6}Wo_{0.3}$	rim
emp-en-ch1-indarch@1436	Mg-enstatite	en-Mg-area	59.23	0.08	0.57	0.55	1.17	0.12	38.31	0.20	0.00	0.00	0.05	100.28	$En_{99.9}Fs_{0.0}Wo_{0.1}$	rim
emp-en-ch1-indarch@1442	Mg-enstatite	en-area	60.43	0.00	0.12	0.02	0.06	0.00	39.56	0.15	0.03	0.01	0.05	100.43	$En_{98.3}Fs_{1.2}Wo_{0.5}$	core
emp-en-ch1-indarch@1443	Mg-enstatite	en-Mg-area	59.68	0.00	0.04	0.00	0.07	0.00	40.65	0.03	0.00	0.00	0.00	100.47	$En_{99.9}Fs_{0.1}Wo_{0.0}$	rim
emp-en-ch1-indarch@1448	Mg-enstatite	en-Mg-area	59.71	0.02	0.07	0.02	0.01	0.01	39.05	0.06	0.02	0.00	0.00	98.96	$En_{99.9}Fs_{0.0}Wo_{0.1}$	mantle
eds-en-fe-ch1-indarch@10695	Mg-enstatite	en-Mg-area	59.98	0.00	0.00	0.00	0.00	0.00	40.02	0.00	0.00	0.00	0.00	100	$En_{100.0}Fs_{0.0}Wo_{0.0}$	mantle
emp-gl-ch1-indarch@1444	Na-rich glass	-	58.28	0.00	22.69	0.06	1.07	0.06	3.28	6.11	7.14	0.05	0.09	98.83	$An_{32.0}Ab_{67.7}Or_{0.3}$	mantle
emp-gl-ch1-indarch@1445	Na-rich glass	-	56.77	0.02	25.03	0.12	1.97	0.05	0.78	7.20	7.43	0.04	0.04	99.43	$An_{34.8}Ab_{65.0}Or_{0.2}$	mantle
emp-gl-ch1-indarch@1446	Na-rich glass	-	57.45	0.02	27.03	0.01	0.31	0.02	0.31	8.89	6.57	0.05	0.00	100.64	$An_{57.1}Ab_{42.6}Or_{0.3}$	mantle
emp-gl-ch1-indarch@1447	Na-rich glass	-	51.71	0.00	30.42	0.01	0.04	0.00	0.75	12.62	4.37	0.05	0.00	99.97	$En_{97.8}Fs_{1.8}Wo_{0.4}$	mantle

Table 4.1: Continued

spot	phase	en-area/ en-Mg-area	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	NiO	total	chem	domain
emp-en-ch1-y74370@1235	Fe-enstatite	en-area	59.87	0.04	0.30	0.09	0.26	0.16	38.95	0.16	0.02	0.00	0.00	99.83	$En_{99.3}Fs_{0.4}Wo_{0.3}$	core
emp-en-ch1-y74370@1236	Fe-enstatite	en-area	59.34	0.05	0.28	0.09	0.30	0.20	38.50	0.16	0.01	0.01	0.00	98.93	$En_{99.3}Fs_{0.4}Wo_{0.3}$	core
emp-en-ch1-y74370@1237	Fe-enstatite	en-area	59.89	0.02	0.17	0.08	0.13	0.19	38.71	0.19	0.01	0.00	0.00	99.40	$En_{99.5}Fs_{0.2}Wo_{0.3}$	core
emp-en-ch1-y74370@1238	Fe-enstatite	en-area	59.01	0.08	0.39	0.10	0.23	0.27	38.47	0.24	0.00	0.01	0.02	98.82	$En_{99.2}Fs_{0.3}Wo_{0.5}$	rim
emp-en-ch1-y74370@1368	Fe-enstatite	en-area	59.15	0.07	0.34	0.16	0.18	0.29	38.77	0.26	0.02	0.00	0.01	99.23	$En_{99.3}Fs_{0.3}Wo_{0.5}$	rim
emp-en-ch1-y74370@1370	Fe-enstatite	en-area	59.84	0.04	0.22	0.14	0.16	0.30	38.99	0.34	0.00	0.01	0.00	100.03	$En_{99.2}Fs_{0.2}Wo_{0.6}$	rim
emp-en-ch1-y74370@1373	Fe-enstatite	en-area	60.13	0.05	0.18	0.17	0.24	0.22	39.39	0.17	0.00	0.01	0.02	100.57	$En_{99.4}Fs_{0.3}Wo_{0.3}$	rim
emp-en-ch1-y74370@1374	Fe-enstatite	en-area	59.41	0.02	0.18	0.14	0.25	0.16	38.78	0.16	0.01	0.01	0.00	99.13	$En_{99.4}Fs_{0.4}Wo_{0.3}$	rim
emp-en-ch1-y74370@1376	Fe-enstatite	en-area	59.05	0.01	0.16	0.11	0.25	0.21	38.64	0.14	0.00	0.01	0.00	98.58	$En_{99.4}Fs_{0.4}Wo_{0.2}$	rim
emp-en-ch1-y74370@1377	Fe-enstatite	en-area	60.31	0.05	0.24	0.12	0.13	0.18	39.64	0.21	0.00	0.00	0.02	100.90	$En_{99.4}Fs_{0.2}Wo_{0.4}$	rim
emp-en-ch1-y74370@1378	Fe-enstatite	en-area	60.95	0.01	0.21	0.11	0.28	0.19	39.74	0.15	0.01	0.00	0.02	101.67	$En_{99.3}Fs_{0.4}Wo_{0.3}$	core
emp-en-ch1-y74370@1379	Fe-enstatite	en-area	59.89	0.03	0.18	0.08	0.15	0.10	39.13	0.16	0.00	0.01	0.00	99.73	$En_{99.5}Fs_{0.2}Wo_{0.3}$	core
emp-en-ch1-y74370@1380	Fe-enstatite	en-area	60.36	0.09	0.33	0.13	0.12	0.22	39.37	0.38	0.00	0.01	0.06	101.06	$En_{99.1}Fs_{0.2}Wo_{0.7}$	core
emp-en-ch1-y74370@1381	Fe-enstatite	en-area	59.20	0.01	0.30	0.14	0.22	0.20	38.39	0.18	0.00	0.00	0.03	98.68	$En_{99.3}Fs_{0.3}Wo_{0.4}$	core
emp-en-ch1-y74370@1382	Fe-enstatite	en-area	59.87	0.01	0.25	0.08	0.25	0.22	39.35	0.15	0.02	0.01	0.00	100.21	$En_{99.4}Fs_{0.3}Wo_{0.3}$	core
emp-en-ch1-y74370@1383	Fe-enstatite	en-area	60.31	0.05	0.26	0.11	0.21	0.19	39.67	0.14	0.00	0.00	0.06	101.01	$En_{99.4}Fs_{0.3}Wo_{0.3}$	core
emp-en-ch1-y74370@1385	Fe-enstatite	en-area	60.23	0.08	0.33	0.17	0.30	0.23	39.37	0.16	0.01	0.00	0.00	100.87	$En_{99.3}Fs_{0.4}Wo_{0.3}$	core
emp-en-ch1-y74370@1386	Fe-enstatite	en-area	59.87	0.10	0.32	0.07	0.11	0.20	38.88	0.34	0.02	0.00	0.00	99.91	$En_{99.2}Fs_{0.2}Wo_{0.6}$	rim
eds-en-fe-ch1-y74370@10704	Fe-enstatite	en-area	59.19	0.08	0.14	0.05	1.07	0.14	39.10	0.17	0.00	0.05	0.00	100	$En_{98.2}Fs_{1.5}Wo_{0.3}$	rim
eds-en-fe-ch1-y74370@10706	Fe-enstatite	en-area	59.36	0.06	0.11	0.11	0.66	0.01	39.44	0.10	0.00	0.00	0.14	100	$En_{98.9}Fs_{0.9}Wo_{0.2}$	rim
emp-en-ch1-y74370@1239	Mg-enstatite	en-Mg-area	59.93	0.00	0.13	0.00	0.04	0.02	39.96	0.02	0.03	0.01	0.00	100.13	$En_{99.9}Fs_{0.1}Wo_{0.0}$	rim
emp-en-ch1-y74370@1240	Mg-enstatite	en-Mg-area	60.054	0	0.081	0.011	0.065	0.026	40.104	0.054	0.03	0.009	0.02	100.454	$En_{99.8}Fs_{0.1}Wo_{0.1}$	rim
emp-en-ch1-y74370@1363	Mg-enstatite	en-Mg-area	60.84	0.01	0.06	0.00	0.01	0.02	40.29	0.02	0.00	0.01	0.00	101.27	$En_{100.0}Fs_{0.0}Wo_{0.0}$	rim
emp-en-ch1-y74370@1364	Mg-enstatite	en-Mg-area	60.58	0.00	0.02	0.03	0.05	0.00	40.05	0.04	0.00	0.02	0.00	100.78	$En_{99.8}Fs_{0.1}Wo_{0.1}$	rim
emp-en-ch1-y74370@1365	Mg-enstatite	en-Mg-area	59.11	0.00	0.05	0.00	0.03	0.02	39.27	0.04	0.00	0.00	0.03	98.55	$En_{99.9}Fs_{0.0}Wo_{0.1}$	rim
emp-en-ch1-y74370@1366	Mg-enstatite	en-Mg-area	59.55	0.01	0.11	0.03	0.07	0.01	39.95	0.05	0.00	0.00	0.00	99.76	$En_{99.8}Fs_{0.1}Wo_{0.1}$	rim
emp-en-ch1-y74370@1367	Mg-enstatite	en-Mg-area	59.83	0.00	0.03	0.00	0.05	0.00	39.54	0.01	0.01	0.00	0.00	99.47	$En_{99.9}Fs_{0.1}Wo_{0.0}$	rim
emp-en-ch1-y74370@1372	Mg-enstatite	en-Mg-area	59.66	0.04	0.18	0.06	0.11	0.03	38.88	0.06	0.17	0.01	0.02	99.20	$En_{99.7}Fs_{0.2}Wo_{0.1}$	rim
emp-en-ch1-y74370@1375	Mg-enstatite	en-Mg-area	59.61	0.00	0.04	0.05	0.00	0.00	39.23	0.05	0.00	0.00	0.00	98.99	$En_{99.9}Fs_{0.0}Wo_{0.1}$	rim
eds-en-mg-ch1-y74370@10703	Mg-enstatite	en-Mg-area	60.18	0.00	0.00	0.00	0.26	0.00	39.45	0.00	0.00	0.03	0.07	100	$En_{99.6}Fs_{0.4}Wo_{0.0}$	rim
emp-en-ch1-y74370@01	Ca-enstatite	en-area	59.40	0.07	0.54	0.05	0.02	0.17	38.26	2.27	0.07	0.02	0.00	100.87	$En_{95.1}Fs_{0.0}Wo_{4.1}$	rim
emp-en-ch1-y74370@02	Ca-enstatite	en-area	57.21	0.00	0.10	0.00	0.01	0.00	42.58	0.60	0.01	0.00	0.00	100.50	$En_{99.0}Fs_{0.0}Wo_{1.0}$	rim
emp-en-ch1-y74370@03	Ca-enstatite	en-area	60.01	0.24	2.30	0.05	0.04	0.08	36.61	0.48	0.62	0.12	0.00	100.56	$En_{99.0}Fs_{0.1}Wo_{0.9}$	rim
emp-ol-ch1-y74370@1241	olivine	-	43.18	0.00	0.04	0.00	0.03	0.01	57.29	0.06	0.00	0.01	0.01	100.63	$Fo_{99.9}Fa_{0.0}Ca_{0.1}$	rim
emp-ol-ch1-y74370@1242	olivine	-	43.54	0.00	0.01	0.01	0.07	0.01	56.99	0.04	0.00	0.00	0.01	100.66	$Fo_{99.8}Fa_{0.1}Ca_{0.1}$	rim

Table 4.1: Continued

spot	phase	en-area/ en-Mg-area	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	NiO	total	chem	domain
emp-ol-ch1-y74370@1370	olivine	-	42.96	0.00	0.02	0.01	0.06	0.05	56.39	0.07	0.00	0.00	0.00	99.56	$For_{99.8}Fa_{0.1}Ca_{0.1}$	rim
emp-ol-ch1-y74370@1371	olivine	-	42.43	0.00	0.00	0.00	0.02	0.02	56.45	0.06	0.00	0.00	0.05	99.02	$For_{99.9}Fa_{0.0}Ca_{0.1}$	rim
emp-ol-ch1-y74370@05	olivine	-	42.80	0.00	0.02	0.00	0.07	0.00	56.96	0.05	0.00	0.00	0.01	99.90	$For_{99.8}Fa_{0.1}Ca_{0.1}$	rim
emp-ol-ch1-y74370@06	olivine	-	42.89	0.00	0.02	0.00	0.05	0.00	56.26	0.03	0.00	0.00	0.00	99.25	$For_{99.9}Fa_{0.1}Ca_{0.0}$	rim
eds-ol-ch1-y74370@10738	Olivine	-	42.55	0.01	0.00	0.03	0.21	0.04	57.05	0.11	0.00	0.00	0.00	100	$For_{99.7}Fa_{0.2}Ca_{0.1}$	rim
emp-pl-ch1-y74370@1243	Na-rich plagioclase	-	69.62	0.00	18.58	0.00	0.00	0.06	0.44	0.01	10.74	0.64	0.02	100.12	$An_{0.0}Ab_{96.2}Or_{3.8}$	core
emp-pl-ch1-y74370@1244	Na-rich plagioclase	-	69.29	0.00	18.90	0.00	0.00	0.00	0.07	0.00	10.88	0.42	0.01	99.56	$An_{0.0}Ab_{97.5}Or_{2.5}$	core
emp-pl-ch1-y74370@1384	Na-rich plagioclase	-	69.61	0.00	18.31	0.01	0.00	0.04	0.35	0.01	10.94	0.65	0.00	99.93	$An_{0.1}Ab_{96.1}Or_{3.8}$	core
emp-pl-ch1-y74370@1387	Na-rich plagioclase	-	68.86	0.00	18.47	0.00	0.01	0.00	0.05	0.10	10.48	0.66	0.00	98.63	$An_{0.5}Ab_{95.5}Or_{4.0}$	core
emp-pl-ch1-y74370@1388	Na-rich plagioclase	-	70.29	0.00	19.12	0.03	0.04	0.00	0.26	0.01	10.42	0.66	0.04	100.86	$An_{0.1}Ab_{95.9}Or_{4.0}$	core
emp-pl-ch1-y74370@1389	Na-rich plagioclase	-	69.70	0.00	18.67	0.00	0.01	0.01	0.27	0.02	10.72	0.52	0.00	99.93	$An_{0.1}Ab_{96.8}Or_{3.1}$	core
emp-pl-ch1-y74370@1390	Na-rich plagioclase	-	69.90	0.00	18.88	0.00	0.02	0.02	0.05	0.01	10.87	0.43	0.00	100.18	$An_{0.0}Ab_{97.5}Or_{2.5}$	core
emp-pl-ch1-y74370@1391	Na-rich plagioclase	-	70.43	0.00	18.91	0.00	0.00	0.00	0.05	0.00	10.90	0.52	0.00	100.81	$An_{0.0}Ab_{97.0}Or_{3.0}$	core
emp-pl-ch1-y74370@1392	Na-rich plagioclase	-	68.36	0.01	18.88	0.00	0.04	0.01	0.35	0.01	10.27	0.46	0.01	98.39	$An_{0.1}Ab_{97.1}Or_{2.8}$	core
emp-pl-ch1-y74370@1393	Na-rich plagioclase	-	69.56	0.00	18.73	0.01	0.03	0.04	0.06	0.01	11.05	0.49	0.02	100.00	$An_{0.0}Ab_{97.1}Or_{2.9}$	core
emp-pl-ch1-y74370@1394	Na-rich plagioclase	-	69.77	0.02	18.68	0.00	0.00	0.02	0.05	0.00	11.22	0.37	0.01	100.14	$An_{0.0}Ab_{97.9}Or_{2.1}$	core
emp-en-ch5-y74370@1223	Fe-enstatite	en-area	60.29	0.04	0.16	0.42	1.00	0.14	39.01	0.16	0.00	0.00	0.00	101.22	$En_{98.3}Fs_{1.4}Wo_{0.3}$	core
emp-en-ch5-y74370@1224	Fe-enstatite	en-area	58.85	0.00	0.11	0.41	0.98	0.06	38.19	0.12	0.00	0.01	0.00	98.73	$En_{98.4}Fs_{1.4}Wo_{0.2}$	core
emp-en-ch5-y74370@1225	Fe-enstatite	en-area	60.01	0.03	0.18	0.34	0.84	0.09	39.15	0.14	0.00	0.00	0.02	100.79	$En_{98.6}Fs_{1.2}Wo_{0.2}$	core
emp-en-ch5-y74370@1226	Fe-enstatite	en-area	59.48	0.06	0.18	0.17	0.67	0.01	38.88	0.14	0.02	0.02	0.02	99.66	$En_{98.8}Fs_{1.0}Wo_{0.2}$	core
emp-en-ch5-y74370@1227	Fe-enstatite	en-area	59.34	0.01	0.12	0.33	1.05	0.05	38.35	0.09	0.01	0.00	0.00	99.35	$En_{98.3}Fs_{1.5}Wo_{0.2}$	core
emp-en-ch5-y74370@1228	Fe-enstatite	en-area	60.37	0.00	0.09	0.31	0.99	0.09	37.82	0.08	0.01	0.00	0.00	99.76	$En_{98.4}Fs_{1.4}Wo_{0.2}$	core
emp-en-ch5-y74370@1400	Fe-enstatite	en-area	60.26	0.04	0.17	0.37	0.79	0.14	39.17	0.20	0.02	0.00	0.00	101.16	$En_{98.5}Fs_{1.1}Wo_{0.4}$	core
emp-en-ch5-y74370@1401	Fe-enstatite	en-area	59.13	0.00	0.12	0.36	0.88	0.09	38.73	0.12	0.00	0.00	0.00	99.43	$En_{98.5}Fs_{1.3}Wo_{0.2}$	core
emp-en-ch5-y74370@1402	Fe-enstatite	en-area	60.42	0.01	0.09	0.31	1.05	0.10	39.27	0.09	0.01	0.00	0.01	101.35	$En_{98.4}Fs_{1.4}Wo_{0.2}$	core
emp-en-ch5-y74370@1403	Fe-enstatite	en-area	59.80	0.01	0.15	0.28	0.78	0.14	39.17	0.14	0.02	0.00	0.01	100.50	$En_{98.6}Fs_{1.1}Wo_{0.3}$	rim
emp-en-ch5-y74370@1404	Fe-enstatite	en-area	59.38	0.01	0.18	0.23	0.69	0.10	38.59	0.15	0.00	0.01	0.00	99.33	$En_{98.7}Fs_{1.0}Wo_{0.3}$	rim
emp-en-ch5-y74370@1405	Fe-enstatite	en-area	59.88	0.01	0.14	0.23	0.79	0.09	38.59	0.16	0.00	0.00	0.00	99.90	$En_{98.6}Fs_{1.1}Wo_{0.3}$	rim
emp-en-ch5-y74370@1406	Fe-enstatite	en-area	60.07	0.01	0.12	0.36	0.77	0.06	38.85	0.15	0.00	0.00	0.00	100.40	$En_{98.6}Fs_{1.1}Wo_{0.3}$	rim
emp-en-ch5-y74370@1407	Fe-enstatite	en-area	60.02	0.08	0.38	0.28	0.49	0.12	39.09	0.28	0.00	0.00	0.00	100.75	$En_{98.8}Fs_{0.7}Wo_{0.5}$	rim
emp-en-ch5-y74370@1408	Fe-enstatite	en-area	60.49	0.10	0.49	0.16	0.17	0.13	39.37	0.43	0.02	0.00	0.02	101.38	$En_{99.0}Fs_{0.2}Wo_{0.8}$	rim
emp-en-ch5-y74370@1409	Fe-enstatite	en-area	59.37	0.06	0.41	0.29	0.41	0.12	38.70	0.25	0.01	0.00	0.08	99.71	$En_{98.9}Fs_{0.6}Wo_{0.5}$	rim
emp-en-ch5-y74370@1410	Fe-enstatite	en-area	60.19	0.03	0.46	0.34	0.39	0.16	38.59	0.37	0.01	0.01	0.00	100.54	$En_{98.7}Fs_{0.6}Wo_{0.7}$	rim
emp-en-ch5-y74370@1411	Fe-enstatite	en-area	60.03	0.02	0.20	0.32	0.65	0.08	38.75	0.18	0.00	0.00	0.00	100.23	$En_{98.7}Fs_{0.9}Wo_{0.3}$	rim
eds-en-fe-ch5-y74370@10718	Fe-enstatite	en-area	58.54	0.16	0.17	0.15	2.09	0.00	38.76	0.12	0.00	0.01	0.00	100	$En_{96.7}Fs_{2.9}Wo_{0.2}$	rim

Table 4.1: Continued

spot	phase	en-area/ en-Mg-area	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	NiO	total	chem	domain
eds-en-fe-ch5-y74370@10723	Fe-enstatite	en-area	59.36	0.01	0.25	0.22	0.31	0.15	39.22	0.15	0.00	0.03	0.29	100	$En_{99.3}Fs_{0.4}Wo_{0.3}$	rim
emp-en-ch5-y74370@07	Mg-enstatite	en-Mg-area	60.35	0.01	0.07	0.00	0.02	0.01	39.96	0.01	0.00	0.01	0.00	100.44	$En_{100.0}Fs_{0.0}Wo_{0.0}$	rim
emp-en-ch5-y74370@08	Mg-enstatite	en-Mg-area	60.56	0.00	0.26	0.00	0.07	0.02	39.60	0.02	0.08	0.01	0.08	100.69	$En_{99.9}Fs_{0.1}Wo_{0.0}$	rim
emp-en-ch5-y74370@09	Mg-enstatite	en-Mg-area	59.86	0.01	0.04	0.00	0.01	0.02	39.63	0.02	0.05	0.00	0.01	99.65	$En_{99.9}Fs_{0.0}Wo_{0.0}$	rim
eds-en-mg-ch5-y74370@10720	Mg-enstatite	en-Mg-area	59.68	0.00	0.18	0.31	0.24	0.11	39.13	0.25	0.01	0.00	0.09	100	$En_{99.2}Fs_{0.3}Wo_{0.5}$	rim
emp-en-ch5-y74370@10	Ca-enstatite	en-area	58.87	0.16	0.43	0.13	0.33	0.18	38.48	0.47	0.02	0.01	0.05	99.11	$En_{98.6}Fs_{0.5}Wo_{0.9}$	rim
emp-en-ch5-y74370@11	Ca-enstatite	en-area	59.15	0.09	0.40	0.06	0.10	0.17	38.58	0.59	0.00	0.00	0.00	99.13	$En_{98.8}Fs_{0.1}Wo_{1.1}$	rim
emp-en-ch5-y74370@12	Ca-enstatite	en-area	59.86	0.08	0.83	0.15	0.15	0.16	38.46	0.49	0.23	0.04	0.00	100.44	$En_{98.9}Fs_{0.2}Wo_{0.9}$	rim
emp-pl-ch5-y74370@1412	Na-rich plagioclase	-	70.14	0.00	18.58	0.02	0.07	0.01	0.09	0.00	11.32	0.52	0.00	100.75	$An_{0.0}Ab_{97.1}Or_{2.9}$	rim
emp-pl-ch5-y74370@1413	Na-rich plagioclase	-	69.20	0.00	18.83	0.00	0.04	0.00	0.08	0.01	11.01	0.38	0.02	99.58	$An_{0.1}Ab_{97.7}Or_{2.2}$	rim
emp-pl-ch5-y74370@01	Na-rich plagioclase	-	69.40	0.00	18.95	0.00	0.08	0.01	0.06	0.00	10.97	0.42	0.00	99.89	$An_{0.0}Ab_{97.6}Or_{2.4}$	rim
emp-pl-ch5-y74370@02	Na-rich plagioclase	-	68.92	0.00	18.62	0.05	0.04	0.02	0.06	0.01	11.04	0.47	0.00	99.22	$An_{0.1}Ab_{97.2}Or_{2.7}$	rim
emp-pl-ch5-y74370@03	Na-rich plagioclase	-	68.70	0.00	19.66	0.01	0.03	0.00	0.11	0.09	10.88	0.56	0.00	100.03	$An_{0.5}Ab_{96.3}Or_{3.2}$	rim
emp-pl-ch5-y74370@04	Na-rich plagioclase	-	68.81	0.00	18.55	0.00	0.06	0.04	0.07	0.00	11.09	0.44	0.00	99.06	$An_{0.0}Ab_{97.4}Or_{2.6}$	rim
emp-pl-ch5-y74370@05	Na-rich plagioclase	-	68.93	0.00	18.66	0.00	0.06	0.00	0.10	0.01	10.50	0.91	0.02	99.19	$An_{0.0}Ab_{94.6}Or_{5.4}$	rim
emp-pl-ch5-y74370@06	Na-rich plagioclase	-	68.79	0.00	18.64	0.00	0.05	0.01	0.04	0.01	11.18	0.54	0.02	99.28	$An_{0.1}Ab_{96.8}Or_{3.1}$	rim

Table 4.2: O-isotope compositions of enstatites and olivines from the EH4 chondrules Indarch-Ch1, Y74370-Ch1, and Y74370-Ch5.

spot	$\delta^{18}\text{O}$	1SD	$\delta^{17}\text{O}$	1SD	$\Delta^{17}\text{O}$	1SD
oxy-en-fe-ch1-indarch@10688	5.71	0.1	3.27	0.3	0.30	0.2
oxy-en-mg-ch1-indarch@10689	5.64	0.1	2.96	0.3	0.03	0.2
oxy-en-fe-ch1-indarch@10690	5.98	0.2	2.18	0.4	-0.93	0.3
oxy-en-mg-ch1-indarch@10691	6.42	0.2	2.94	0.3	-0.40	0.2
oxy-en-fe-ch1-indarch@10692	8.21	0.2	4.24	0.4	-0.03	0.3
oxy-en-fe-ch1-indarch@10693	6.07	0.1	2.76	0.3	-0.39	0.2
oxy-en-mg-ch1-indarch@10695	8.17	0.2	5.20	0.3	0.95	0.2
oxy-en-mg-ch1-y74370@10701	6.63	0.1	2.56	0.4	-0.89	0.3
oxy-en-fe-ch1-y74370@10702	6.91	0.2	3.11	0.4	-0.48	0.2
oxy-en-mg-ch1-y74370@10703	6.20	0.1	3.03	0.4	-0.19	0.2
oxy-en-fe-ch1-y74370@10704	6.80	0.2	3.97	0.3	0.43	0.3
oxy-en-mg-ch1-y74370@10705	6.93	0.2	3.72	0.4	0.11	0.3
oxy-en-fe-ch1-y74370@10706	6.28	0.2	2.62	0.4	-0.65	0.3
oxy-en-mg-ch5-y74370@10717	8.42	0.2	2.63	0.3	-1.75	0.2
oxy-en-fe-ch5-y74370@10718	7.30	0.2	1.87	0.3	-1.93	0.3
oxy-en-fe-ch5-y74370@10719	5.99	0.1	2.60	0.5	-0.51	0.3
oxy-en-mg-ch5-y74370@10720	6.44	0.2	2.72	0.4	-0.63	0.2
oxy-en-fe-ch5-y74370@10721	7.18	0.1	2.95	0.3	-0.78	0.2
oxy-en-fe-ch5-y74370@10722	6.35	0.2	3.42	0.4	0.12	0.2
oxy-en-fe-ch5-y74370@10723	7.14	0.2	2.83	0.3	-0.89	0.2
oxy-ol-ch1-y74370@10735	6.15	0.2	1.10	0.3	-2.10	0.3
oxy-ol-ch1-y74370@10736	6.17	0.1	2.26	0.3	-0.95	0.2
oxy-ol-ch1-y74370@10738	5.82	0.2	2.24	0.3	-0.79	0.2
oxy-ol-ch1-y74370@10739	6.83	0.1	2.93	0.4	-0.62	0.3

Table 4.3: Li-isotope compositions of enstatites and olivines from the EH4 chondrules Indarch-Ch1, Y74370-Ch1, and Y74370-Ch5.

spot	$\delta^7\text{Li}$	σ_δ	[Li]	phase	domain
liso-en-ch1-indarch@1229	-5.20	2.50	2.90	Fe-enstatite	mantle
liso-en-ch1-indarch@1230	-7.00	2.70	1.78	Fe-enstatite	core
liso-en-ch1-indarch@1231	-1.40	2.30	1.62	Fe-enstatite	mantle
liso-en-ch1-indarch@1232	-6.20	2.00	1.88	Fe-enstatite	mantle
liso-en-ch1-indarch@1233	-4.80	1.30	2.65	Fe-enstatite	mantle
liso-en-ch1-indarch@1234	-6.00	2.00	2.34	Fe-enstatite	core
liso-en-ch1-indarch@1425	32.50	3.10	2.10	Fe-enstatite	mantle
liso-en-ch1-indarch@1426	4.30	1.60	1.83	Fe-enstatite	mantle
liso-en-ch1-indarch@1427	2.20	1.20	1.59	Fe-enstatite	mantle
liso-en-ch1-indarch@1428	-3.50	2.60	2.48	Fe-enstatite	mantle
liso-en-ch1-indarch@1429	-8.90	3.50	2.13	Fe-enstatite	core
liso-en-ch1-indarch@1430	-5.00	2.30	1.66	Fe-enstatite	core
liso-en-ch1-indarch@1435	-0.80	2.80	2.55	Fe-enstatite	rim

Table 4.3: Continued

spot	$\delta^7\text{Li}$	σ_δ	[Li]	phase	domain
liso-en-ch1-indarch@1437	-3.10	1.40	2.41	Fe-enstatite	mantle
liso-en-ch1-indarch@1438	-2.30	1.50	2.13	Fe-enstatite	mantle
liso-en-ch1-indarch@1439	-8.80	1.40	4.11	Fe-enstatite	mantle
liso-en-ch1-indarch@1440	-4.70	1.30	1.88	Fe-enstatite	rim
liso-en-ch1-indarch@1441	-5.80	1.60	2.70	Fe-enstatite	core
liso-en-ch1-indarch@1442	-1.80	1.30	1.61	Fe-enstatite	core
liso-en-ch1-indarch@1431	-7.10	2.60	1.99	Mg-enstatite	rim
liso-en-ch1-indarch@1432	-5.60	2.20	1.89	Mg-enstatite	rim
liso-en-ch1-indarch@1433	-3.40	3.20	1.53	Mg-enstatite	rim
liso-en-ch1-indarch@1434	-7.60	3.40	091	Mg-enstatite	rim
liso-en-ch1-indarch@1436	-11.00	4.20	1.35	Mg-enstatite	rim
liso-en-ch1-indarch@1443	0.04	1.80	2.53	Mg-enstatite	rim
liso-en-ch1-indarch@1448	-3.50	2.60	1.59	Mg-enstatite	mantle
liso-gl-ch1-indarch@1445	2.60	5.50	4.02	Na-rich glass	mantle
liso-gl-ch1-indarch@1446	12.80	3.10	3.84	Na-rich glass	mantle
liso-gl-ch1-indarch@1447	1.30	2.00	7.31	Na-rich glass	mantle
liso-en-ch1-y74370@1235	-3.40	1.60	1.60	Fe-enstatite	core
liso-en-ch1-y74370@1236	-5.50	2.00	1.09	Fe-enstatite	core
liso-en-ch1-y74370@1237	-8.80	4.60	2.24	Fe-enstatite	core
liso-en-ch1-y74370@1238	-3.90	2.40	1.49	Fe-enstatite	rim
liso-en-ch1-y74370@1368	1.40	2.00	1.34	Fe-enstatite	rim
liso-en-ch1-y74370@1369	-5.50	2.30	1.73	Fe-enstatite	rim
liso-en-ch1-y74370@1373	-4.70	2.00	2.56	Fe-enstatite	rim
liso-en-ch1-y74370@1374	-7.50	1.70	1.40	Fe-enstatite	rim
liso-en-ch1-y74370@1376	5.30	2.90	1.33	Fe-enstatite	rim
liso-en-ch1-y74370@1377	-4.30	1.90	1.17	Fe-enstatite	rim
liso-en-ch1-y74370@1378	-13.40	4.30	1.29	Fe-enstatite	core
liso-en-ch1-y74370@1379	-4.90	1.50	1.29	Fe-enstatite	core
liso-en-ch1-y74370@1380	-3.70	3.70	3.47	Fe-enstatite	core
liso-en-ch1-y74370@1381	-3.80	2.10	1.12	Fe-enstatite	core
liso-en-ch1-y74370@1382	-0.20	1.10	1.48	Fe-enstatite	core
liso-en-ch1-y74370@1383	-8.30	2.00	2.15	Fe-enstatite	core
liso-en-ch1-y74370@1385	-7.20	3.00	2.37	Fe-enstatite	core
liso-en-ch1-y74370@1386	-5.30	2.10	1.93	Fe-enstatite	rim
liso-en-ch1-y74370@1239	-10.60	2.50	2.76	Mg-enstatite	rim
liso-en-ch1-y74370@1240	-7.60	2.50	2.69	Mg-enstatite	rim
liso-en-ch1-y74370@1363	14.90	2.50	0.62	Mg-enstatite	rim
liso-en-ch1-y74370@1364	7.60	3.10	0.91	Mg-enstatite	rim
liso-en-ch1-y74370@1365	21.00	3.20	0.57	Mg-enstatite	rim
liso-en-ch1-y74370@1366	3.40	1.80	3.81	Mg-enstatite	rim
liso-en-ch1-y74370@1367	4.20	1.90	4.30	Mg-enstatite	rim
liso-en-ch1-y74370@1372	-0.20	1.80	0.78	Mg-enstatite	rim
liso-en-ch1-y74370@1375	2.10	2.50	0.49	Mg-enstatite	rim
liso-ol-ch1-y74370@1241	10.00	4.10	0.37	Olivine	rim

Table 4.3: Continued

spot	$\delta^7\text{Li}$	σ_δ	[Li]	phase	domain
liso-ol-ch1-y74370@1242	-5.70	3.90	2.31	Olivine	rim
liso-ol-ch1-y74370@1370	1.60	2.90	0.12	Olivine	rim
liso-ol-ch1-y74370@1371	-3.60	2.50	0.48	Olivine	rim
liso-pl-ch1-y74370@1243	-19.10	1.80	2.38	Plagioclase	core
liso-pl-ch1-y74370@1244	-4.60	2.10	1.98	Plagioclase	core
liso-pl-ch1-y74370@1384	-17.00	1.60	1.44	Plagioclase	core
liso-pl-ch1-y74370@1387	-15.60	97.00	1.91	Plagioclase	core
liso-pl-ch1-y74370@1388	-11.40	1.20	1.98	Plagioclase	core
liso-pl-ch1-y74370@1389	-10.70	1.70	2.31	Plagioclase	core
liso-pl-ch1-y74370@1390	-13.50	1.00	1.55	Plagioclase	core
liso-pl-ch1-y74370@1391	-15.90	1.40	2.00	Plagioclase	core
liso-pl-ch1-y74370@1392	-12.80	2.50	2.42	Plagioclase	core
liso-pl-ch1-y74370@1393	-17.00	1.40	1.10	Plagioclase	core
liso-pl-ch1-y74370@1394	-13.00	2.00	1.68	Plagioclase	core
liso-en-ch5-y74370@1223	-0.90	1.30	1.51	Fe-enstatite	core
liso-en-ch5-y74370@1224	1.30	2.20	1.06	Fe-enstatite	core
liso-en-ch5-y74370@1225	-7.50	3.40	1.89	Fe-enstatite	core
liso-en-ch5-y74370@1226	-2.10	0.90	1.39	Fe-enstatite	core
liso-en-ch5-y74370@1227	-3.00	1.10	1.94	Fe-enstatite	core
liso-en-ch5-y74370@1228	-3.30	1.10	1.99	Fe-enstatite	core
liso-en-ch5-y74370@1400	-0.40	81.00	1.90	Fe-enstatite	core
liso-en-ch5-y74370@1401	-2.40	81.00	1.80	Fe-enstatite	core
liso-en-ch5-y74370@1402	-0.90	90.00	1.55	Fe-enstatite	core
liso-en-ch5-y74370@1403	-3.10	1.90	1.24	Fe-enstatite	rim
liso-en-ch5-y74370@1404	-1.60	1.40	1.15	Fe-enstatite	rim
liso-en-ch5-y74370@1405	-3.50	1.40	1.15	Fe-enstatite	rim
liso-en-ch5-y74370@1406	-2.10	1.70	1.46	Fe-enstatite	rim
liso-en-ch5-y74370@1407	-2.60	1.50	1.82	Fe-enstatite	rim
liso-en-ch5-y74370@1408	-0.40	2.00	1.53	Fe-enstatite	rim
liso-en-ch5-y74370@1409	-2.10	2.00	1.61	Fe-enstatite	rim
liso-en-ch5-y74370@1410	-3.10	5.50	1.29	Fe-enstatite	rim
liso-en-ch5-y74370@1411	-1.60	2.20	1.13	Fe-enstatite	rim
liso-pl-ch5-y74370@1412	-6.70	1.60	2.06	Plagioclase	rim
liso-pl-ch5-y74370@1413	-0.50	1.60	2.29	Plagioclase	rim

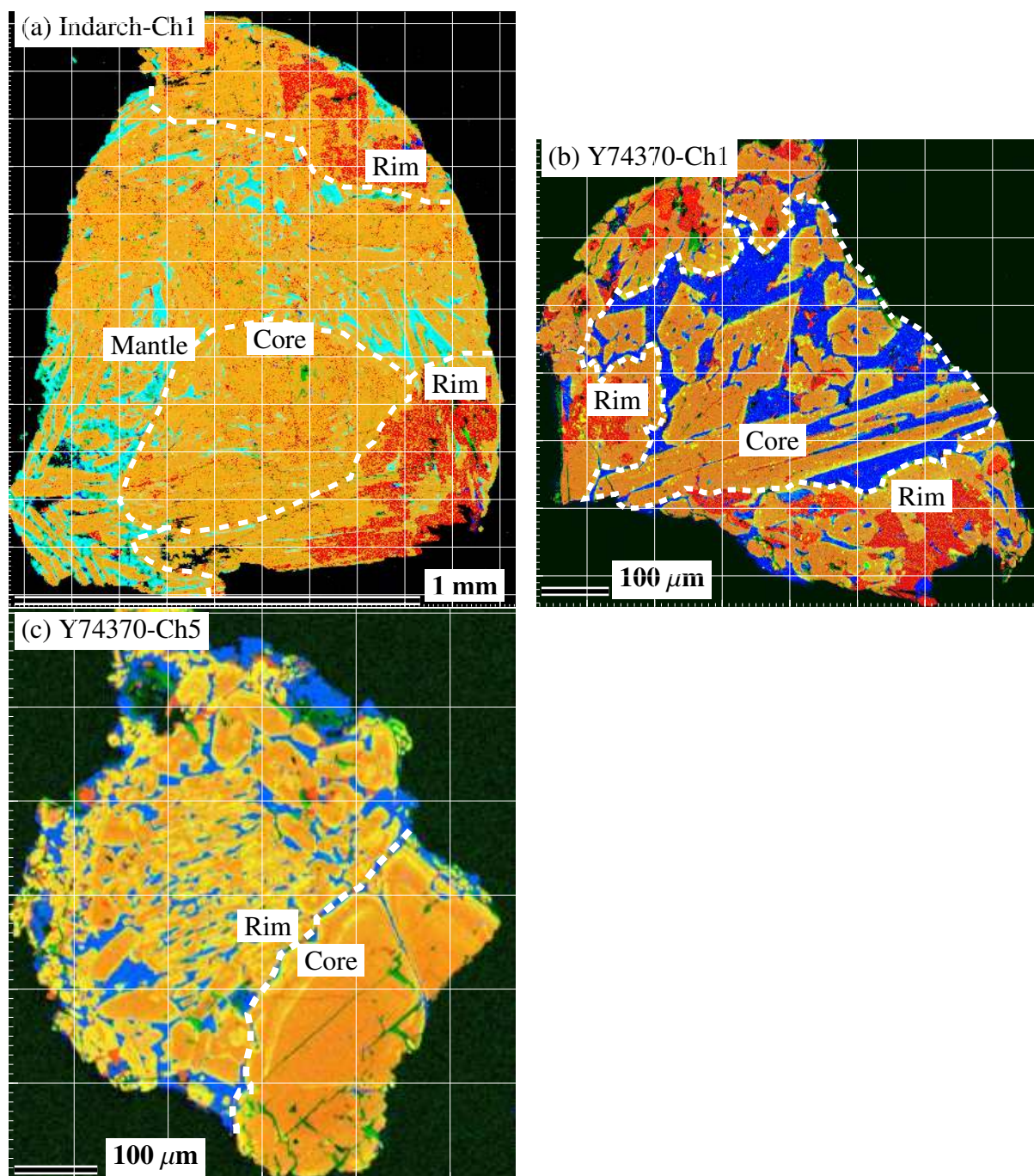


Figure 4.1: Mg-Ca-Al maps using the R-G-B colour scheme showing the domains in 3 EH4 chondrules:

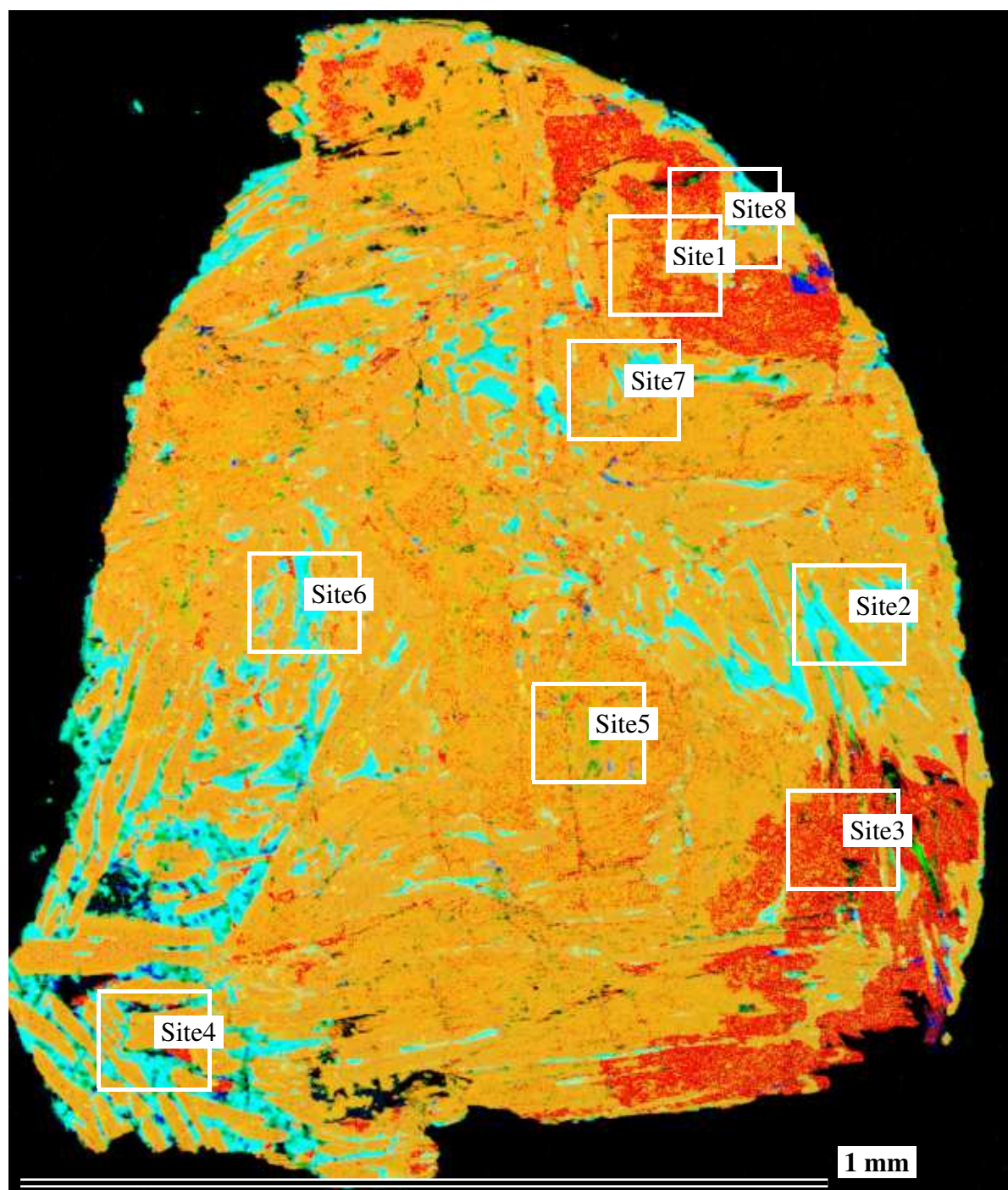


Figure 4.2: Map of Indarch with locations for sites in where textural relationships between the different phases were examined:

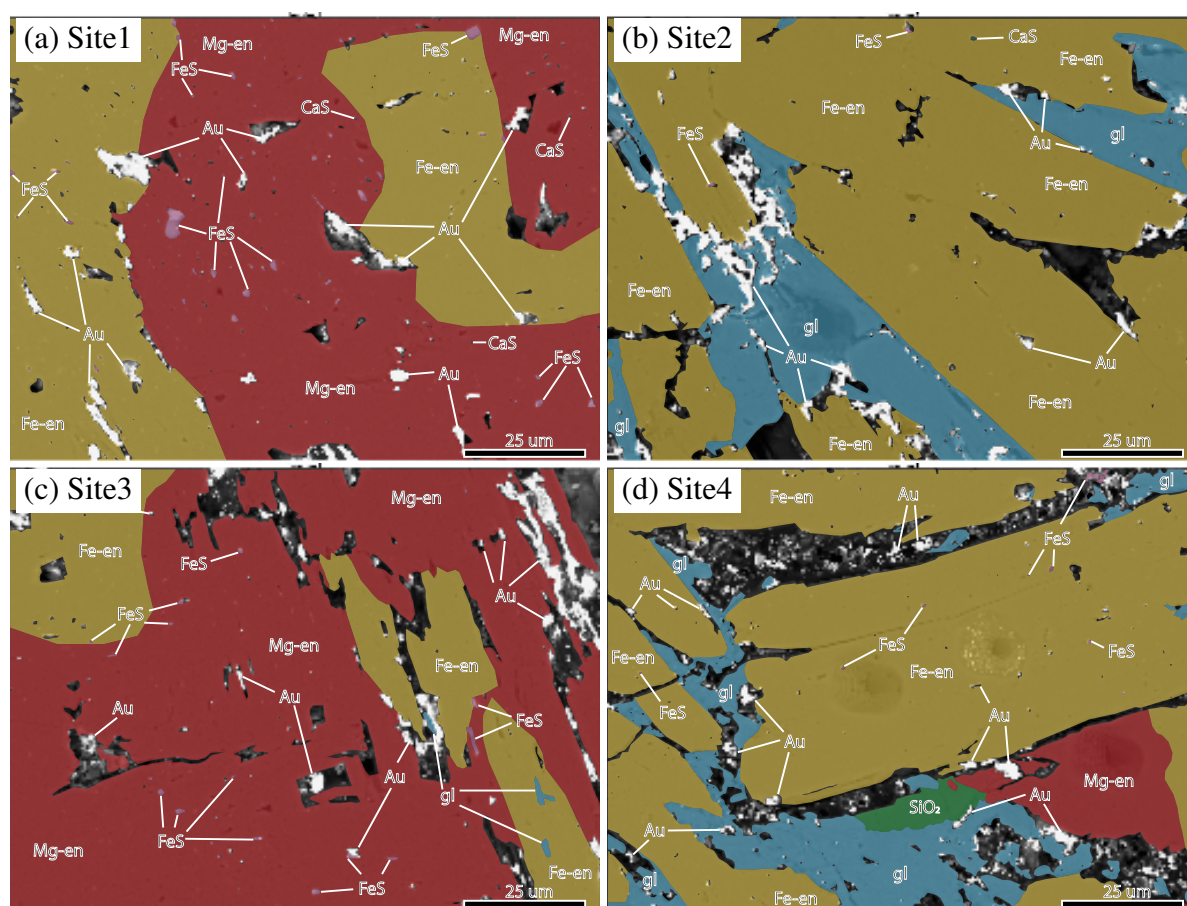


Figure 4.3: Petrography of Site1–4 in Indarch-Ch1: For location see Figure 4.2.

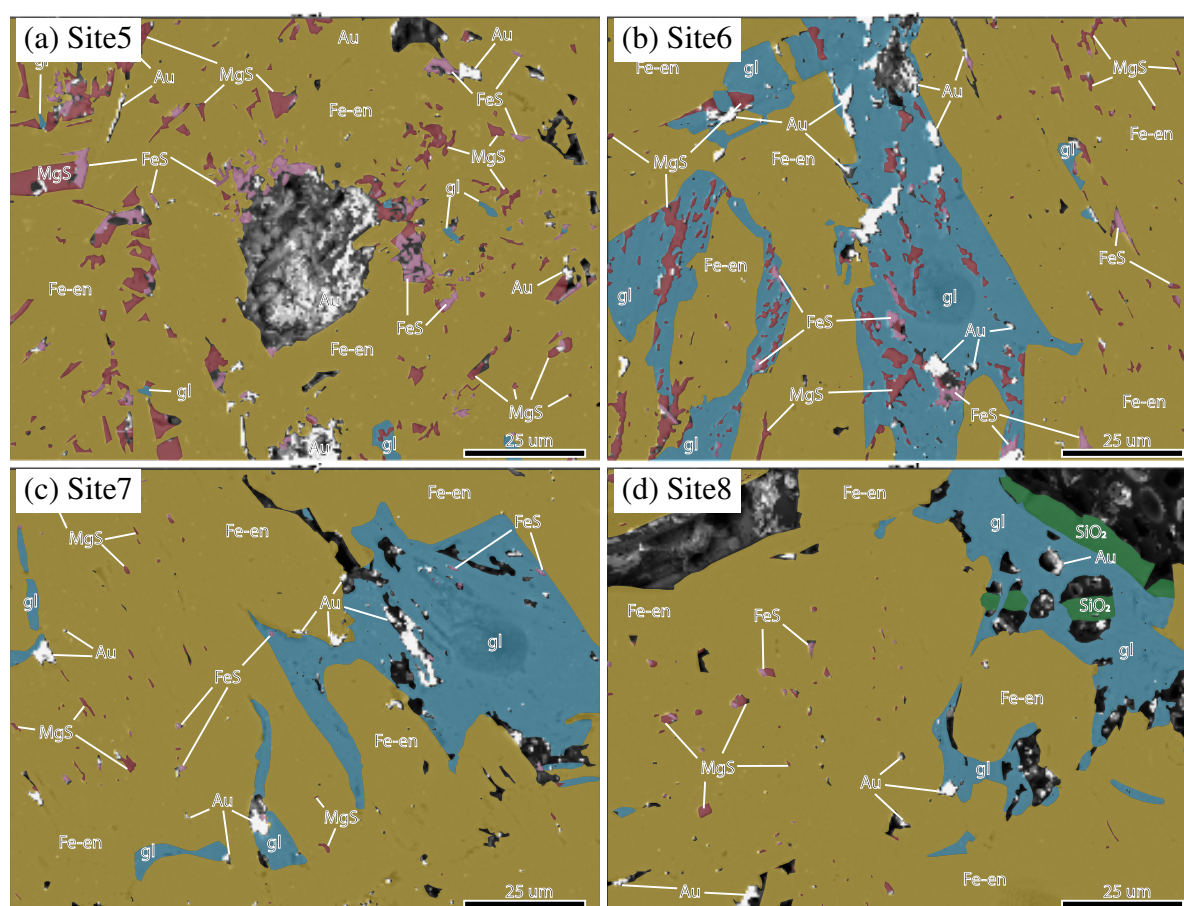


Figure 4.4: Petrography of Site5–8 in Indarch-Ch1: For location see Figure 4.2.

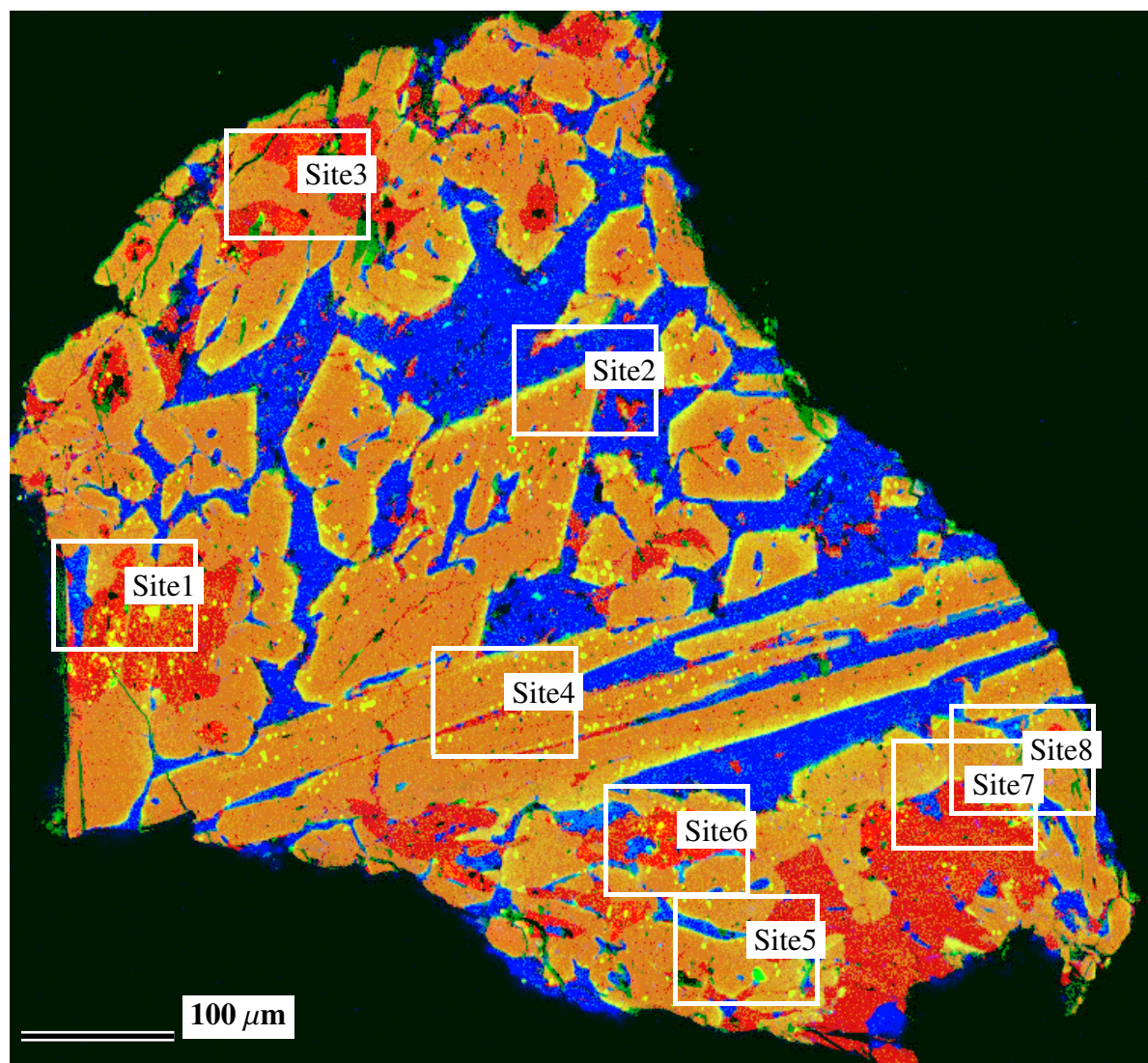


Figure 4.5: Map of Y74370-Ch1 with locations for sites where textural relationships between the different phases were examined:

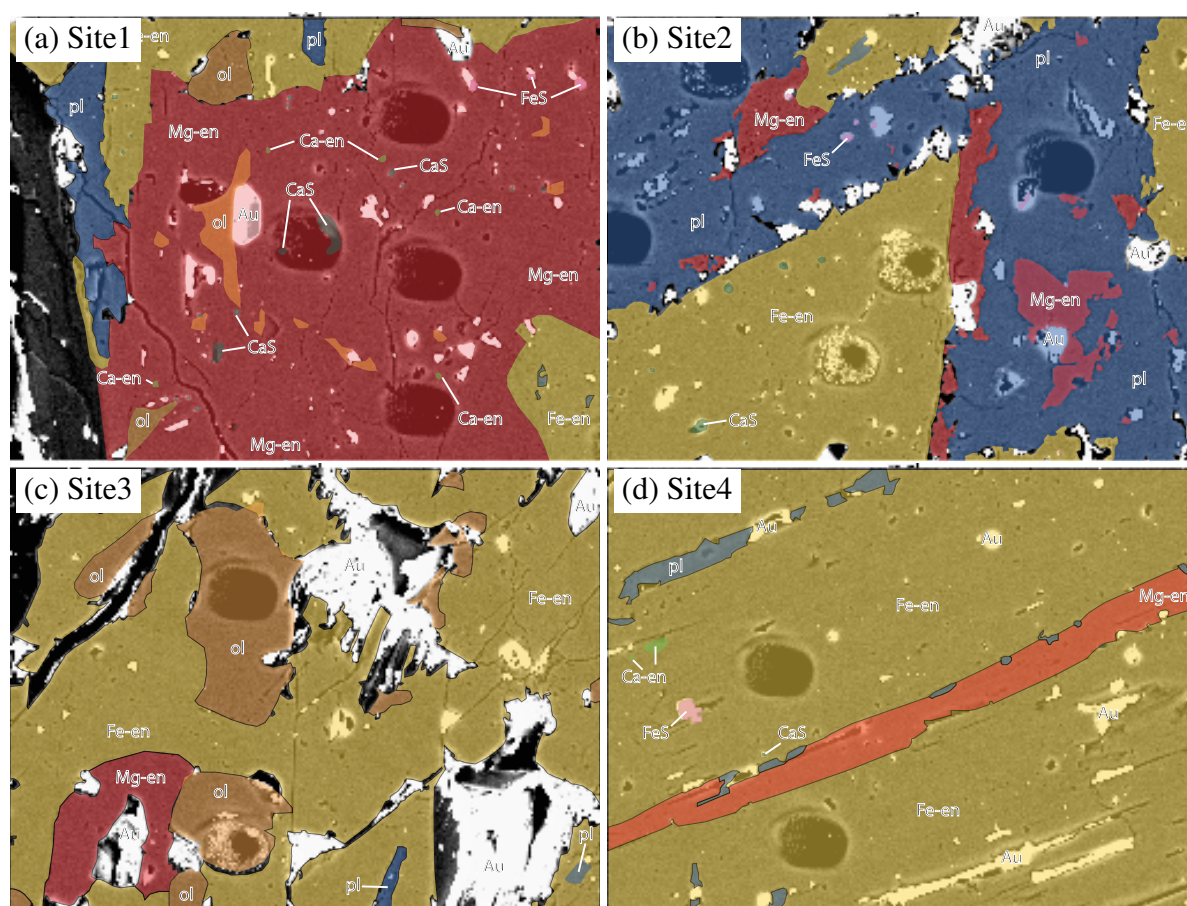


Figure 4.6: Petrography of Site1–4 in Y74370-Ch1: For location see Figure 4.5.

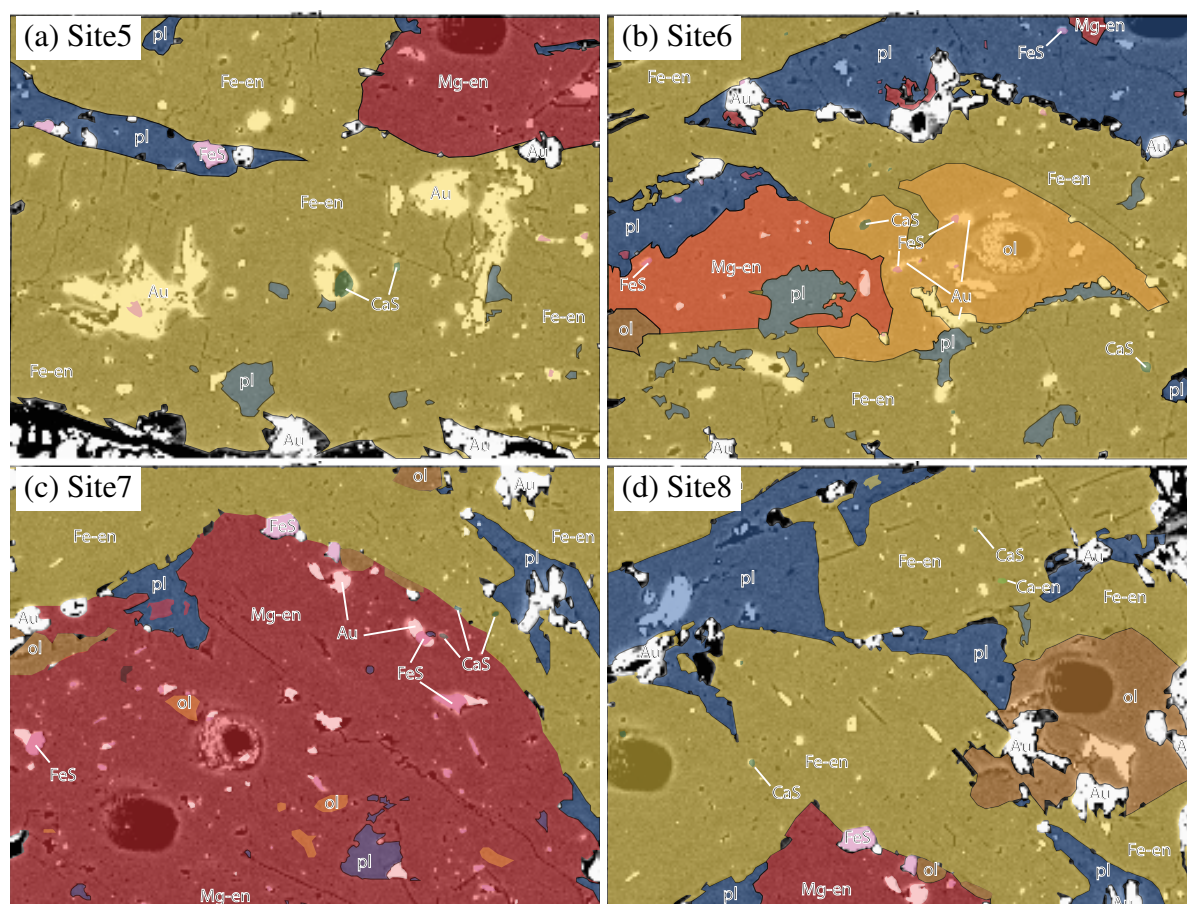


Figure 4.7: Petrography of Site5–8 in Y74370-Ch1: For location see Figure 4.5

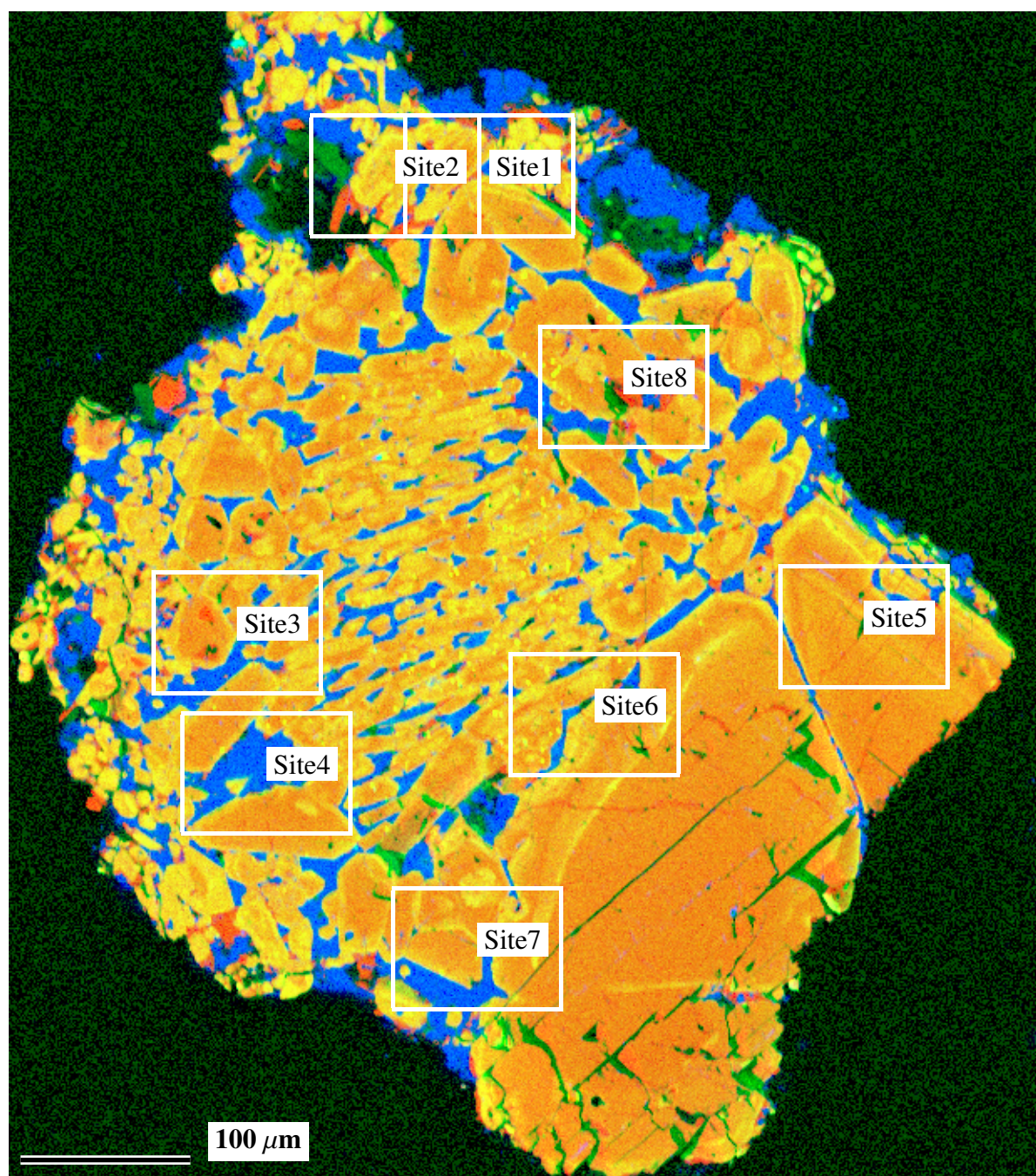


Figure 4.8: Map of Y74370-Ch5 with locations for sites where textural relationships between the different phases were examined:

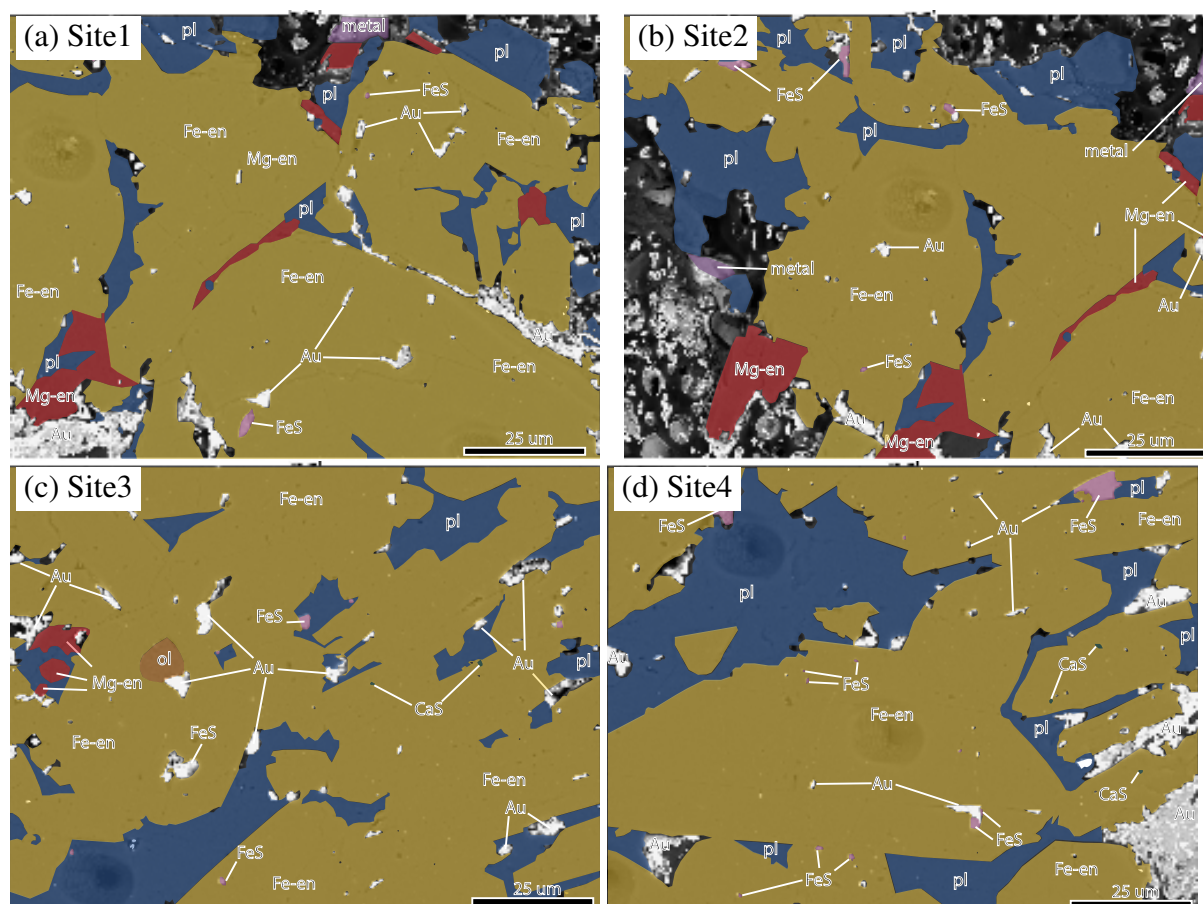


Figure 4.9: Petrography of Site1–4 in Y74370-Ch5: For location see Figure 4.8.

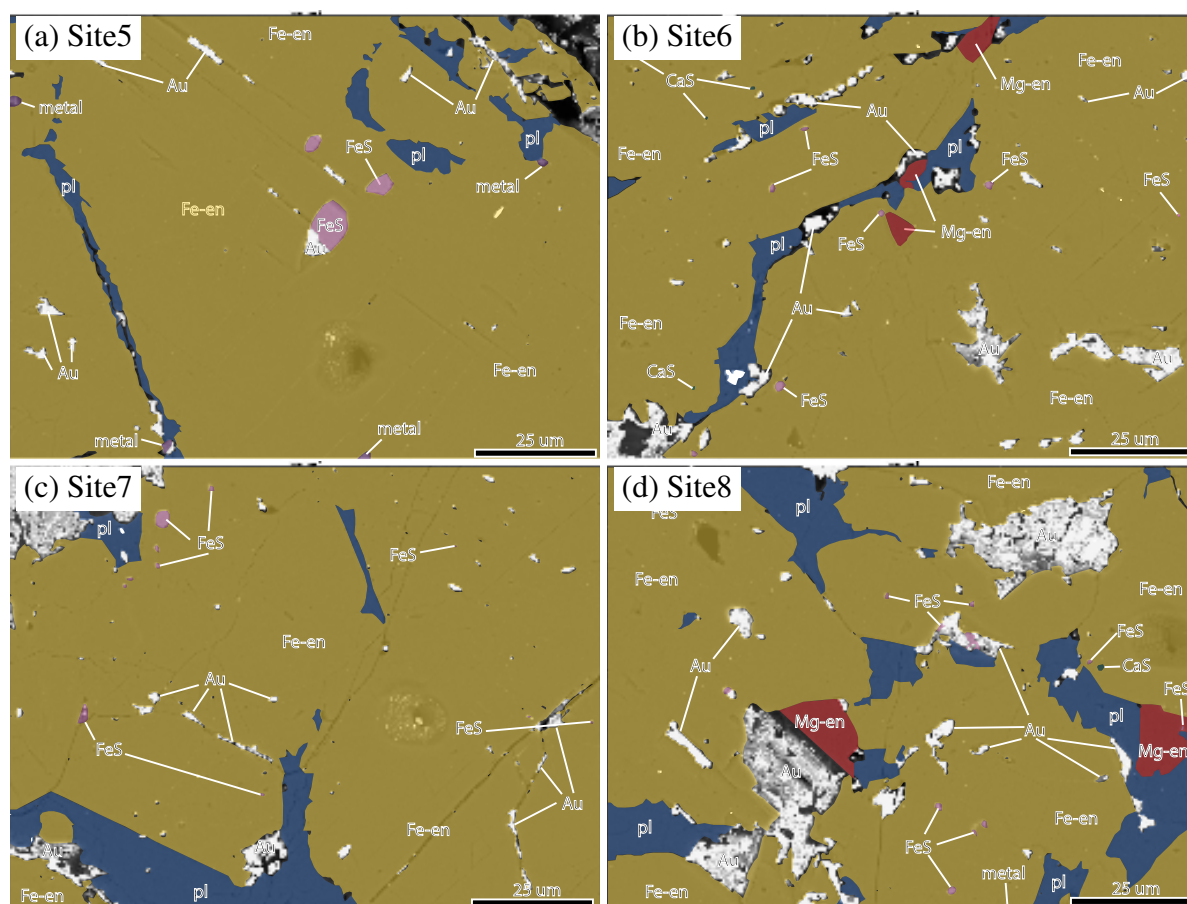


Figure 4.10: Petrography of Site5–8 in Y74370-Ch5: For location see Figure 4.8.

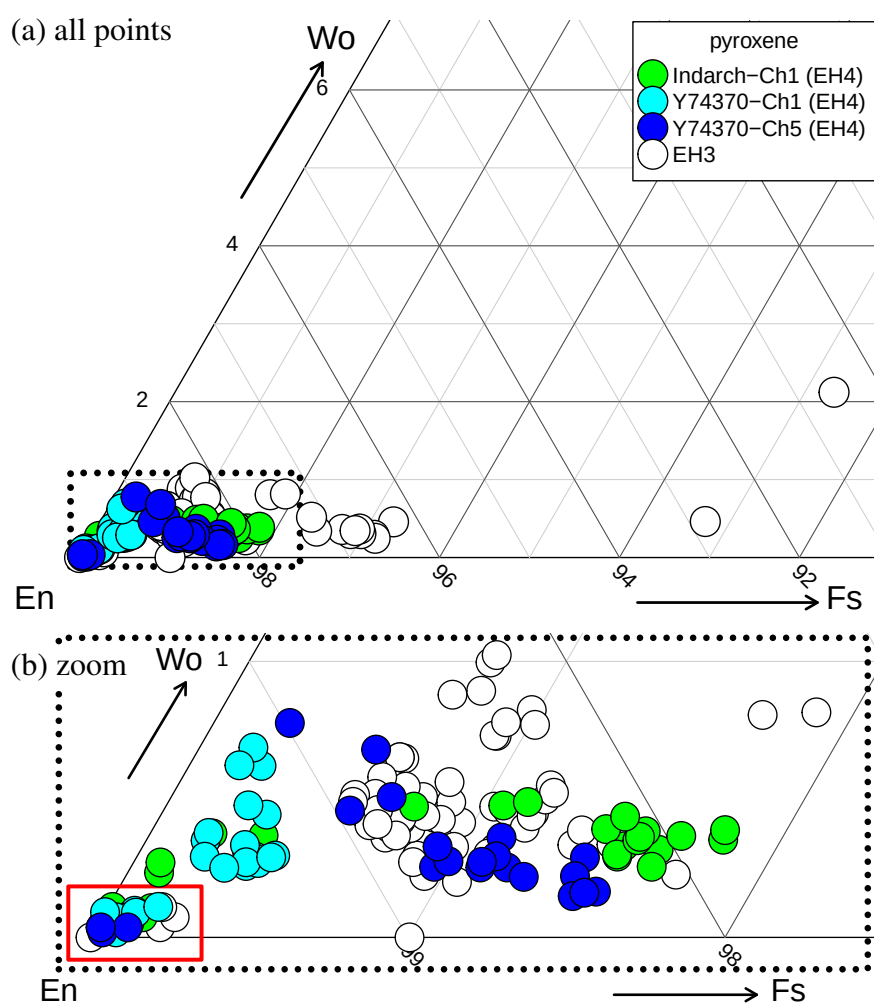


Figure 4.11: Major-element compositions of the enstatites in the chondrules of Indarch (EH4), Y74370 (EH4), and Sahara 97103 (EH3): (a) all of the enstatites probed. (b) zoomed in portion of the plot to better indicate the distribution of the EH4 enstatites.

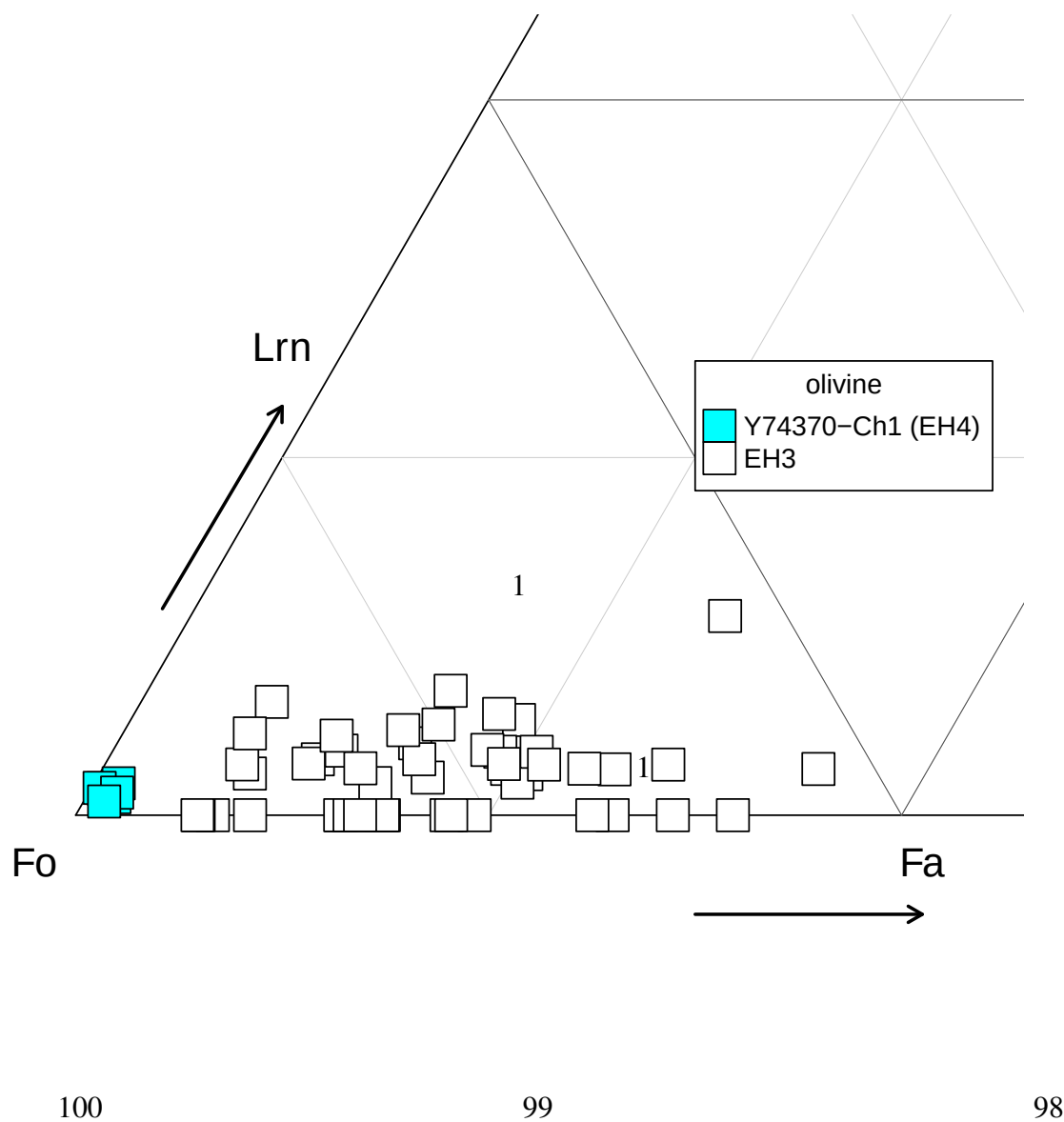


Figure 4.12: Major-element compositions of the olivines in the chondrules of Y74370 (EH4) and Sahara 97103 (EH3).

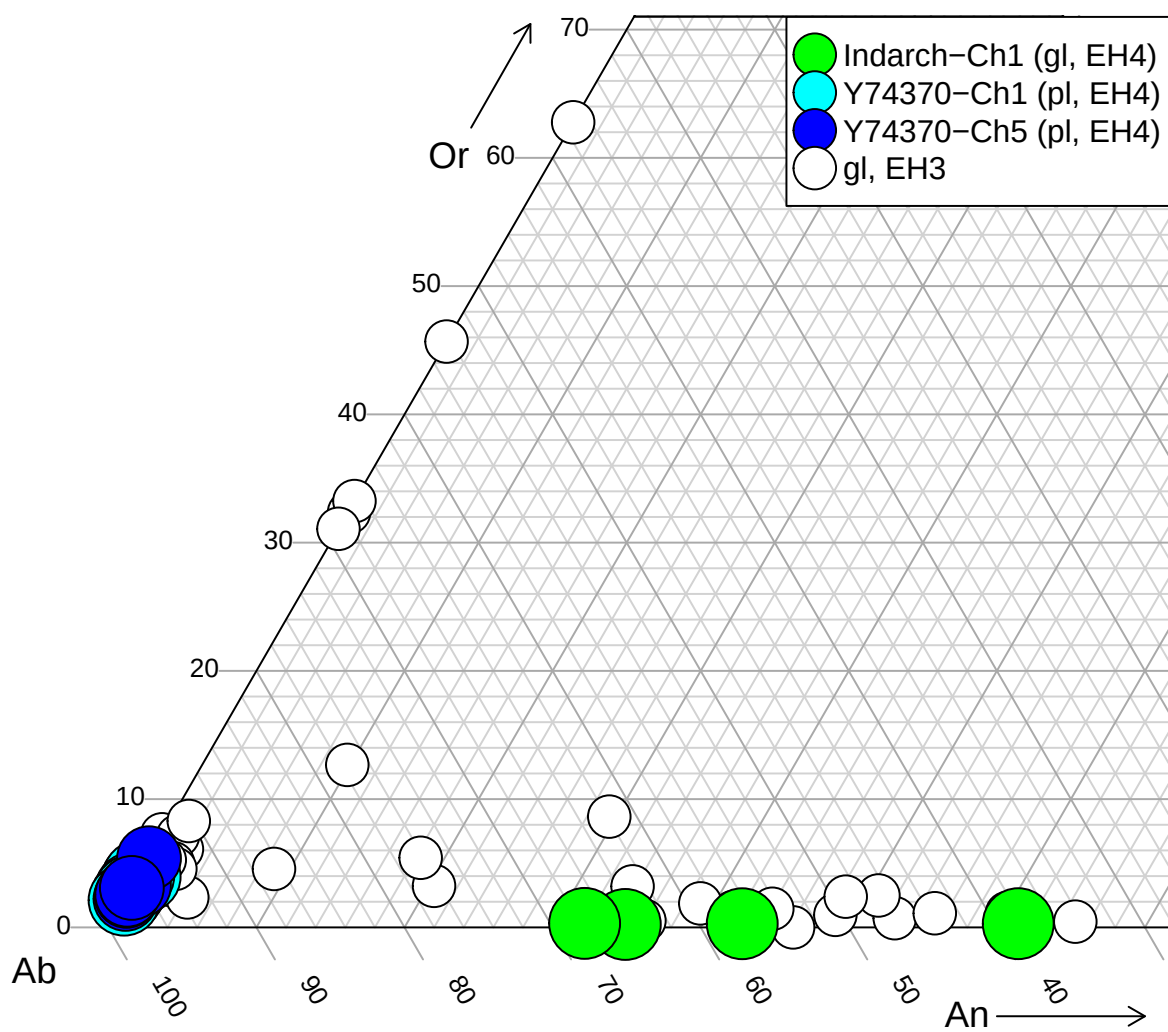
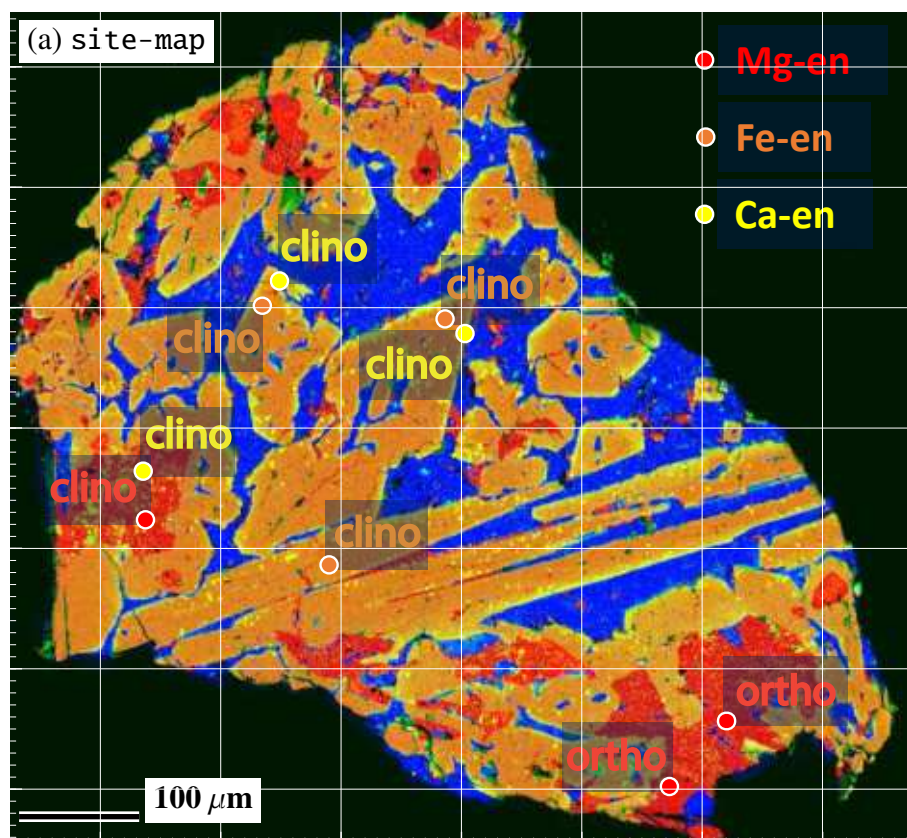


Figure 4.13: Major-element compositions of glass and plagioclase.



(b) raman-y74370-Ch1

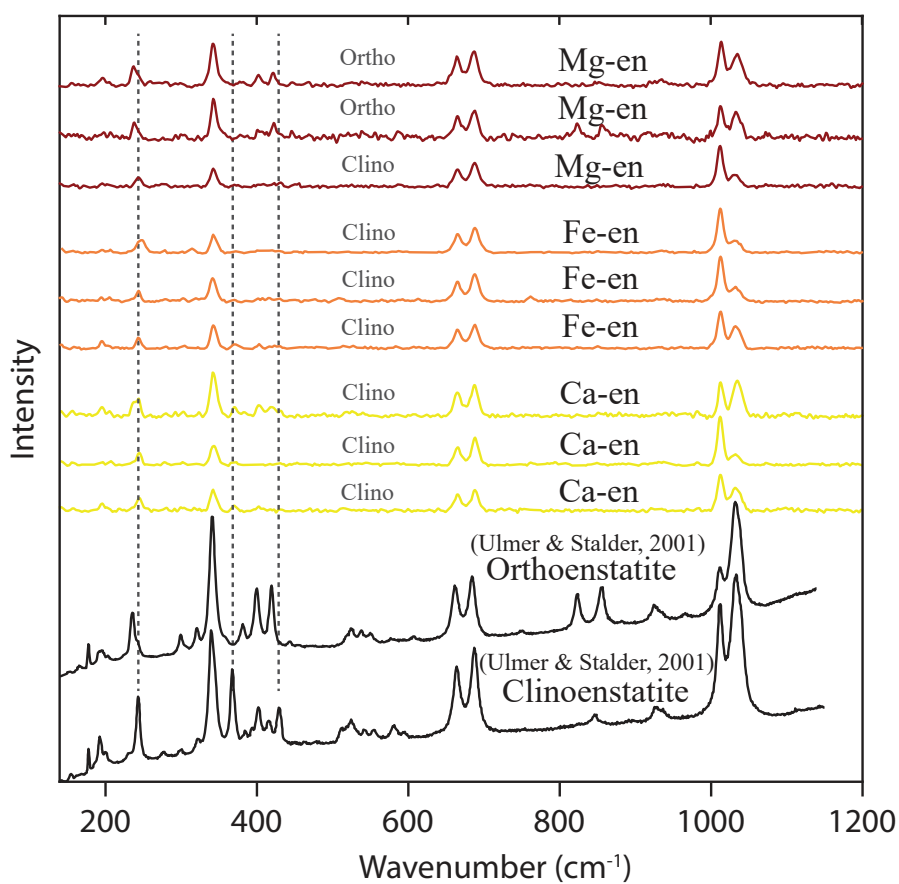


Figure 4.14: Raman spectroscopy results for Y74370-Ch1:

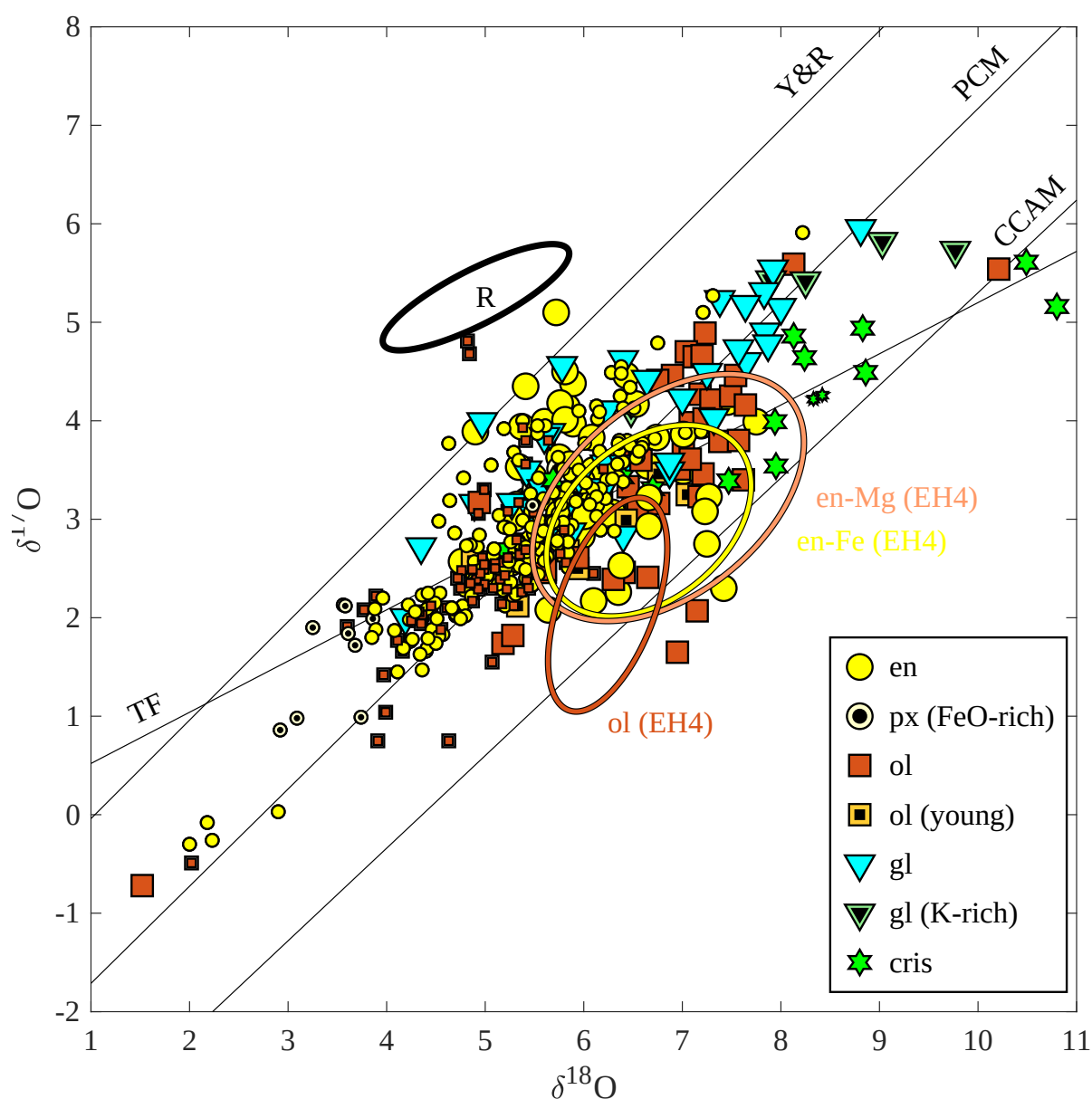


Figure 4.15: O-isotope compositions of the EH4 and E3 chondrule components: Orange, yellow and red ellipses represent the ranges of Mg-enstatite, Fe-enstatite, and olivine in the EH4 chondrules in this study. The larger symbols represent the individual results from the EH3 chondrules analysed in previous sessions. Smaller symbols indicate the results from E3 chondrule components from Weisberg et al. (2011) and Weisberg et al. (2021). Range of O-isotope composition for R chondrites are shown for comparison (Weisberg et al., 1991; Schulze et al., 1994).

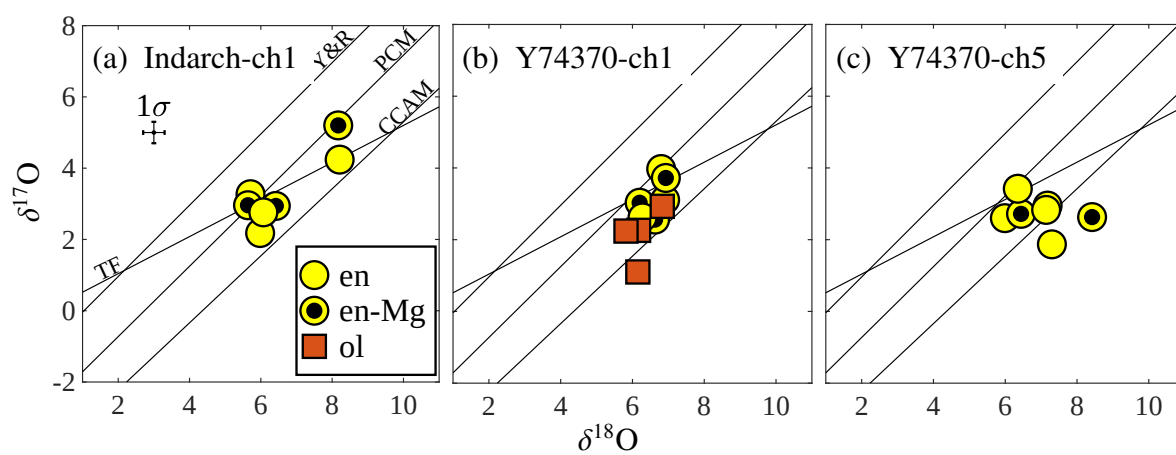


Figure 4.16: The O-isotope compositions of individual EH4 chondrules: (a) Indarch-ch1, (b) Y74370-ch1, and (c) Y74370-ch5.

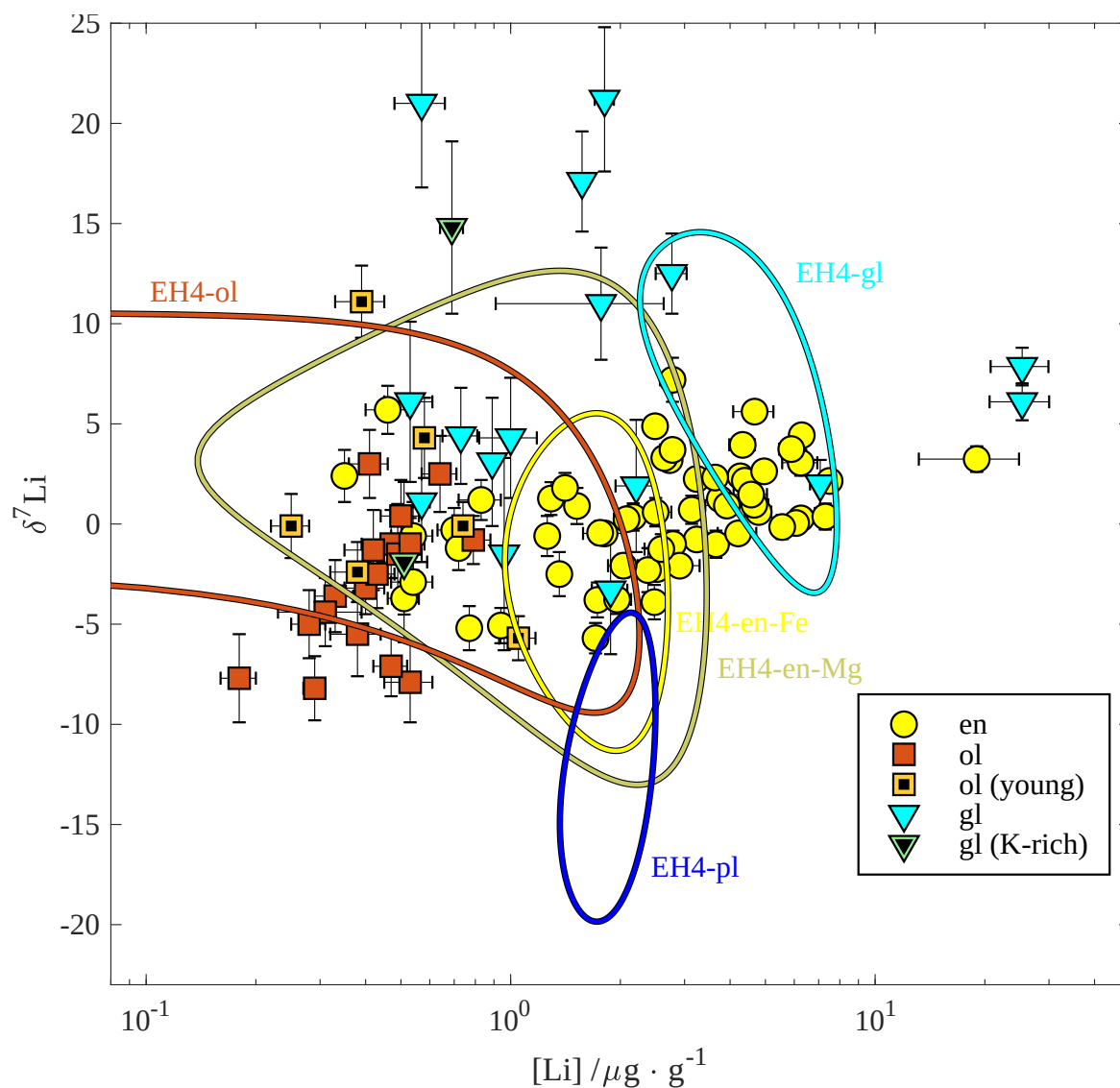


Figure 4.17: Li concentrations and Li-isotope compositions of chondrule components in the EH4 chondrules Indarch-Ch1, Y74370-Ch1, and Y74370-Ch5 and the chondrules in the EH3 Sahara 97103: Symbols represent individual spots in the EH3 chondrules. Ellipses represent the range of the EH4 spots. Yellow circles and ellipses represent enstatite. Red squares and ellipses represent olivine. Orange squares with black cores represent euhedral olivine. Cyan reverse triangles and ellipses represent glass. Dark blue ellipse represent plagioclase.

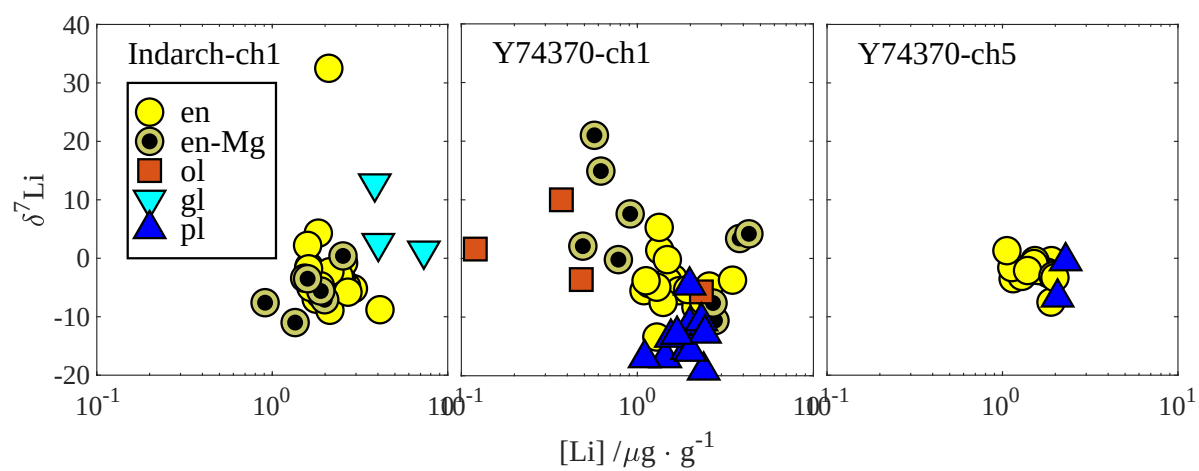


Figure 4.18: Li concentration and Li-isotope composition of individual spots in the EH4 chondrules Indarch-Ch1 (left), Y74370-Ch1 (middle), and Y74370-C5 (right): Yellow circles represent Fe-enstatite. Yellow circles with black cores represent Mg-enstatite. Red squares represent olivine. Cyan reverse triangles represent Na-rich glass. Dark blue triangles represent plagioclase.

Chapter 5

Conclusions

5.1 Occurrence of silicification and sulphidation prior to accretion

In Chapter 2 the petrology of an array of enstatite meteorites including EH, EL, achondrites and an EH impact melted chondrite, with petrological types ranging from 3 to 7 is described. This survey was carried out to determine when silicification and sulphidation occurs during the evolution of the enstatite chondrite, and when the Mg/Si ratio of the olivine-rich precursors lowers to the value of the enstatite chondrites.

The survey showed that at the first order the mineralogy of the different chondrites showed only minor variations. Chondrules and olivine were present in E3 and E4 chondrites. In the E5 to E7 chondrites, the achondrites, and the EH impact melted chondrite, chondrules and olivine were absent. This is consistent with the observations of previous studies such as Schneider et al. (2002). The grain size increased with petrological types and glass was determined to have been converted to plagioclase. The changes that were observed were attributed to reheating of the chondrites on their respective asteroids.

The presence of olivine in the E3 and E4 chondrules but its absence from the E5 to E7 chondrites indicates that silicification will have needed to have occurred prior to accretion. Likewise the presence of sulphides in the E3 and E4 chondrules and matrix indicates that sulphidation will have also taken place prior to accretion. The large abundance of sulphides in the E5 to E7, achondrites, and EH impact melted chondrites suggests that sulphidation will have likely taken place on the asteroid as well. This implies that the Mg/Si ratio of the olivine-rich precursor is lowered to the enstatite chondrite value during chondrule formation. The presence of metal in the E3 and E4 chondrites suggests that they will have formed in a reduced environment before accreting. The association of metal and sulphides in the enstatite chondrites indicated that sulphidation is an important process in causing the reduction of the protosolar nebula.

5.2 Silicification from a Si-rich gas in the enstatite-chondrite forming-region

The major-element, trace-element, O-, and Li-isotope compositions of chondrules in the EH3 Sahara 97103, and the EH4 Indarch and Y74370 meteorites were determined in order to estimate the geochemical properties of a Si-rich gas in the enstatite-chondrite forming-region. Previous studies showed that enstatite can be produced from an olivine-rich precursor by two processes, silicification (addition of Si) and sulphidation (production of sulphides from sili-

cates). These processes can occur in the solar nebula and on the enstatite asteroid. The initial survey showed that both processes played an important role in enstatite-chondrule formation.

Petrography and REE-composition showed that silicification was the dominate process to produce enstatite from olivine-rich precursors in the enstatite-chondrite forming-region. If sulphidation was the dominant process, then abundant MgS would have been observed. However, this was not the case in all chondrules except K4-0. In K4-0 the MgS was accompanied by SiO₂, indicating that the enstatite had been sulphidised, not the olivine. Sulphidation was shown to play an important role in the reduction of the enstatite chondrules. The major element and trace-element compositions of the chondrule components indicated that the Si-rich gas that interacted with the melted or partially melted precursor chondrule was enriched in alkali elements, such as Na and Li. These element then infiltrate into the chondrule melt during gas-melt interactions. Due to the influence of CaS, Eu and Yb are arguably the most important REE for determining the evolution of the chondrule melt to the chondrule components in the enstatite chondrites.

From the O- and Li-isotope composition of the enstatites and olivines in the EH3 chondrules, the isotopic composition of the Si-rich gas was estimated using mass balance equations. The O-isotope composition of the Si-rich gas in the enstatite-chondrite forming-region was determined to be ($\delta^{18}\text{O}$, $\delta^{17}\text{O}$, $\Delta^{17}\text{O}$)=(5.4, 3.7, 1.0‰). The Li-isotope composition of the Si-rich gas in the enstatite-chondrite forming-region was estimated to be 2‰. The Li-isotope composition of the Si-rich gas in the enstatite-chondrite forming-region differs from its counter part in the carbonaceous-chondrite forming-region which was estimated to be -11‰ by Kunihiro et al. (2019a). Comparing the Li concentrations of the enstatites, glass and the estimate for the melt compositions indicated that some Li was lost from the system, possibly via evaporation. This is because according to the enstatite/melt Li coefficient from Ottolini et al. (2008), the glass should have a larger Li concentration than the enstatite, but this was often not the case.

McClure et al. (2025) report on the astronomical detection of hot gas reservoirs that have been attributed to planetary body formation. McClure et al. (2025) stated that the James Webb Space Telescope (JWST) and the Atacama Large Millimeter Array (ALMA) recently observed a warm Si-rich gas reservoir and crystalline silicates at a distance of 2.2 Au from the young proto-star HOPS-315 (Figure 5.3). The SiO vibrational fundamental gas band and crystalline silicates were detected by integral field spectroscopy (IFU) modes of the near-infrared spectrograph (NIRSpec) and mid-infrared instrument (MIRI) with high signal-to-noise-ratio (McClure et al., 2025). The silicates and gas were tested to see if they were consistent with a high temperature environment (McClure et al., 2025). Comparing laboratory mineral data to the solid-state absorption features allowed for the identification of olivine, enstatite, and possibly silica (McClure et al., 2025). This supports silicification being the dominant process for the production of enstatite from an olivine-rich precursor. The results from McClure et al. (2025) suggests that the evaporation of interstellar solids and the recondensation of refractory solids from the gas reservoir would likely occur on timescales similar to what was experienced in our solar system. This implies that the Si-rich gas in the inner solar system existed as a steady gas, which is consistent with the estimated isotope compositions of the Si-rich gas in the enstatite-chondrite forming-region. Whereas the Si-rich gas in the carbonaceous-chondrite forming-region was not necessarily a steady gas.

5.3 Recycling of enstatite chondrite material

The EH4 chondrules contained two primary types of enstatite referred to here as the Fe- and Mg-enstatites. The Mg-enstatites were interpreted to be the older of the two. Weisberg and

Kimura (2012) states that the enstatites in heated enstatite chondrites have compositions that are closer to pure enstatite. The major-element compositions of the Mg-enstatite are also close to pure enstatite (En_{99} to En_{100}). These compositions give an indication that the Mg-enstatites may have originated from enstatite chondrules on the enstatite asteroids. They were likely broken off of the asteroid before being recycled into the EH4 chondrules. The Fe-enstatites were younger and had compositions closer to that of the enstatites in the EH3 chondrules, indicating that these enstatites formed during the last melting event. Raman spectroscopy showed that the Fe-enstatites had a clino-enstatite structure, whereas the Mg-enstatites had an orthorhombic structure. The semi-stable clino-enstatites will cooled more rapidly than the stable ortho-enstatites (Smyth, 1974). The clino-enstatite structure of the Fe-enstatites supports their production during chondrule formation as they would have cooled rapidly prior to accretion. The orthorhombic Mg-enstatites supports the Mg-enstatites asteroid origin as prolonged heating and cooling will have allowed the clino-enstatites to turn into ortho-enstatites.

At the first order, there was no significant differences between the O-isotope compositions of EH3 and EH4 chondrule components. The O-isotope composition variation of the olivines does not differ significantly from that of the enstatites in the same chondrule. This implies that the EH4 olivines were not necessarily relict. However, as the Mg-enstatites were determined to be material from enstatite chondrules on the asteroid are recycled due to their major-element composition and orthorhombic structure, the olivines may have survived the first enstatite chondrule formation event. The O-isotopes of the EH4 chondrule components suggest that the O-isotope composition of enstatite chondrules is maintained on the enstatite asteroid.

The Li-isotope composition of the EH4 chondrule components are similar to the EH3 chondrule components, with some evidence to support that the EH4 Li-isotope compositions were becoming more homogenised due to heating on the enstatite asteroid. The EH4 glass typically had a larger Li concentration compared to the enstatite, which was expected. However, the plagioclase had Li concentrations that were close to those of the Fe-enstatites. This implies that during heating on the enstatite asteroid, some Li was lost due to evaporation. The Li-isotope compositions suggests that there were four generations of heating events. In the first event enstatite chondrules are produced from olivine-rich precursors. The second event processes these chondrules on the enstatite asteroid. Enstatites broken off of the asteroid are then recycled in a second chondrule forming event. The chondrules are then processed on the newly accreted enstatite asteroid.

5.4 Perspectives

The isotope compositions determined in this study suggest that the solid material and gas in the enstatite-chondrule forming-region are more homogeneous compared to their counterparts in the carbonaceous-chondrule forming-region. Its uncertain from the data in this study if the enstatite asteroids were internally heated to a higher metamorphic temperature, or for a longer period time compared to the carbonaceous asteroids. This is outside the scope for this study but something that could be addressed in future work. Currently, it is unknown why this is the case. However, it can be inferred that the carbonaceous-chondrite forming-region inherited its heterogeneity from the precursors of the solar system. This would imply that foreign Boron with extreme isotope compositions would be preserved in enstatite within carbonaceous chondrules. This boron would react with the Si-rich gas, the results of which are uncertain.

Silicification and sulphidation have been shown to be the result of chondrules and chondrule precursors interacting with Si-rich and S-rich gases (Tissandeer et al., 2002; Libourel et al., 2006; Chaussidon et al., 2008; Lehner et al., 2013; Tanaka and Nakamura, 2017; Tanaka

et al., 2021). The mechanisms responsible for producing the Si-rich and S-rich gases in the protosolar nebula are currently unknown. There are two possibilities for the production of the Si-rich gas. The first is that there was abundant Si-rich dust that may have been sticking to the chondrule precursors. The dust was then evaporated. Alternatively the Si existed as a steady gas which excluded refractory elements. Krot et al. (2004a) suggests silica-rich igneous rims (SIR) around carbonaceous chondrules formed by direct Si-rich gas condensation into chondrule melts. Alternatively, silica-rich material condensing onto the chondrule surface prior to melting or partial melting (Krot et al., 2004a). The fractionated nebula gas would have likely been enriched in Si, Na, K, Mn, and Cr compared to Mg (Krot et al., 2004a). The sulphur in the inner solar system ($<1\text{Au}$) will likely have existed as H_2S , SO , or SO_2 . Lehnert et al. (2013) suggests that H_2S is the most common form of sulphur in the nebula. The inner solar system will have remained hotter for longer than the outer solar system due to proximity to the early sun and turbulent dissipation (Balbus and Hawley, 2000; Makalkin and Dorofeeva, 2009). This will have allowed sulphur to exist as a gas in the inner solar system and as a solid, likely locked into sulphide phases such as FeS .

Based on the O- and Li-isotope composition of the Si-rich gas in the enstatite-chondrite forming-region, the gas reservoir is inferred to be well-mixed. The isotopic similarities of enstatite chondrites and the Earth (Javoy et al., 1984; Clayton, 1993; Meisel et al., 1996; Dauphas et al., 2004; Trinquier et al., 2007, 2009; Regelous et al., 2008; Fischer-Gödde and Kleine, 2017; Huang and Jacobsen, 2017) implies that they formed from the same well-mixed reservoir. However, there is a lack of evidence to support a direct first-class genetic link between enstatite chondrites and the Earth. From this study, it is inferred that the Mg/Si ratio and Si-isotope composition of enstatite chondrites and Earth differ from each other due to interactions with or without Si-rich gas.

5.5 Future work

Future work would be to determine the REE compositions of the EH4 chondrule components to investigate the influence of CaS and see if it correlates with existing works such as Hammouda et al. (2022). Similar studies then would be carried out on an array of enstatite, ordinary and carbonaceous chondrules in order to quantify how the geochemical properties of Si-rich gases change with distance from the Sun. Understanding these geochemical properties in the protosolar nebula may provide valuable insight into the evolutionary pathway of the Earth and other terrestrial planetary bodies from pre-solar precursor material.

As seen in this and previous studies such as Tissandier et al. (2002), Libourel et al. (2006), Chaussidon et al. (2008), Tanaka and Nakamura (2017) and Tanaka et al. (2021) the addition of silica to the chondrule melt (silicification) is arguably the most important process in producing enstatite from an olivine-rich precursor. In order to gain a further understanding of how silicification influences the evolution pathway of enstatite chondrites and how that differs from the evolution of Earth, the Si-isotope composition of individual chondrule components in an array of EH3 and EH4 should be determined. The Si-isotope composition of the Si-rich gas can then be determined. This may aid in explaining why the Si-isotope composition and the Mg/Si ratios of the bulk silicate Earth and enstatite chondrites differ from each other. Kadlag et al. (2019) determined that the Si-isotope composition of bulk EH chondrules do not support enstatite chondrites as the building blocks of Earth. This is in agreement with the conclusions from Tanaka et al. (2021). However, Kadlag et al. (2019) suggests that the heavy Si-isotope compositions and refractory-element-rich material in carbonaceous and ordinary chondrites are more closely aligned with Earth's Si-isotope composition. Raman spectroscopy should be em-

ployed to examine a wider range of the enstatites in E3 and E4 chondrules and then compared with the enstatites of the heated enstatite chondrites. This would aid in investigating the recycling of enstatite chondrite components from the asteroid into enstatite chondrules. If there was wide scale recycling of the enstatite chondrite material, this could imply that there were multiple occurrences of silicification and sulphidation in the enstatite-chondrite forming-region. This would have implications as to how the Si-rich and S-rich gas reservoirs were produced.

Ebel and Alexander (2011) proposed that enstatite chondrite impact melts are imperfect petrological and geochemical analogues for Mercury. This is due to their high abundance of metal (Ebel and Alexander, 2011). These meteorites may aid in understanding the geochemical properties and high temperature processes due to similar mineralogies, Fe-metal-rich and FeO-poor silicate abundances, and low oxygen fugacities (Ebel and Alexander, 2011). Enstatite chondrites and impact melts contain Fe, Ni metal and a variety of sulphides such as troilite-FeS, niningerite (MgS), daubreelite (FeCr_2S_4), oldhamite (CaS), and caswellsilverite (NCrS_2) (Ebel and Alexander, 2011). Mercury was determined to have a low metal/sulphide ratio with 3.3wt% and 6-7wt% for metal and sulphides respectively (Nittler et al., 2011; Evans et al., 2012; Starr et al., 2012). This implies that further investigation into the sulphides in enstatite chondrites and Mercury may shed some light on the presence of a S-rich gas reservoir in the inner solar system.

Table 5.1: Summary of methods.

meteorite	chondrule	EPMA	EDS	trace	O-isotope	Li-isotope
Sahara 97103	I6p	x	x	x	x	x
	D6a	x	x	x	x	x
	D3g	x	x	x	x	x
	J5l	x	x	x	x	x
	C5b	x	x	x	x	x
	K4	x	x	x	x	x
Indarch	Ch1	x	x	pending	x	x
Y74370	Ch1	x	x	pending	x	x
	Ch5	x	x	pending	x	x

Table 5.2: Summary of the average O- and Li-isotope compositions.

meteorite	chondrule	phase	n	$\delta^{18}\text{O}$	σ_{18}	$\delta^{17}\text{O}$	σ_{17}	$\Delta^{17}\text{O}$	σ_{Δ}	n	$\delta^7\text{Li}$	σ_7
Sahara 97103	I6p	enstatite	6	5.56	0.19	3.41	0.33	0.52	0.31	7	0.18	0.67
		Na-rich glass	6	7.54	1.08	4.93	0.77	1.01	0.33	2	-1.10	3.11
		crystalite	5	8.14	1.76	4.40	0.98	0.17	0.38	-	-	-
	D6a-0	enstatite	4	6.21	0.58	3.45	0.28	0.22	0.35	5	-1.60	2.18
		FeO-rich pyroxene	2	5.64	0.18	3.41	0.14	0.48	0.06	-	-	-
		crystalite	1	10.8	-	5.16	-	-0.45	-	-	-	-
	D6a-1	enstatite	5	5.7	0.29	3	0.52	0.04	0.51	6	-3.01	2.03
		Na-rich glass	5	6.47	0.83	3.75	0.92	0.38	0.6	-	-	-
		crystalite	4	6.61	1.2	3.57	0.92	0.14	0.35	-	-	-
	D3g	enstatite	12	6.12	0.63	3.03	0.42	-0.13	0.58	8	-1.79	2.61
		olivine	8	6.27	0.88	2.83	0.82	-0.43	0.43	4	-5.45	2.40
		Na-rich glass	6	7.05	0.71	4.73	0.45	1.06	0.21	3	2.33	0.67
	J51	enstatite	11	5.8	0.57	4.23	0.36	1.21	0.47	10	1.53	1.76
		olivine	11	6.42	1.79	3.97	1.68	0.63	0.78	5	-3.04	4.80
		Na-rich glass	5	5.93	1.11	4.17	0.56	1.07	0.39	4	3.33	3.32
	C5b	enstatite	11	6.64	0.71	3.28	0.64	-0.17	0.39	10	1.70	1.90
		olivine	17	7.34	0.81	3.53	0.97	-0.29	0.73	7	-2.19	2.10
		Na-rich glass	7	6.57	0.72	3.52	0.61	0.1	0.36	3	18.23	4.97
		crystalite	3	8.25	0.53	4.01	0.48	-0.27	0.27	-	-	-
	K4-0	enstatite	6	6.37	0.65	3.01	0.33	-0.31	0.59	3	2.50	3.15
		olivine	2	5.82	0.19	3.17	0.37	0.15	0.27	1	2.50	-
		K-rich glass	5	8.29	1.24	5.3	0.69	0.99	0.28	2	6.45	11.81
	K4-1	enstatite	10	5.91	0.55	3.43	0.54	0.35	0.43	11	2.46	2.81
		olivine	5	6.18	0.39	3.02	0.48	-0.19	0.33	1	-5.00	1.90
		euhedral olivine	11	6.14	0.64	2.94	0.42	-0.25	0.29	6	1.18	0.34
		Na-rich glass	8	5.37	0.93	3.11	0.64	0.32	0.27	4	10.52	4.84
Indarch	Ch1	Fe-enstatite	4	6.49	1.16	3.11	0.87	-0.26	0.53	19	-1.91	8.99
		Mg-enstatite	3	7.07	0.96	3.57	1.43	-0.11	0.95	7	-5.40	3.66
		Na-rich glass	-	-	-	-	-	-	-	3	5.57	6.30
Y74370	Ch1	Fe-enstatite	3	6.66	0.34	3.23	0.68	-0.23	0.58	18	-4.65	4.08
		Mg-enstatite	3	6.59	0.37	3.10	0.58	-0.32	0.51	9	3.87	9.94
		olivine	4	6.24	0.42	2.13	0.76	-1.12	0.67	4	0.58	6.99
		plagioclase	-	-	-	-	-	-	-	11	-13.69	3.97
	Ch5	Fe-enstatite	5	6.79	0.59	2.73	0.57	-0.80	0.74	18	-2.18	1.82
		Mg-enstatite	2	7.43	1.40	2.68	0.06	-1.19	0.79	-	-	-
		plagioclase	-	-	-	-	-	-	-	2	-3.60	4.38

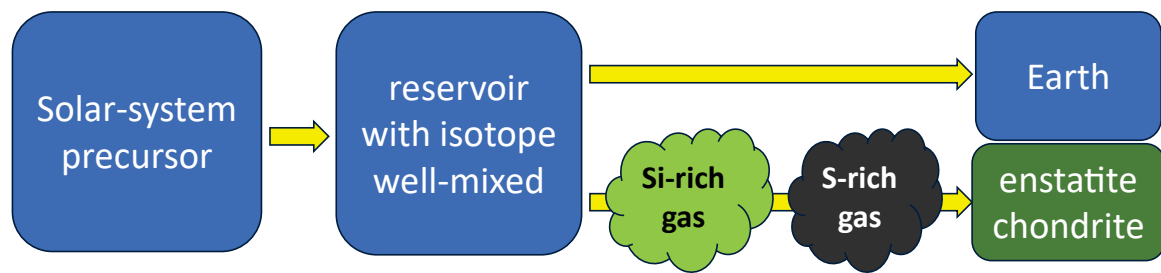


Figure 5.1: Evolutionary pathways of enstatite chondrites and Earth.

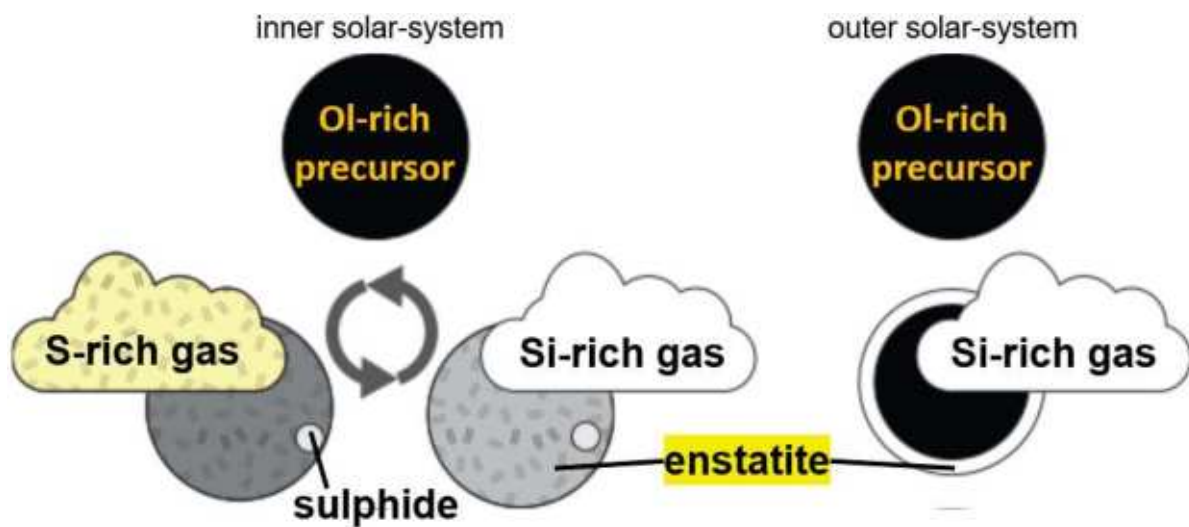


Figure 5.2: Comparison of enstatite production in the inner and outer solar systems:

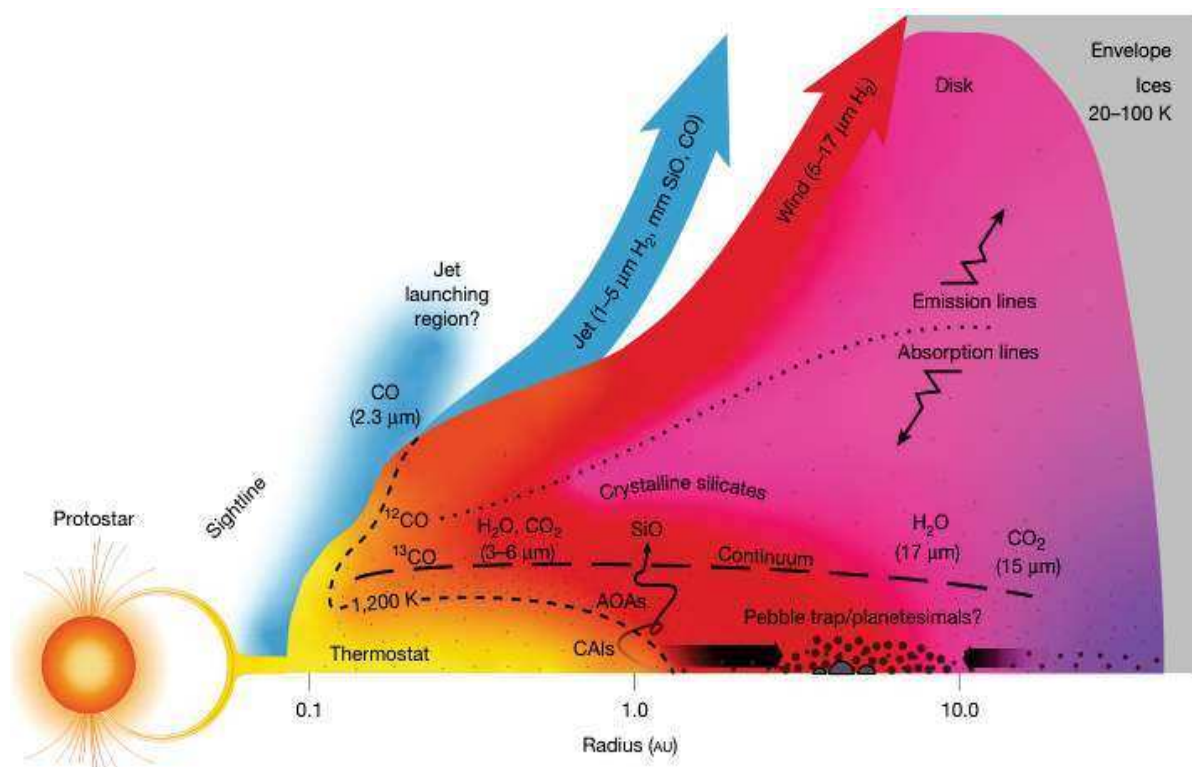


Figure 5.3: Structure of HOPS-315's inner disk from McClure et al. (2025): The dotted line indicates the temperature minimum. Line with large dashes indicates the disk photosphere. The line with the short dashes indicates the border of the thermostat region.

Acknowledgment

I would like to thank Kunihiro Takuya for his role as a supervisor during this project. In addition I would like to thank Ota Tsutomu, Yamanaka Masahiro, and Kitagawa Hiroshi for their advice and technical expertise. I would also like to thank Christian Potiszi1 and Tanaka Ryoji for their roles as co-supervisors and for their advice during this study. Thank you as well to Mathew Izawa, Yamashita Shigeru, Kanzaki Masami, and Moriguti Takuya for their advice and technical expertise during the survey detailed in Chapter 2. A special thank you to Yoshino Takashi, Kobayashi Katsura, and Micheal K. Weisberg for their roles as examiners. I would like to thank the remaining members of the Pheasant Memorial Laboratory (PML) team (Nakamura Eizo, Sakaguchi Chie, Tanaka Kayo, Shimizu Yukari, Eloise Brown, Dilan Madusanka Ratnayake, Elena Kalinina, Tsuchida Hidehisa, Nghiem Van Dao, Adam Corbett, Rahul Kumar, and Noah Miklusicak) for their advice, encouragements and aid in laboratory maintenance. This study was performed using joint-use facilities of the Institute for Planetary Materials (IPM), Okayama University, thus I would like to thank IPM for the use of their facilities and financial aid. A final thank you to my family for their constant support and encouragement.

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