

Fayalite-pyroxene-silica (Fa-Px-Si) symplectite formation in extraterrestrial materials: New insights from lunar meteorites

A. Sedaghat^{a,*}, C.L. McLeod^a, M. Loocke^b, B.J. Shaulis^c

^a Department of Geology and Environmental Earth Science, Miami University, Oxford, OH 45056, USA

^b Department of Geology and Geophysics, Louisiana State University, Baton Rouge, LA 70803, USA

^c Trace Element and Radiogenic Isotope Laboratory (TRAIL), University of Arkansas, Fayetteville, AR 72701, USA

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ABSTRACT

Through integrated textural, mineralogical, and geochemical studies, symplectites provide fundamental constraints on the evolution and stability of geological systems. The returned 2018–2019 Antarctic Search for Meteorites Dominion (DOM) Range lunar meteorites contain ubiquitous three-phase symplectites consisting of fayalitic olivine (Fa), Ca-Fe-rich pyroxene (Px), and a silica phase (Si). Here, the textures and compositions of two textural symplectite types in DOM 18509 and DOM 18543 are investigated. Typical symplectites are characterized by a relatively uniform distribution of Fa-Px-Si and fine grain sizes ($\leq 5 \mu\text{m}$). Fayalite is Fe-rich (Fa_{91-96}) with associated pyroxene at $\text{Wo}_{31-40}\text{En}_{6-11}\text{Fs}_{51-61}$. Bulk compositions determined via reconstruction and broad beam analyses yielded lunar pyroxferroite compositions. The preservation of rare pyroxferroite in lunar materials is reported for DOM 18509: $\text{Wo}_{12-13}\text{En}_{9-10}\text{Fs}_{77-78}$. In contrast, non-typical symplectites exhibit variable grain sizes and consist of a Ca-rich host pyroxene ($\text{Wo}_{23-40}\text{En}_{8-18}\text{Fs}_{49-68}$) containing blebs of olivine (Fa_{86-95}) and silica. Reconstruction for the bulk precursor material yields a metastable pyroxene ($\text{Wo}_{24-26}\text{En}_{12-16}\text{Fs}_{58-64}$). While both symplectite types are interpreted as subsolidus breakdown products during slow cooling, their formation is associated with different breakdown pathways from distinct precursor phases. During late-stage crystallization in highly evolved lunar basaltic systems, pyroxene compositions enter the forbidden zone. At this stage, metastable Ca-rich pyroxene forms, followed by crystallization of metastable pyroxferroite during extreme Fe-enrichment. Subsequently, non-typical symplectites form through the subsolidus multistep breakdown of metastable Ca-rich pyroxene, whereas typical symplectites form through the direct subsolidus breakdown of pyroxferroite. These two symplectite textures record the evolution of metastable phases within reduced magmatic conditions in extraterrestrial environments.

1. Introduction

Symplectites, fine-grained intergrowths of minerals, are important textural features found across a wide range of materials in both terrestrial and extraterrestrial environments (e.g., Ashworth and Chambers, 2000; Rost et al., 2009; Váci et al., 2024; Velázquez Santana et al., 2025). Collectively, their range of grain sizes, shapes, and compositions have provided unique insights into the evolution of planetary systems and advanced understanding of fundamental geological processes, e.g., the composition of primordial solar system ice, mass transfer within the lithosphere, orogenic belt exhumation rates, and deformation during magma ascent (e.g., Anderson and Moecher, 2007; Spruzeniece et al., 2016; Wallace et al., 2019; Matsumoto et al., 2022; Yudovskaya

et al., 2022).

From decades of detailed petrographic studies and accompanying experimental investigations that encompass a range of magmatic and metamorphic conditions, several processes have been proposed to explain symplectite formation in geological systems. These include direct crystallization from highly fractionated melts, subsolidus reactions between minerals, mineral-melt (or -fluid) interactions, and the breakdown of a pre-existing (metastable) phase in response to changes in pressure and/or temperature, including impact-related processes (e.g., Ashworth and Chambers, 2000; Aramovich et al., 2002; Fagan et al., 2003; Špaček et al., 2013; Vernon, 2018; Keevil et al., 2020; Váci et al., 2022, 2024; Dhar et al., 2025).

Three-phase symplectites specifically composed of Fe-rich olivine

* Corresponding author.

E-mail address: sedagha@miamioh.edu (A. Sedaghat).

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(Fa), Ca-rich pyroxene (Px), and an accompanying silica phase (Si) have so far only been reported in extraterrestrial samples including Martian, lunar, and the Vesta-derived howardite and eucrite meteorites (e.g., McSween et al., 1996; Warren and Ulf-Møller, 1999; Buchanan et al., 2000; Oba and Kobayashi, 2001; Aramovich et al., 2002; Barrat et al., 2003; Arai et al., 2005; Rost et al., 2009; Patzer and McSween Jr., 2012; Mayne and Gross, 2024). Early work on the occurrence and formation of these assemblages in lunar materials proposed an origin via breakdown of metastable pyroxferroite: $(\text{Ca}_{-1/7}\text{Fe}_{-6/7})\text{SiO}_3$, a single chain 7-repeat (Siebenerketten) pyroxenoid (Lindsley and Burnham, 1970; Grove and Lindsley, 1981). Alongside armalcolite and tranquillityite, pyroxferroite is one of the few minerals to first be discovered on the Moon, specifically in the Apollo 11 Type B low-pressure lunar basalts (LSPET (Lunar Science Preliminary Examination Team), 1969; Chao et al., 1970; Lindsley et al., 1972).

From initial experiments, Lindsley et al. (1972) proposed that in order to preserve metastable pyroxferroite in pyroxene-bearing basaltic systems, cooling would have to have occurred rapidly enough to prevent breakdown to a stable assemblage. In contrast, Grove and Lindsley (1981) later suggested that pyroxferroite could also persist metastably under relatively slow cooling conditions ($<1^\circ\text{C}$ per day) based on the preservation of mm-sized pyroxferroite in Apollo basalts 12021 and 15065.

From the experiments of Lindsley and Burnham (1970), pyroxferroite plots in the forbidden zone on the pyroxene ternary and was shown to be unstable at pressures <1 GPa (Fig. S1). Later experiments conducted by Lindsley et al. (1972) demonstrated that pyroxferroite, once formed metastably, could later break down to a 3-phase symplectite composed of fayalitic olivine (Fa), hedenbergitic pyroxene (Px), and silica phase (Si) when held at $990^\circ\text{C} \pm 3^\circ\text{C}$ over 68 h. Reported in the same study, Lindsley et al. (1972) also demonstrated that when a pyroxferroite crystal was heated for longer, over 5 days 23 h at $960 \pm 3^\circ\text{C}$, no three-phase breakdown was observed. The breakdown of pyroxferroite results in the redistribution of Ca, Fe, and Si and the production of a stable assemblage composed of fayalitic olivine, hedenbergitic pyroxene, and silica. From the experiments of Lindsley et al. (1972), this breakdown is likely kinetically sluggish and is shown to be highly temperature and time dependent, with the higher-temperature experiment (990°C) over 68 h resulting in complete breakdown, whereas at lower temperatures and longer durations (960°C at >5 days) no observable reaction occurred.

Since this early seminal work, several other Fa-Px-Si symplectite formation mechanisms have been proposed. Collectively, these include (1) low-pressure instability and breakdown of Fe-rich pyroxene during late-stage crystallization, (2) breakdown of pyroxferroite that formed at high pressure (in equilibrium), (3) oxide-pyroxene interaction after exsolution of primary pyroxene into augite and pigeonite, (4) shock-induced breakdown from metastable pyroxferroite, (5) direct crystallization from a melt, and (6) multi-stage breakdown of Fe-rich sub-calcic augite (e.g., Oba and Kobayashi, 2001; Borden et al., 2022; Xirouchakis et al., 2002; Liu et al., 2009; Fagan et al., 2003; and Buchanan et al., 2000 respectively).

In this work, a detailed petrographic and geochemical characterization of two texturally distinct types of Fa-Px-Si lunar symplectites from two basaltic regolith breccias is presented, alongside the rare identification of pyroxferroite in a lunar meteorite. Results are consistent with Fa-Px-Si symplectite formation via breakdown of metastable pyroxene and metastable pyroxferroite, both of which were derived from highly fractionated basaltic melts at low pressure. These observations and inferences have implications for late-stage iron enrichment of lunar magmas, metastable phase formation, and differentiation of extraterrestrial magmatic systems.

2. The 2018–2019 lunar dominion (DOM) range meteorites

Samples returned from the lunar surface via the Apollo, Luna, and

Chang'e missions, alongside lunar meteorites, provide invaluable constraints on the nature and timing of the Moon's evolution, including initial differentiation, magmatic processes, crustal evolution, and bombardment history (e.g., Warren, 1985; Shearer, 2006; Morbidelli et al., 2012; Li et al., 2021). While lunar meteorites were once referred to as “the poor man's space probe” by Anders (1968), these samples fundamentally advance our knowledge of lunar evolution by expanding the sampling of materials outside surface mission landing sites (e.g., Simon et al., 1983; Joy et al., 2023).

The 2018–2019 Antarctic Search for Meteorites (ANSMET) returned 8 paired lunar basaltic breccias from the Dominion Range (DOM): DOM 18242, 18244, 18262, 18509, 18543, 18545, 18666, and 18678 (Richter et al., 2023). All are highly brecciated, clast-poor, and consist of lithic fragments, mineral fragments, and several glass components (Fig. 1a–f, Gross et al., 2020; Zeigler et al., 2021; Hayden, 2023; Schweitzer et al., 2026; McLeod et al., n.d.). Lithic clasts are often several millimeters in length and include coarse-grained gabbros, basalts, granulites, anorthosites, recrystallized impact melts, quartz monzoniorites, and symplectites. The mineral fragment population is dominated by subhedral to anhedral clinopyroxene and plagioclase, with minor olivine and ilmenite, alongside rarer apatite, alkali feldspar, silica, troilite, and ilvospinel. These components are all set within a glassy matrix characterized by melt veins, pockets, and glass spherules. Collectively, these meteorites are classified as basaltic lunar regolith breccias and are reported across three Antarctic Meteorite Newsletters (Richter, 2019, 2020, 2022) and three Meteoritical Bulletins (Gattacceca et al., 2020, 2021, 2023). Previous work on this particular lunar DOM suite has proposed derivation from an ancient (c. 3.8–3.9Ga), low-Ti, highly fractionated basaltic terrane on the lunar surface with ferroan anorthositic material locally available and/or delivered to the ejection site via impact (e.g., Zeigler et al., 2021; Schweitzer et al., 2026). Prior studies of samples DOM 18262, 18543, and 18666 in particular report radial fractures in plagioclase grains, glassy and isotropic melt veins up to 1 mm in width, with localized mixed melt regions throughout the brecciated matrix. From this, moderately shocked stages of M-S3/4 were proposed, corresponding to ~ 20 – 34 GPa equilibration shock pressures and up to $\sim 250^\circ\text{C}$ post-shock temperatures (Hayden et al., 2022; Hayden, 2023; Schweitzer et al., 2026; or shock stages 2a and 2b after Stöffler and Grieve, 2007). In addition, from Schweitzer et al. (2026), the lack of vesiculated melt veins in DOM 18543 produced via plagioclase melting precludes M-S5 shock conditions (~ 42 – 45 GPa, up to 900°C ; Stöffler et al., 2018). In this study, the symplectite populations of DOM 18509 and DOM 18543 are investigated and later considered within this existing petrological framework. In the discussion that follows, the first detailed investigation of typical and non-typical symplectite formation in lunar samples is presented, along with a proposed formation mechanism for non-typical Fa-Px-Si symplectites in extraterrestrial materials. These are discussed and considered within the existing petrological framework that has informed pyroxferroite and Fa-Px-Si symplectite formation since the seminal work of Lindsley and Burnham (1970), Lindsley et al. (1972).

3. Analytical methods

First, entire thin section images of DOM 18509 and DOM 18543 (mounted in 1-in. rounds) were acquired in plane-polarized light and cross-polarized light using a Leica DM2700 microscope at Miami University. Next, high-resolution whole thin section backscatter electron (BSE) images were obtained on a Thermo Axia ChemiSEM at the Trace Element and Radiogenic Isotope Lab (TRAIL) at the University of Arkansas. An accelerating voltage of 25 kV and a working distance of 10 mm was used. From these BSE images, symplectites throughout each thin section were identified and representative examples of distinct textural types were selected for further textural and chemical investigation. Energy-dispersive X-ray spectroscopy spectra (EDS), and

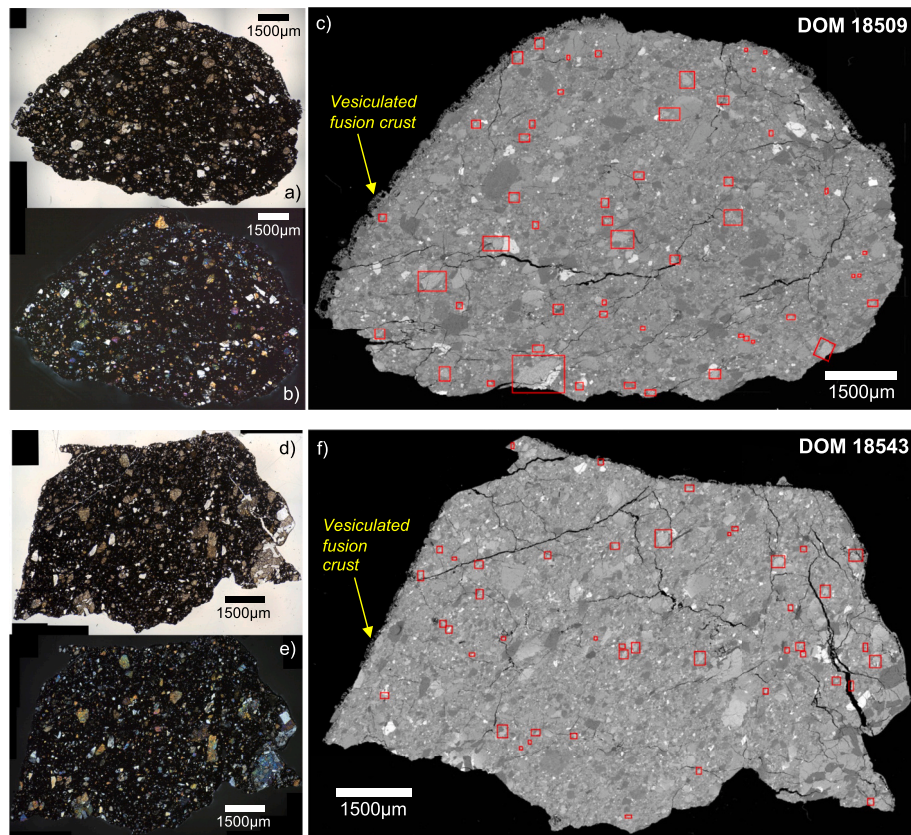


Fig. 1. a) Entire thin section of DOM 18509 in plane-polarized light (PPL). b) Entire thin section of DOM 18509 in cross-polarized light (XPL). c) Back scatter electron (BSE) image of entire DOM 18509 thin section. d) Entire thin section of DOM 18543 in PPL. e) Entire thin section of DOM 18543 in XPL. f) BSE image of entire DOM 18543 thin section (see also, [Schweitzer et al., 2026](#)). The locations of 3-phase symplectites in DOM 18509 and 18543 are shown by red rectangles in c) and f) respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

elemental maps of chosen symplectites across the two thin sections were obtained using a Zeiss Supra 35 VP FEG SEM equipped with Bruker Quantax 100 Energy Dispersive x-ray microanalysis system at the Center for Advanced Microscopy and Imaging (CAMI) at Miami University using an accelerating voltage of 20–25 kV and a working distance of 10 mm.

Guided by BSE and EDS data, in situ analyses of bulk symplectite (via broad beam) and constituent mineral phases for major and select minor elements were conducted on a JEOL JXA-8230 Electron Probe Micro-analyzer, at the Chevron Geomaterials Characterization Laboratory in the Department of Geology & Geophysics at Louisiana State University. For pyroxene and olivine, an accelerating potential of 15 kV, beam current of 20 nA and a spot size of 1 μm were used. For bulk symplectite analysis, a 40 nA beam current with a 20 μm spot size was used. Detailed electron microprobe operating conditions, spectrometer configurations, and standard information are provided in the supplementary materials (Table S1). The broad beam values were corrected for mineral density as described by [Warren \(1997\)](#).

In addition to broad beam bulk symplectite analyses, the bulk compositions of Fa-Px-Si breakdown assemblages were reconstructed using phase proportions determined with ImageJ ([Schneider et al., 2012](#)) and accompanying electron probe microanalysis (EPMA) data. First, BSE images were processed using ImageJ to quantify modal phase abundances of Fa, Px, and Si. Phases were segmented using grayscale thresholding with non-overlapping intensity ranges which ensures unique pixel assignment. Binary masks were subsequently refined prior to measurement by applying a despeckle filter to all phases to remove isolated noise, and a “Remove Outliers” filter to the Px mask to eliminate thin boundary artifacts derived from adjacent phases. Phase proportions were determined from mask areas within a defined region of interest

(symplectitic area) and normalized to 100%.

Phase segmentation uncertainty was calculated through 3 repeated analyses using a ± 5 variation in thresholding and mean values with standard deviations calculated and reported. Phase volume percentages were converted to weight percentages (wt%) using phase densities as informed by EPMA data. Uncertainties in both modal proportions and densities were propagated using Monte Carlo simulations ($n = 10,000$). In each iteration, phase volume proportions and densities were randomly sampled from normal distributions defined by their means and standard deviation. Then volume proportions were renormalized to 100% and multiplied by the sampled densities to obtain relative masses and then normalized to 100% to yield phase wt%. The mean of the determined distributions, with uncertainties at one standard deviation, is reported as phase wt%.

Major element compositions of the individual phases within each symplectite were obtained by EPMA, from which mean compositions and associated standard deviations were calculated. By combining phase proportions (wt%) with EPMA data, bulk (reconstructed) symplectite compositions were determined. Uncertainties were propagated by combining errors in quadrature, assuming independent variables. Pyroxene cation proportions were calculated, normalized to six oxygens per formula unit, and endmember components determined. Uncertainties of normalized cations and endmembers were propagated using a second Monte Carlo approach ($n = 10,000$), where reconstructed oxide compositions were randomly sampled within their analytical uncertainties to obtain mean values and standard deviations.

4. Results

4.1. Petrography

In DOM 18509, 51 distinct 3-phase symplectites composed of Fa-Px-Si are observed as discrete clasts throughout the matrix (Fig. 1c). Their distribution throughout the sample appears random, ranging in size from ~20 to 856 μm and comprises <2 vol% of the sample. DOM 18543 contains 44 symplectites, comprising <1 vol% (Fig. 1f). Most symplectite are generally smaller than those in DOM 18509, with lengths ranging from ~20 to ~400 μm . Consistent in both DOM samples is the occurrence of two symplectite textural types. The first is a classic vermicular intergrowth of the three-phases, with individual phases commonly being <5 μm and a ~2:2:1 distribution between Fa, Px, and Si respectively. This is referred to as a typical symplectite with multiple examples shown in Fig. 2. A few typical symplectites exhibit discrete textural domains within a single, modally uniform symplectite region, similar to the discrete textural domains described for pyroxferroite breakdown material (PBM) by Warren et al. (2004). However, in the absence of crystallographic orientation data, the origin of these textural domains cannot be determined. (Fig. S2a, b). Second textural type is dominated by a host pyroxene that contains limited, non-uniform, blebs of olivine and silica (Fig. 3). Hereafter, these are referred to as non-typical symplectites. Both typical and non-typical symplectite varieties occasionally exhibit micron-sized ilmenite inclusions (Fig. S2c-d). These Ti-rich components within Fa-Px-Si symplectites have previously been attributed to TiO_2 release during breakdown of the precursor phase. In this scenario Ti is incorporated into Ca-rich pyroxene, but once saturation is reached, a discrete Ti oxide crystallizes (Rost et al., 2009). On occasion, both types of symplectite also contain comparatively larger olivine, silica, or pyroxene domains (e.g., Figs. 2d, 3b). This observation is similar to that of Rost et al. (2009) where coarse-grained domains were reported to co-exist with compositionally similar phases in finer-grained domains, both within the context of Fa-Px-Si symplectite formation via pyroxferroite breakdown. While a formation mechanism for these larger domains is unclear, a possible explanation is grain coarsening during the breakdown, although other processes cannot be excluded. Among the non-typical symplectites, one grain exhibited a classic myrmekitic texture (Fig. 3b). Some non-typical symplectites also exhibit a ~10–15 μm fayalitic rim at the boundary between pyroxene and a distinct ilmenite grain (see discussion section 5.2 Insight from DOM 18509 and 18543 symplectites). A few non-typical symplectites also appear to develop at the edge of pyroxene grains, while others do not follow this trend (e.g., Fig. S3).

Finally, we identified a pyroxferroite domain in DOM 18509. This exists adjacent to a clinopyroxene grain, exhibiting 1st-order interference colors in XPL (Fig. 4a), and is pale yellow in PPL (Fig. 4b). This is in contrast to the 3rd-order interference colors of the neighboring clinopyroxene (Fig. 4a). From BSE imaging, there is a subtle but distinct greyscale difference between the two phases. The boundaries between the pyroxferroite and clinopyroxene domains are irregular. Within the pyroxferroite domain there are discrete, anhedral, slivers of clinopyroxene which are identified by their higher-order interference colors and distinct BSE greyscale contrast (Fig. 4c). As also shown in Fig. 4c, both typical and non-typical symplectites are present at the boundaries. The pyroxferroite composition is confirmed via EPMA: $\text{Wo}_{12-13}\text{En}_{9-10}\text{Fs}_{77-78}$ (Table S2).

4.2. Mineral chemistry

The Fe and Mn systematics of DOM 18509 and 18543 pyroxenes are consistent with a lunar origin, where the Moon exhibits relatively low Mn compared to its inner Solar System neighbors due to its history of volatile depletion (Fig. 5; Papike et al., 2005; Tartèse et al., 2021; Dai et al., 2025). Symplectic pyroxene in typical symplectites from DOM 18509 ranges from $\text{Wo}_{31-40}\text{En}_{6-11}\text{Fs}_{51-61}$ ($n = 21$), whereas in non-

typical symplectite ($n = 4$), compositions are $\text{Wo}_{33-37}\text{En}_{12-14}\text{Fs}_{51-54}$. Symplectic pyroxene in typical symplectite in DOM 18543 ranges from $\text{Wo}_{34-40}\text{En}_{6-11}\text{Fs}_{51-57}$, ($n = 14$), whereas in non-typical symplectite compositions are $\text{Wo}_{23-40}\text{En}_{8-18}\text{Fs}_{49-68}$ ($n = 24$). These mol% systematics are summarized in Fig. 6a-c, where collectively, typical symplectite pyroxenes exhibit higher mol% Wo contents across a similar range of mol% Fs, and lower mol% En contents, compared to non-typical symplectite pyroxenes. In Fig. 6d, the Ti (apfu) vs. Cr (apfu) systematics for all analyzed pyroxenes are summarized. As shown, Ti (apfu) values are similar, often between 0.02 and 0.04. Corresponding Cr (apfu) values are, however, distinct with typical symplectites for both DOM 18509 and 18543 lower (<0.003) than in non-typical symplectites which generally range from ~0.002 to ~0.0055. In summary, pyroxenes from typical symplectites exhibit relatively higher Ca (mol% Wo), lower Mg (mol% En), and lower Cr contents compared to pyroxenes in non-typical symplectites (Tables S3–S6). In Fig. 6e, f, the compositions of olivines in the DOM 18509 and 18543 symplectites are shown. Olivines associated with typical symplectites from both meteorites exhibit higher wt% FeO (higher fayalite components; Fa_{91-96} , $n = 28$) than those in non-typical symplectites; Fa_{86-95} , $n = 17$ (see also Fig. 6e). The olivine components within the two symplectite types can also be distinguished based on their wt% MnO signatures where olivines within typical symplectites generally exhibit wt% MnO >1.05 and olivines within non-typical symplectites are often <1.05 (Fig. 6f; Tables S7–S10).

A Welch's two-sample *t*-tests was used to statistically evaluate the differences in pyroxenes Wo, En, and Cr contents and olivines Fa and MnO contents between typical and non-typical symplectites. Results indicate that these differences are statistically significant (all $p < 0.001$; Tables S11–S12).

4.3. Bulk symplectite reconstruction

The bulk chemical compositions of six typical symplectites from DOM 18509 and 18543 are shown in Fig. 7. For two of these typical symplectites, bulk compositions were reconstructed from EPMA data collected on the three-phases and the ImageJ-derived volume proportions (Table S13). For the other four typical symplectites, their bulk compositions were determined using a broad defocused beam of 20 μm . The broad beam values were subsequently corrected based on mineral density (Warren, 1997). Bulk typical symplectite compositions determined via reconstruction are tightly constrained to $\text{Wo}_{15-16}\text{En}_{6-7}\text{Fs}_{78}$ and are consistent with a pyroxferroite composition (Fig. 7; Table S14). In comparison, uncorrected bulk compositions determined via broad beam are more variable ($\text{Wo}_{17-20}\text{En}_{5-8}\text{Fs}_{73-76}$; Table S15), with corrected values more consistent with a pyroxferroite composition ($\text{Wo}_{15-18}\text{En}_{5-8}\text{Fs}_{75-78}$; Table S16).

The bulk compositions of two non-typical symplectites (Figs. 3c and 8a) reconstructed from EPMA data and corresponding ImageJ-derived volume proportions (Table S17) are shown in Fig. 8b. Their compositions exhibit the following range: $\text{Wo}_{24-26}\text{En}_{12-16}\text{Fs}_{58-64}$ (Table S18). Comparing these to the bulk typical symplectites, bulk non-typical symplectites record higher mol% Wo (Ca), higher mol% En (Mg), lower mol% Fs (Fe), and higher Cr (apfu) components. This implies that the precursor phases that existed prior to breakdown and formation of the two texturally distinct symplectites were different, and that typical symplectites are likely derived from a relatively more Fe-rich environment. This is further explored in the discussion that follows.

5. Discussion

Three-phase (Fa-Px-Si) typical symplectites with uniform phase abundances are well established in the literature and are often attributed to metastable pyroxferroite breakdown (e.g., Aramovich et al., 2002; Warren et al., 2004; Rost et al., 2009). In contrast, fewer studies report on the occurrence of non-typical symplectites and their formation mechanisms, where blebs of silica and olivine are hosted in pyroxene (e.

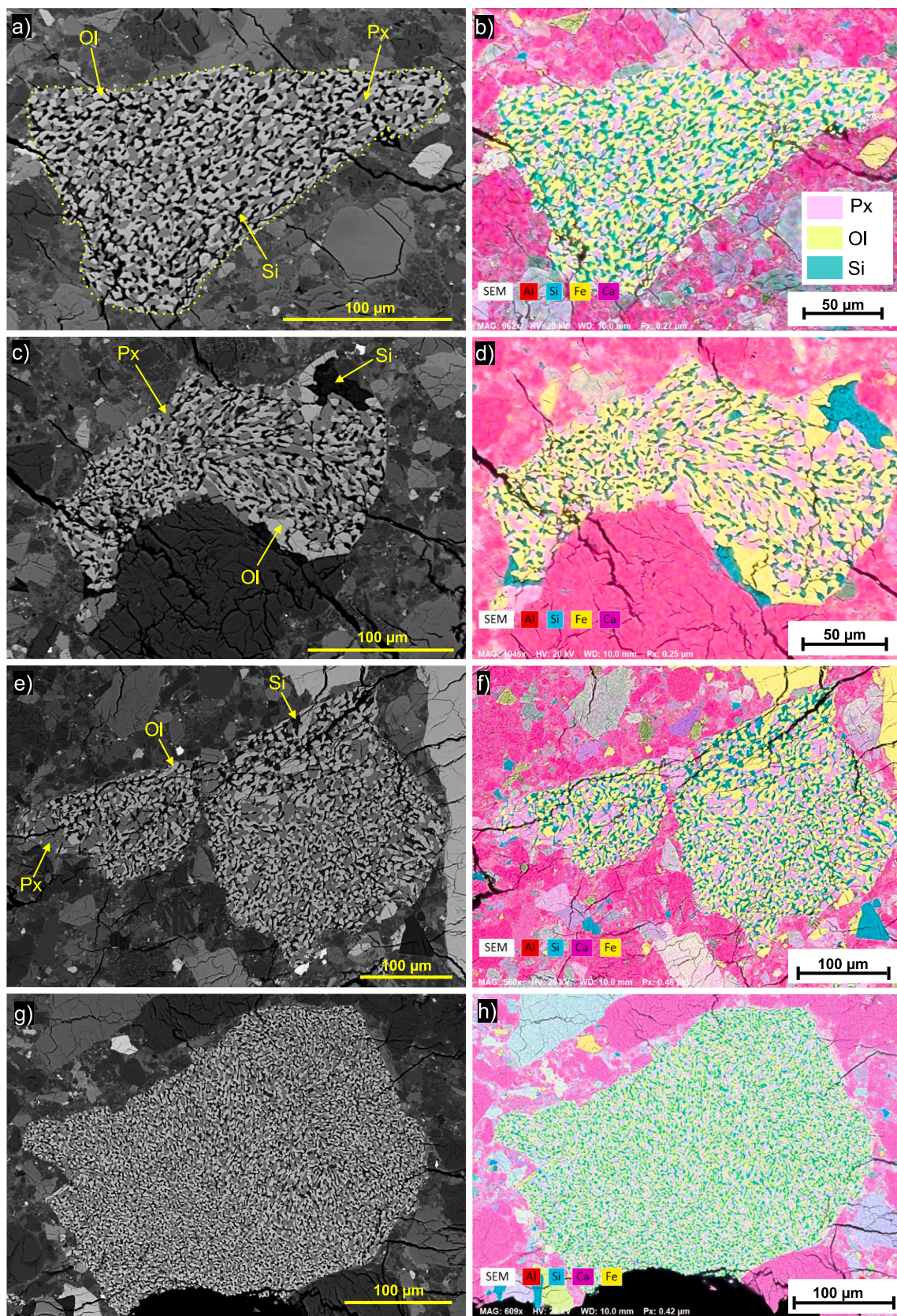


Fig. 2. a-h) Representative typical symplectites in DOM 18543 (a-d) and 18509 (e-h). These exhibit uniform ($\sim 2:2:1$) proportions of Fe-rich olivine, pyroxene, and a silica phase. Ol: olivine, Px: pyroxene, Si: silica. BSE images are shown on the left, and corresponding energy dispersive x-ray spectroscopy (EDS) elemental maps are on the right.

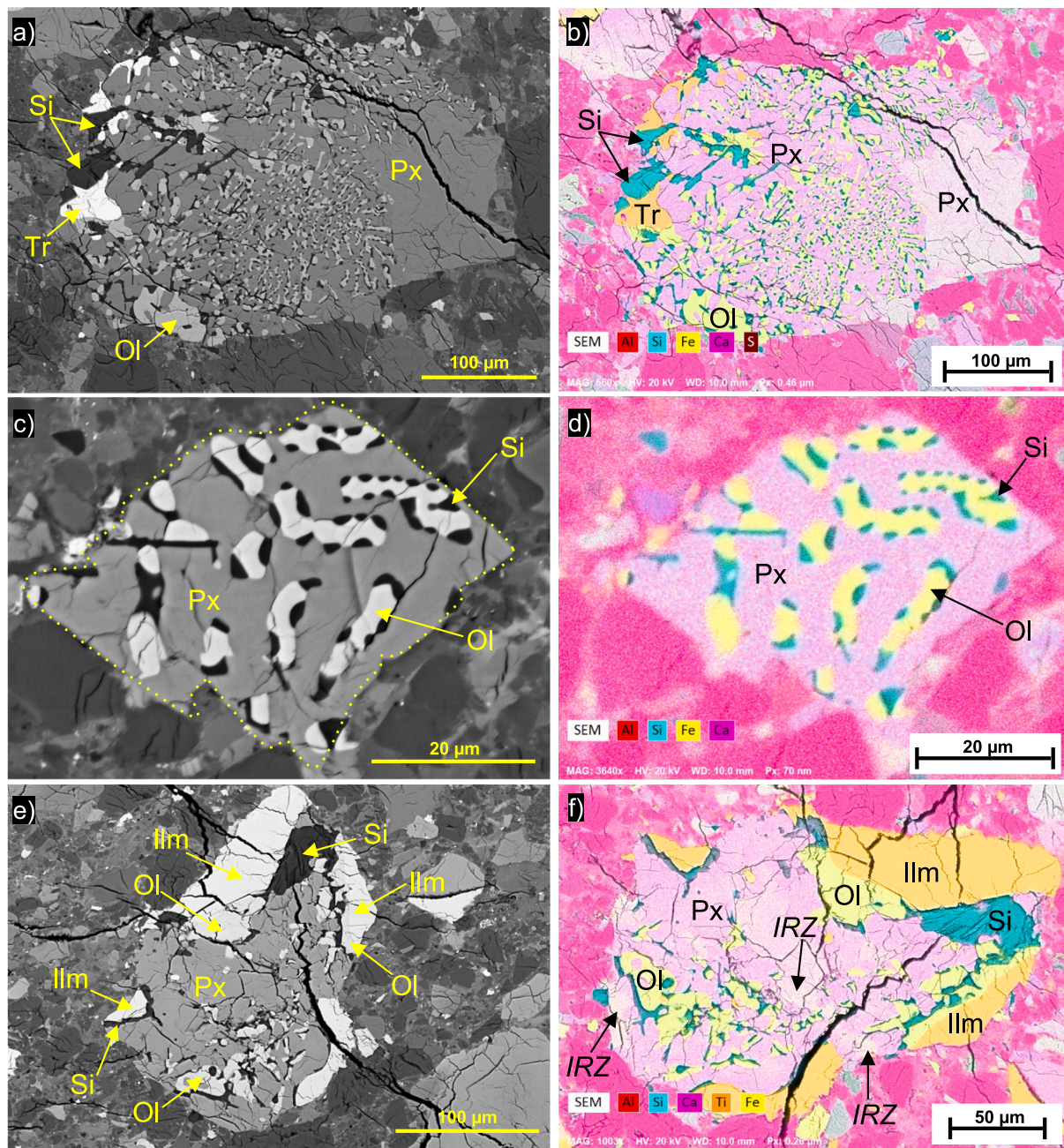


Fig. 3. a-f) Representative non-typical symplectite in DOM 18543 characterized by a nonuniform texture and blebs of olivine and silica. BSE images are shown on the left with corresponding EDS elemental maps on the right. Ol: olivine, Px: pyroxene, Si: silica, Ilm: ilmenite, Tr: troilite. In a)-b), olivine and silica define a myrmekitic texture within the host pyroxene. In f), iron rich zones (IRZ) are identified within the host pyroxene.

g., Fagan et al., 2003; Patzer and McSweeney Jr., 2012, see also Fig. 3). From the study of the ferroan Martian meteorite Los Angeles, Warren et al. (2004) previously documented a transition zone between a typical (uniform) symplectite and an adjacent pyroxene that was characterized by high-Ca, ferroan pyroxene with minor fayalite and silica, and which exhibited a texture consistent with that of the non-typical symplectites documented here. From Warren et al. (2004), it was concluded that the origin of the transitional intergrowth was unclear and possibly reflected either late-stage igneous crystallization or subsolidus decomposition of pyroxferroite accompanied by a reaction with the adjacent pyroxene.

5.1. Proposed Fa-Px-Si symplectite formation mechanisms

Pyroxferroite has the formula $(\text{Ca}_{\sim 1/7}\text{Fe}_{\sim 6/7})\text{SiO}_3$, where Mg can substitute for the Fe up to at least $\sim 1/7$ (Lindsley and Burnham, 1970). In this structure, the Ca component is not restricted to a single site but partially distributed among three of the seven M sites, indicating significant structural disorder and suggesting that pyroxferroite with higher than 14 mol% Wo is possible (Burnham, 1971; Aramovich et al., 2002). From Lindsley et al. (1972), the composition of lunar pyroxferroite was constrained to $\text{Wo}_{12-14}\text{En}_{4-13}\text{Fs}_{75-82}$. This was based on the characterization of pyroxferroite from the Apollo 12 sample 12021.

As pyroxferroite has been shown to be stable only at pressures > 1 GPa, breakdown of pyroxferroite that formed metastably in non-equilibrium conditions has been proposed as a mechanism through

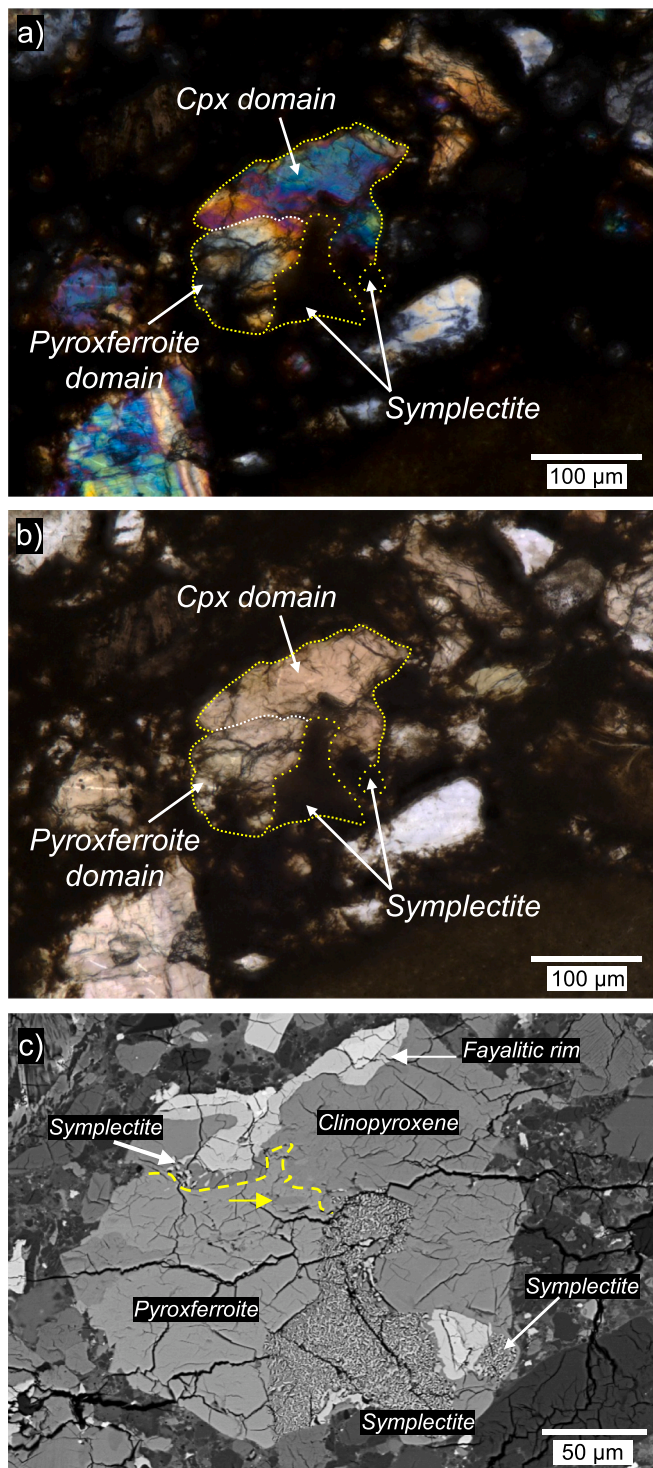


Fig. 4. a) Pyroxferroite (first order interference colors) and clinopyroxene (cpx, 3rd order interference colors) domains in DOM 18509 grain, image taken in XPL. Cpx: clinopyroxene. b) Same view as in a) taken in PPL. c) BSE image of grain outlined in a) and b), with pyroxferroite, clinopyroxene, symplectite domains and fayalitic rim identified. The yellow arrow indicates a region with higher order interference colour, consistent with a clinopyroxene domain near the pyroxferroite-clinopyroxene boundary. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

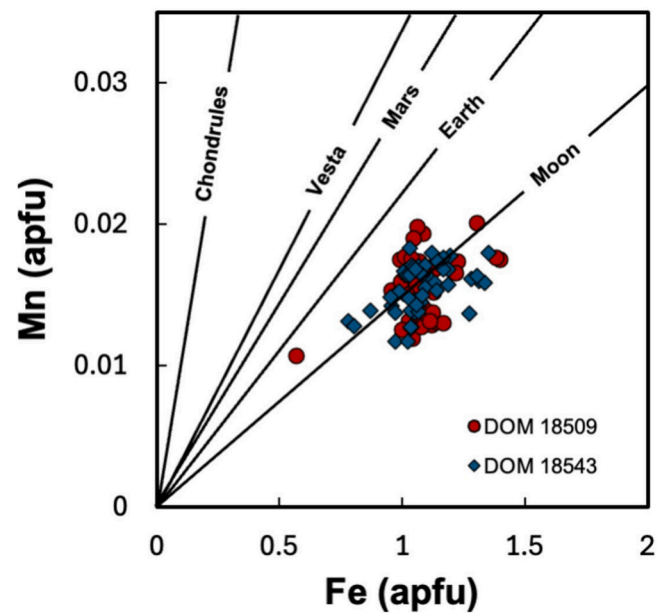


Fig. 5. Fe vs Mn atom per formula unit (apfu) for pyroxenes associated with all investigated symplectites from DOM 18543 and 18509. Calculated apfu values are based on 6 oxygens. Parent body lines after Fagan et al. (2003).

which three-phase, Fa-Px-Si symplectites form (Lindsley and Burnham, 1970; Lindsley et al., 1972). Furthermore, in the study of lunar meteorite Asuka-881757, Oba and Kobayashi (2001) propose that one possibility for Fa-Px-Si symplectite formation is the decomposition of Fe-rich pigeonite at low pressure (<1.15 GPa). A more recent example for pyroxferroite breakdown specifically was presented in Borden et al. (2022) and the study of Apollo 12 pigeonite basalt 12031, where incomplete breakdown is preserved as “mesostasis textures”. In this samples’ magmatic context, Borden et al. (2022) propose that the pyroxferroite regions are xenolithic in nature and originated from a Fe-rich magma in a plutonic environment at depth. These were later entrained within an ascending magma and transferred to lower pressures where the pyroxferroite was unstable. In this scenario, the reaction did not go to completion hence, pyroxferroite was preserved. This interpretation also relies on the relatively high-pressure stability field of pyroxferroite (1.0–1.75 GPa), implying its relatively deep formation (down to ~ 330 km; Jing et al., 2022) prior to partial breakdown during entrainment. The resulting symplectitic textures were also observed to be localized in coarser crystals and were associated with voids and grain boundaries, rather than being uniformly distributed. It is also notable that silica was not observed in the symplectitic breakdown products and that the dark regions on BSE images were void spaces interpreted to have formed during the breakdown process as a result of volume reduction (Borden et al., 2022).

Similarly, a study by Xirouchakis et al. (2001, 2002) on the Los Angeles Martian meteorite reported the occurrence of two-phase symplectites composed of olivine and augite which were not ubiquitously accompanied by a silica phase. In this scenario, symplectite formation at ≤ 900 – 950 °C, at FMQ of -1.0 to 0.2 , was a 2-step process where an initially unstable pyroxene exsolved to produce augite and pigeonite, followed by the following reaction: pigeonite + Ti-magnetite = olivine + augite + ilmenite (see also, Rost et al., 2009). This was accompanied by conditions where pyroxenes were Mg-rich enough to prevent primary pyroxenoid crystallization (Xirouchakis et al., 2002). While this was later refuted by Warren et al. (2004) who argued that the silica phase had not been considered, Xirouchakis et al. (2002) did not rule out potential contributions from shock related plagioclase, alkali, or Si-rich glass, nor the role of low Ca-pyroxene breakdown during cooling at

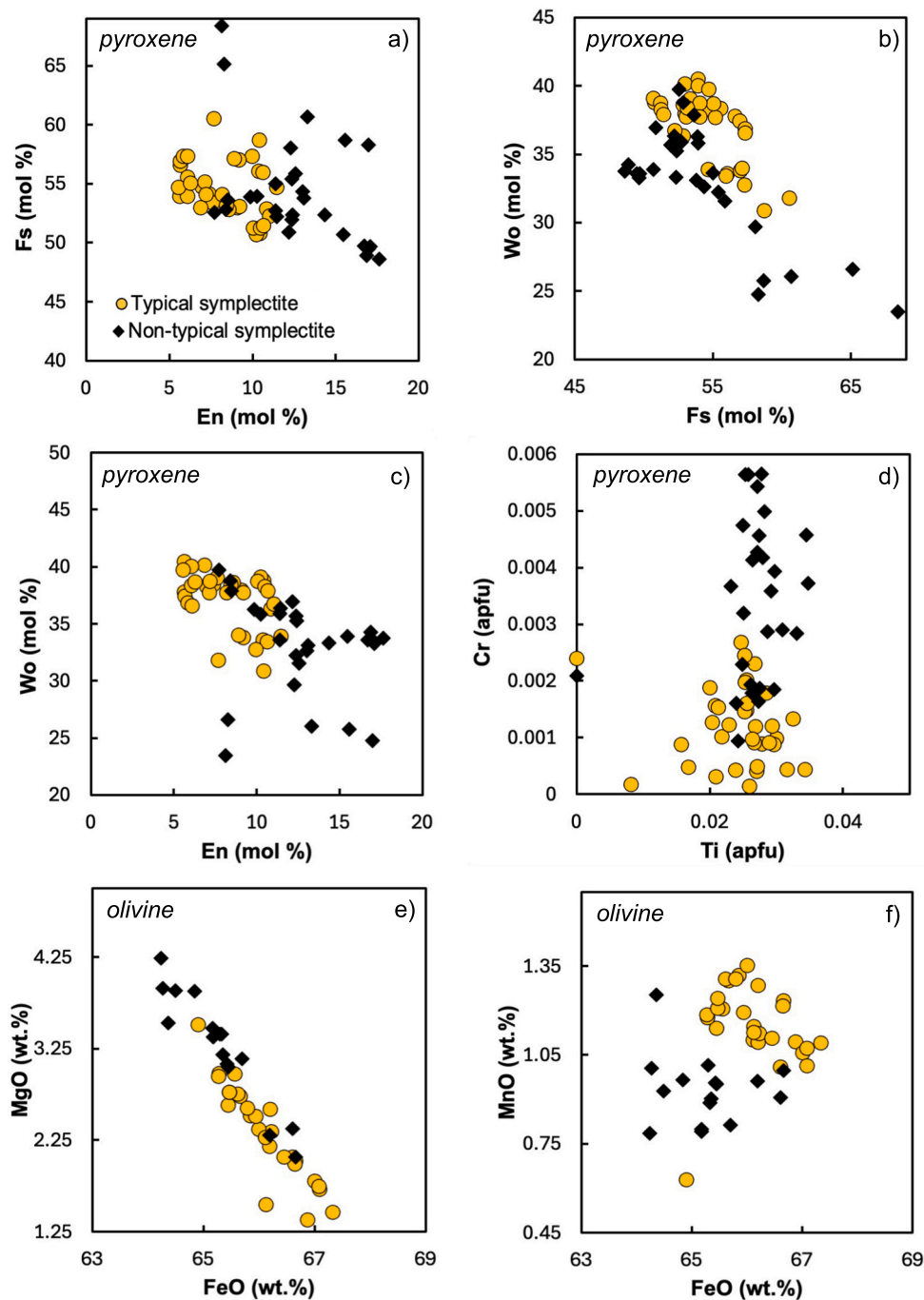


Fig. 6. Comparison of pyroxene and olivine compositions in typical and nontypical symplectites from both DOM 18509 and 18543. a-c) pyroxene endmember compositions comparing typical (yellow circles) and nontypical (black diamonds) symplectites. d) Cr vs. Ti (apfu) for typical and non-typical symplectites; symbols as in a)-c). e) wt% FeO vs. wt% MgO and, f) wt% FeO vs. wt% MnO for olivine in typical and non-typical symplectites. Symbols as in a)-d). Typical symplectites exhibit higher wt% FeO and MnO contents compared to non-typical symplectitic olivine. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

<~900 °C in order to explain similar symplectites observed in Martian meteorites. From the study of the Los Angeles, Shergotty, and Queen Alexandra Range (QUE) 94201 Martian meteorites by [Aramovich et al. \(2002\)](#), no pyroxferroite or two-phase olivine + pyroxene symplectites were reported. Instead, Fa-Px-Si symplectites were observed and occurred in association with late-stage mineral assemblages of oxides, Fe-sulfides, and phosphates. Reconstructed bulk compositions were consistent with a pyroxferroite composition, used to infer pyroxferroite as the precursor phase, and that the cooling rates of these Martian

basalts were slow enough to allow pyroxferroite breakdown. From [Aramovich et al. \(2002\)](#), there had not been any reports of metastable pyroxferroite preserved in Martian samples.

The occurrence and formation of Fa-Px-Si three-phase symplectites has also been reported in the eucrite and howardite meteorites. From [Buchanan et al. \(2000\)](#), strongly zoned pyroxenes with rims composed of Fe-rich augite that host vermicules and lamellae of Fe-rich olivine and silica in Clast A of the Macibini polymict eucrite were documented (see Fig. 6c in [Buchanan et al., 2000](#)). From bulk symplectite analysis via

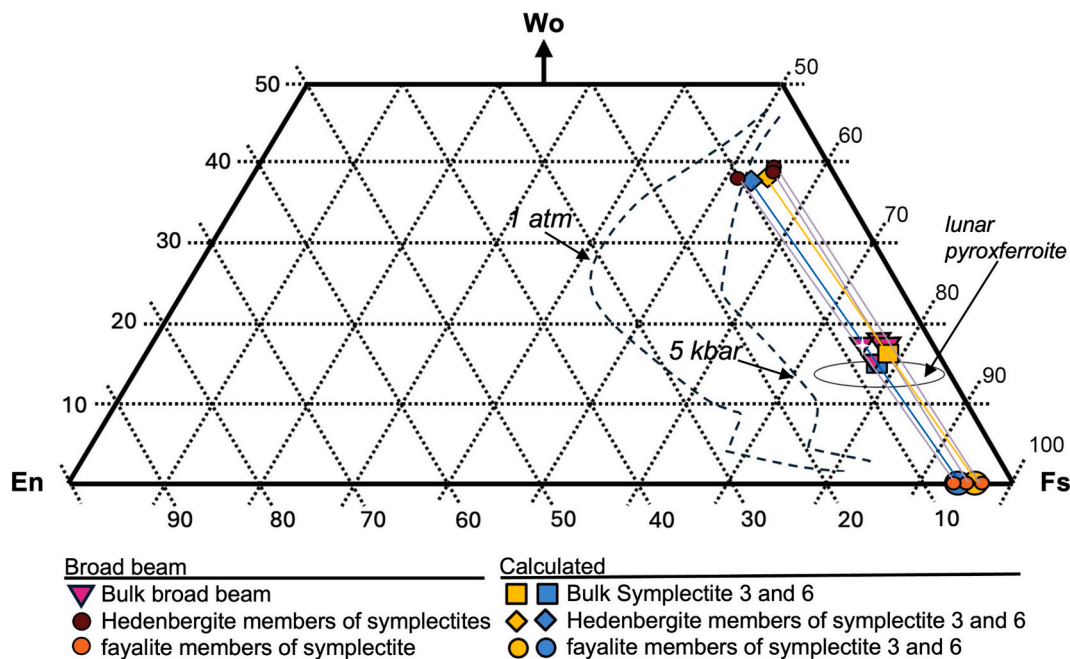


Fig. 7. Results from typical symplectite reconstruction using the reconstruction and broad beam approaches discussed in the text. Tie lines connect compositions of hedenbergite (Px) and fayalite (Fa) components of each symplectite to its reconstructed composition. The region to the right of the curved lines at atmosphere (atm) and 5 kilobars (kbar) represent the approximate “forbidden region” after Lindsley (1983). The pink upside-down triangle with a white cross and the blue square are data from the same symplectite reconstructed using both techniques. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

EPMA raster beam analysis, a bulk composition of $Wo_{26}En_{16}Fs_{58}$ (Fig. 8b) was obtained. Given that this is significantly more Ca-rich than pyroxferroite, an origin via pyroxferroite breakdown was rejected. Instead, Buchanan et al. (2000) proposed that the symplectite precursor phase was Fe-rich, sub-calcic augite which initially exsolved into augite plus low-Ca pyroxene lamellae. Subsequently, and at lower temperatures, these low-Ca pyroxene lamellae decomposed into olivine + silica, producing the observed intergrowths. Thus, the 3-phase symplectite textures were interpreted to result from a two-step, subsolidus decomposition of Fe-rich augite during cooling and occurring during the late-stage evolution of eucritic magmas.

Patzner and McSweeney Jr. (2012) in a study of howardites, described three-phase symplectites as fine to very fine-grained vermicular intergrowths of ferroan augite, fayalitic olivine, and silica. They also reported textures of stubby lamellae and sublamellar inclusions of olivine and silica within host ferroan clinopyroxene. The authors interpret that the three-phase symplectites were breakdown products of metastable pyroxene, formed under low-pressure, near-surface conditions and during rapid cooling. In this scenario, Fe-rich pyroxene (pyroxferroite or subcalcic augite) decomposed into augite + olivine + silica. The observed lamellar or inclusion textures were interpreted to represent localized or incomplete decomposition features related to the same process.

While some studies attribute symplectite formation to slow cooling and associated decomposition of metastable pyroxene/pyroxenoid (e.g., Aramovich et al., 2002), other studies invoke the effect of shock-induced heating. From the work of Liu et al. (2009) on lunar meteorite Miller (MIL) Range 05035, it was proposed that the observed Fa-Px-Si three-phase symplectite was the result of primary pyroxferroite and pyroxene being shock transformed. The numerous shock features in MIL 05035, including the complete transformation of plagioclase to maskelynite were used to support the inference of a shock-related process in Fa-Px-Si symplectite formation. In contrast, a shock-related origin for Fa-Px-Si symplectites was argued against by Rubin et al. (2000) from study of the Los Angeles Martian meteorite based on the presence of shock-induced faults that ruptured a previously decomposed zone of

pyroxferroite. Aramovich et al. (2002) further supported a non-shock heating related origin by citing both the insufficient time required for pyroxferroite decomposition to occur, and the relatively low post-shock temperatures of the shergottites (≤ 350 °C; see also Stöffler, 2000).

Finally, the role of direct crystallization processes in Fa-Px-Si symplectite formation are considered. From the work of Fagan et al. (2003) on lunar meteorite NWA 773, Fe-enrichment during late-stage fractionation of basaltic magmas was proposed to have resulted in Fa-Px-Si symplectite crystallization. This was supported by the non-stoichiometric, K_2O and Al_2O_3 -bearing Si-phase which accompanied the symplectites, precluded the breakdown from a “pre-existing stoichiometric solid”, and implied formation via crystallization or quenching. This is inconsistent with a pyroxferroite precursor. Fagan et al. (2003) further suggested that the presence of two immiscible liquids, accompanied by slow diffusion in those liquids and rapid growth rates could have contributed to the direct production of the Fa-Px-Si textures in highly fractionated, Fe-rich magmas. Similarly, during the study of lunar meteorite Asuka-881757, Oba and Kobayashi (2001) proposed an alternative mechanism to Fa-Px-Si formation via Fe-rich pyroxene breakdown, that being fayalite and silica replacing pyroxene crystallization due to extreme Fe-enrichment in the melt.

5.2. Insights from DOM 18509 and 18543 symplectites

The two textural types of symplectite preserved within DOM 18509 and 18543 are both characterized by three-phase, Fa-Px-Si assemblages with both types occurring in each meteorite (Figs. 2, 3). In typical symplectites (Fig. 2), the spatial distribution of the Fa-Px-Si components is uniform and similar to those reported for the Los Angeles and Asuka-881757 meteorites which are of Martian and lunar origin, respectively (e.g., Oba and Kobayashi, 2001; Aramovich et al., 2002). In contrast, in non-typical symplectites (Fig. 3), the Fa and Si components are more isolated, and their distribution is non-uniform. These textures are similar to those reported in the Macibini eucrite and NWA 773 lunar meteorites (Buchanan et al., 2000; Fagan et al., 2003).

When reconstructed, bulk typical symplectites, either reconstructed

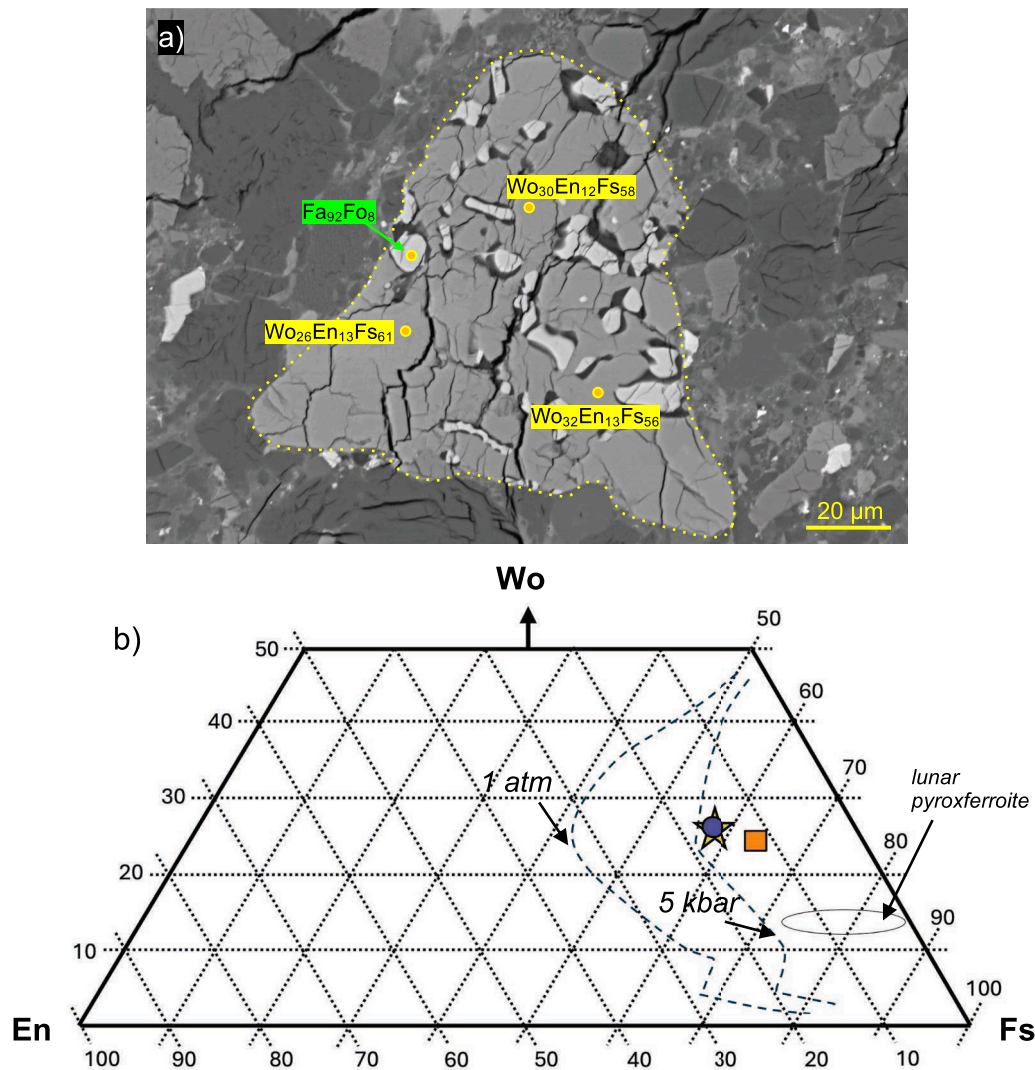


Fig. 8. a) Example of non-typical symplectite from DOM 18543 with compositions (and EPMA analysis locations) of Fa and Px shown. b) Bulk non-typical symplectite where the orange square represents the symplectite shown in Fig. 8a and the purple circle is the symplectite shown in Fig. 3c). The star represents the bulk symplectite composition of Clast A in the Macibini polymict eucrite after Buchanan et al. (2000), as determined by rastered beam analysis. The region to the right of the curved lines at 1 atm and 5 kbar represent the approximate “forbidden region” after Lindsley (1983). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

or determined via broad beam, generally overlap metastable lunar pyroxferroite compositions (Fig. 7). This is consistent with the observations of Aramovich et al. (2002) for bulk symplectite reconstructions in Los Angeles, QUE 94201, and Shergotty which were “within error” of the metastable pyroxferroite compositional field. For comparison, the compositions of the associated olivines are slightly more Fe-rich in lunar DOM 18509 and 18543 with olivines defined by $\sim \leq 3.25$ wt% MgO at ≥ 65 wt% FeO (Fig. 6e) compared to the Martian typical symplectite olivines at < 2.7 wt% MgO at ~ 62 –65 wt% FeO. No Cr or Mn data for symplectitic olivine were reported in Aramovich et al. (2002).

In contrast, the reconstructed bulk compositions of non-typical symplectites in DOM 18509 and 18543 do not yield (metastable) pyroxferroite chemical signatures. When reconstructed, bulk compositions are constrained to $Wo_{24-26}En_{12-16}Fs_{58-64}$ (see Fig. 8b), plot inside the pyroxene forbidden zone, and exhibit higher mol% Wo, higher mol% En, and lower mol% Fe contents than pyroxferroite. In Fig. 8b, these are compared to the electron probe rastered beam analysis of a non-typical symplectite in Clast A of the Macibini eucrite ($Wo_{26}En_{16}$) which is characterized by elongate, sub-parallel blebs and lamellae of Fe-rich olivine and silica (Buchanan et al., 2000). As shown, this is also distinct from pyroxferroite and overlaps exactly with the bulk

composition of one of the non-typical symplectites reported here (see Figs. 3c and 8b). For comparison, the wt% MnO contents of Macibini olivines range from 1.32 to 1.42, which are slightly higher than those reported in this study, for any of the symplectites (Fig. 6f). When considering wt% FeO and wt% MgO signatures, the olivines are more Mg-rich and Fe-poor, and trend to higher MgO contents at lower FeO contents on Fig. 6e: wt% MgO values of 4.38 to 7.26 and wt% FeO values of 60.4 to 63.1, all Fa contents ≤ 89 (Buchanan et al., 2000).

In the DOM 18509 and 18543 non-typical symplectites, host pyroxenes exhibit broader compositional ranges than the pyroxene components of typical symplectites, e.g., mol% Fs from 48 to 68 at mol% Wo from 23 to 40 compared to mol% Fs 51 to 61 at mol% Wo from 31 to 40 respectively. In the studied range of non-typical symplectites, iron-rich zones (IRZ) were observed (e.g., Figs. 3f, 9a). Adjacent to these IRZs, calcium enrichment also occurs (Fig. 9a). In Fig. 9b the compositions of the different pyroxene components in one of these grains is shown and its history interpreted. From an initially stable, augitic composition ($Wo_{20-23}En_{37-38}Fs_{40}$), progressive crystallization from a fractionating melt drives the pyroxene composition into the forbidden zone forming metastable pyroxene ($Wo_{22-26}En_{8-10}Fs_{65-69}$). These are compositionally distinct from the metastable pyroxferroite field by exhibiting ~ 10 mol%

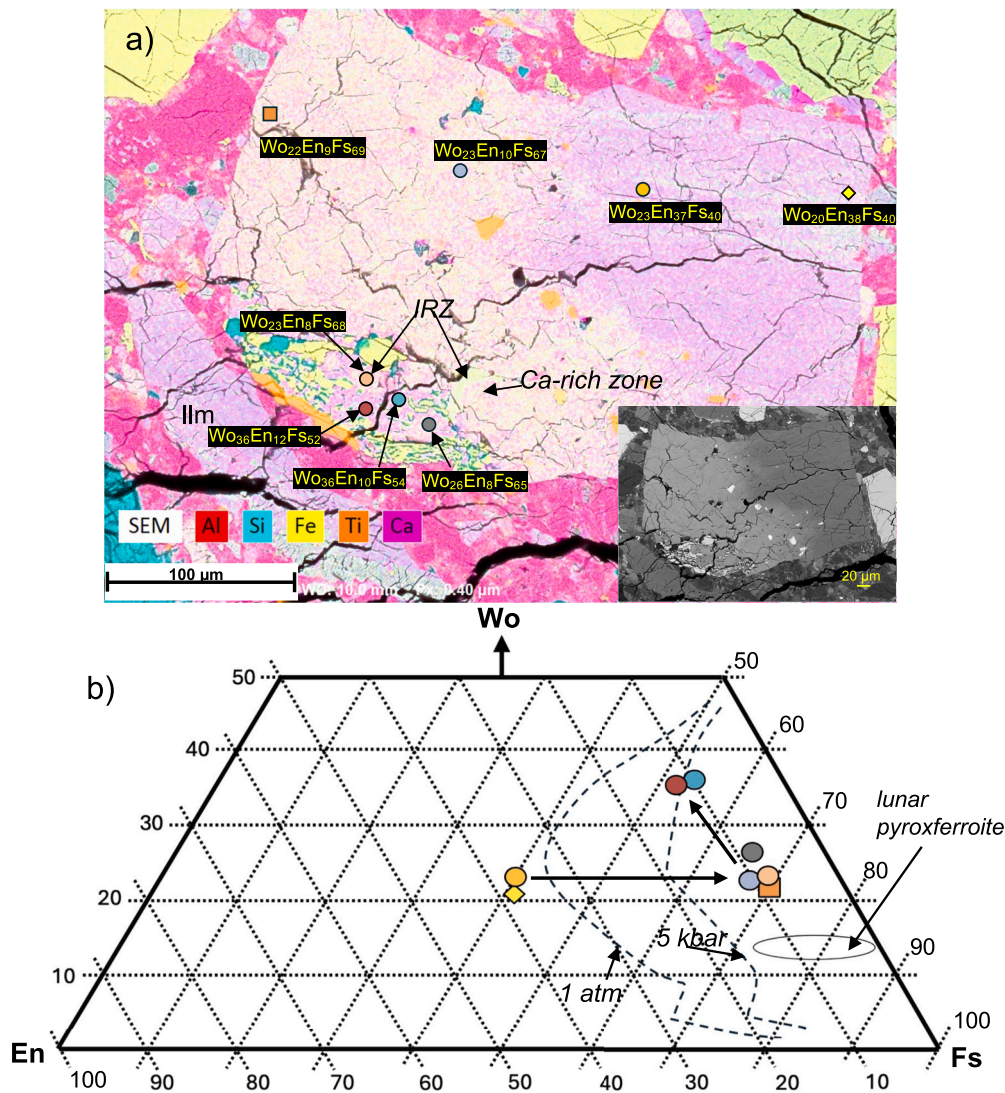


Fig. 9. a) Elemental map of a pyroxene grain exhibiting progressive Fe enrichment and breakdown to a non-typical symplectite along the grain edge. EPMA spot locations and corresponding pyroxene compositions are shown. Iron-rich zones (IRZ) are observable. Adjacent to these IRZ, localized calcium enrichment occurs. Inset: BSE image of the same grain. b) Pyroxene ternary diagram showing the compositions of grain in a) at different spots. Progressive crystallization from a fractionating melt drives the pyroxene composition into the forbidden zone, forming metastable pyroxene. The metastable pyroxene exsolves into low-Ca, high-Fe (IRZ) and high-Ca pyroxene components, followed by the breakdown of the IRZ into olivine and a silica phase. The region to the right of the curved lines at 1 atm and 5 kbar represents the approximate “forbidden region” after Lindsley (1983).

higher Wo (and ~ 10 mol% lower Fs). Here, being unstable, the metastable pyroxene exsolves to low-Ca (recorded as IRZs zones) and high-Ca components, the low-Ca pyroxene subsequently breaks down to stable Fe-rich olivine and silica. The pyroxene component is now more Ca-rich as recorded by $Wo_{36}En_{10-12}Fs_{52-54}$ in the Ca-rich zones (Fig. 9a, b).

The observed spatio-chemical signatures summarized in Fig. 9 are comparable to the inferences of Buchanan et al. (2000) where the formation of Fa and Si symplectite components in the Macibini eucrite were interpreted as inconsistent with a pyroxferroite precursor and subsequent breakdown. Instead, a metastable Fe-rich, sub-calcic augite precursor ($Wo_{26}En_{16}Fs_{58}$) was proposed in order to explain the textures and pyroxene chemistry observed. Given the overlap in bulk non-typical symplectite compositions discussed above (Fig. 8), and the preservation of the textures and pyroxene chemistry captured in Fig. 9, it is proposed that Fa-Px-Si non-typical symplectites are not the result of metastable pyroxferroite breakdown and therefore record a different petrogenetic process than the Fa-Px-Si typical, uniform, symplectites (Figs. 3, 7).

In order to explain the eventual formation of Fa-Px-Si non-typical

symplectites, the presence of a metastable precursor pyroxene with a sub-calcic, augitic composition (as described earlier) is proposed (see Fig. 9). This subsequently exsolves to form stable augite and low-Ca pyroxene lamellae which break down at lower temperatures to the stable assemblage of olivine + silica and produce the observed Fa + Si intergrowths (Buchanan et al., 2000). This mechanism proposed by Buchanan et al. (2000), and in-part caught in the act in Fig. 9, is also supported by the work of Oba and Kobayashi (2001) that report the instability of a “ferrosilite-like” bulk composition at low pressure. This “ferrosilite-like” composition subsequently breaks down into a stable Fa + Si assemblage. In Figs. 3f and 9b, the low Ca-pyroxene lamellae component of Buchanan et al. (2000), and the “ferrosilite-like” component of Oba and Kobayashi (2001), are represented by the low-Ca, IRZ regions.

Throughout the studied DOM 18509 and 18543 meteorites, there are numerous examples of preserved metastable pyroxene existing alongside in-part grain breakdown to the Fa-Px-Si assemblage. Several of these are shown in Fig. 10a-b with compositions distinct from pyroxferroite (higher mol% Wo) and consistent with a pyroxene in the

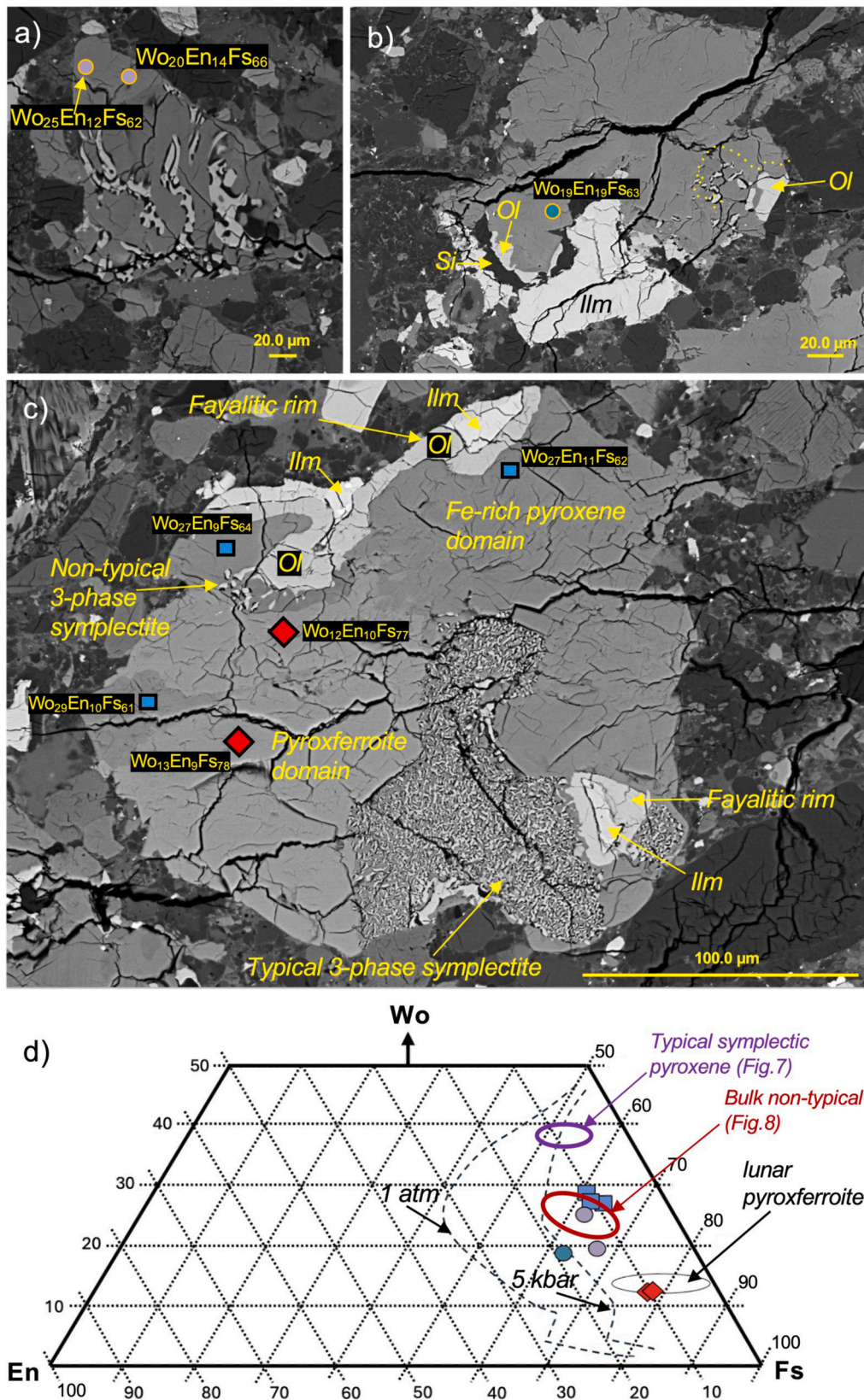


Fig. 10. a-b) Representative grains showing partial preservation of metastable pyroxene alongside areas that have transformed into a breakdown assemblage. c) Grain exhibiting compositional variation, with pyroxferroite on one side and metastable pyroxene on the other; both typical and non-typical symplectites are present (see also, Fig. 4). The fayalitic rims which enclose the ilmenite and are in contact with the pyroxene domain are highlighted at the top and lower right of the image. d) Pyroxene ternary diagram showing the compositions of preserved metastable pyroxene and pyroxferroite from regions identified in a)-c). The region to the right of the curved lines at 1 atm and 5 kbar represent the approximate "forbidden region" after Lindsley (1983).

forbidden zone region. In Fig. 10c, a multi-domain pyroxene grain is shown. A distinct pyroxferroite domain ($\text{Wo}_{12-13}\text{En}_{9-10}\text{Fs}_{77-78}$) is optically consistent with pyroxferroite characteristics (see Fig. 4a-b) and exists adjacent to a Ca-rich pyroxene domain ($\text{Wo}_{27-29}\text{En}_{9-10}\text{Fs}_{61-64}$). These Ca-rich domains overlap the compositions of the reconstructed bulk compositions of the non-typical symplectite and the preserved metastable pyroxenes (Figs. 8b, 9b, 10d). This multi-domain pyroxene grain also exhibits both non-typical and typical Fa-Px-Si symplectite textures (Fig. 10c). As shown, the development of the non-typical symplectite texture is spatially associated with the presence of Ca-rich pyroxene ($\text{Wo}_{27}\text{En}_9\text{Fs}_{64}$) where discrete blebs of olivine and silica have developed. In contrast, the development of the typical symplectite is spatially associated with the pyroxferroite domain. The boundary of the typical Fa-Px-Si symplectite is interpreted to reflect the extent of precursor metastable pyroxferroite prior to incomplete breakdown. Overall, this grain is interpreted to capture the late-stage crystallization of metastable pyroxene from a highly evolved, Fe-rich melt during the final stages of fractionation. In this scenario, the relatively Ca-rich pyroxene (Fig. 10d) formed first prior to the fractionation of Fe-rich pyroxferroite. This is further supported by the higher Mg and Cr contents of pyroxene associated with the non-typical symplectites, as shown in Fig. 6d, e. In addition, the Mg and Cr components of the reconstructed bulk non-typical symplectites (Table S18) are higher than those of the reconstructed bulk typical symplectites (Table S14), further supporting the inference that pyroxferroite formed during the later stages of melt fractionation and extreme Fe-enrichment.

From this crystallization sequence, the “transition zone” of Warren et al. (2004) can also be explained. With progressive crystallization from a fractionating basaltic melt, pyroxene composition enters the forbidden region, followed by the formation of metastable pyroxene and then pyroxferroite. When conditions favor the breakdown of both metastable phases, the former breaks down to form non-typical symplectites, whereas the latter breaks down to form typical symplectites. This suggests that non-typical symplectites do not represent an intermediate stage between stable pyroxene and typical symplectites. Instead, they reflect the breakdown of a different metastable phase.

The preservation of metastable pyroxferroite phases has previously been attributed to both relatively fast (Lindsley et al., 1972) and slow cooling regimes (Grove and Lindsley, 1981). From Lindsley et al. (1972), cooling rapidly to 990 °C within 3 days preserved pyroxferroite whereas in Grove and Lindsley (1981) slow cooling at <1 °C/day also resulted in the persistence of metastable pyroxferroite. From Fig. 10c, a slow cooling regime is preferred as an explanation. This is supported by the presence of a fayalitic reaction rim on the pyroxene grain which is interpreted to have formed as a direct result of a subsolidus reaction between ilmenite-ulvöspinel and the host pyroxene. This textural and mineralogical association was observed in Apollo 15 sample 15075, a coarse-grained gabbro (Taylor and Misra, 1975). From Taylor and Misra (1975), both Fa-Px-Si symplectites and pyroxferroite are also preserved, however the fast cooling rates of Lindsley et al. (1972) were determined to be inconsistent with the observed partitioning behavior of Zr between ilmenite and ulvöspinel in 15075. Therefore, a slow cooling rate of <3 °C/day was proposed and is similarly invoked here.

The possibility that Fa-Px-Si symplectites are direct products of late-stage crystallization (or quenching) from one or more liquids was previously proposed by Fagan et al. (2003) during study of lunar meteorite NWA 773. This was based on the presence of non-stoichiometric, Al_2O_3 -bearing silica components (reported as glass with up to 12.7 wt% Al_2O_3). In Supplementary Fig. S4, the EDS elemental maps of a typical symplectite are shown with no evidence for the presence of an Al_2O_3 component (EDS detection limit ≤ 0.08 wt%, Kuisma-Kursula, 2000). While formation of Fa-Px-Si symplectites in DOM 18509 and 18543 via direct crystallization is not preferred here, their presence in NWA 773 did similarly support derivation from a highly fractionated, Fe-rich mafic igneous system (Fagan et al., 2003).

Finally, the formation of Fa-Px-Si symplectites via shock

transformation proposed by Liu et al. (2009) is considered. As shown in Supplementary Fig. S5a, a melt vein/pocket consumes part of a pre-existing typical symplectite. Additionally, in Supplementary Fig. S5b, part of a typical symplectite is offset by a right-lateral fault. This spatial context preserves a relative temporal framework and supports formation of the preserved symplectites prior to the impact event(s) which generated the observed shock features (i.e., melt veins, pockets, fractures). In addition, no evidence of shock metamorphism such as the transformation of plagioclase to maskelynite is observed. Similarly, for the martian shergottite meteorites, a shock-related origin was ruled out based on the low post-shock temperatures and the relatively rapid nature of shock-related processes (seconds), which do not provide the necessary time required for pyroxferroite breakdown (Lindsley et al., 1972; Stöffler, 2000; Aramovich et al., 2002).

While petrographic observations suggest that shock is unlikely to be the primary mechanism for formation of symplectites investigated in DOM 18509 and 18543, localized modification of pre-existing symplectites during subsequent shock events cannot be precluded (Warren et al., 2004). The presence of discrete textural domains in some symplectites is consistent with this possibility. However, without crystallographic orientation data, it is not known whether these domains preserve shock-related modification, inherited precursor orientation, or another textural process. Future investigations of Fa-Px-Si symplectites should therefore integrate Electron Backscatter Diffraction (EBSD) into the analytical workflow.

From Schweitzer et al. (2026) and McLeod et al. (n.d.), the 2018–2019 ASNMET lunar DOM meteorite clan are proposed to have originated from an ancient, mare-dominated, low-Ti terrane on the Moon where highly fractionated basaltic magmas record lunar Fenner, Fe-enrichment trends (Fenner, 1929; Lu et al., 1989; Day et al., 2006). The detailed textural and geochemical study of the DOM 18509 and 18543 Fa-Px-Si symplectites presented here supports this. Furthermore, it is proposed that during extreme fractionation of extraterrestrial basaltic magmas and during the final stages of melt evolution, progressive Fe-enrichment drives pyroxene into the forbidden region. These Fe-enriched, reduced, magmatic environments are favored, at least within a lunar context, due to low oxygen fugacities where iron oxide exists as FeO and not Fe_2O_3 (e.g., Day et al., 2006; Warren and Korotev, 2022). Under these highly evolved conditions, a metastable pyroxene fractionates, followed specifically by pyroxferroite. Subsequently, both phases can experience subsolidus breakdown during cooling in low-pressure magmatic environments.

No three-phase Fa-Px-Si symplectites, either typical or non-typical, have been reported in basalts on Earth. This could potentially be explained by the relatively oxidized nature of basaltic magmas, the evolution of which prevents the Fe-enrichment required to form metastable pyroxenes as is otherwise observed throughout extraterrestrial materials (lunar, Martian, and Vesta). Future studies should therefore, in detail, explore the textural, mineralogical, and geochemical association of the Fa-Px-Si components in extraterrestrial symplectites in order to advance understanding of magmatic processes operating on other differentiated objects. This is of particular importance (and relevance) when considering late-stage fractionation mechanisms and elemental enrichment processes in residual melts.

6. Conclusion

Fayalite-pyroxene-silica (Fa-Px-Si) symplectites occur as two distinct textural types in lunar meteorites DOM 18509 and 18543, including in association with preserved pyroxferroite. While previous work often invokes the role of metastable pyroxferroite breakdown to account for these assemblages, a detailed study of two textural types and their chemical components reveals two petrogenetic pathways and breakdown processes. First, typical symplectites are characterized by a relatively uniform distribution of Fa-Px-Si (~2:2:1) and grain sizes of ≤ 5 μm . The Px component of these symplectites is tightly constrained to

Wo₃₁₋₄₀En₆₋₁₄Fs₅₁₋₆₁, with olivine Fa contents ranging from Fa₉₁ to Fa₉₆. Determination of their bulk compositions via phase reconstruction and broad beam analysis is consistent with lunar pyroxferroite compositions: Wo₁₅₋₁₈En₅₋₈Fs₇₅₋₇₈. Second, non-typical symplectites are characterized by a non-uniform distribution of Fa-Px-Si with the Fa + Si components occurring together as blebs within a Ca-rich, pyroxene host (Wo₂₃₋₄₀En₈₋₁₈Fs₄₉₋₆₈). These are compositionally distinct from, and more variable than, typical symplectite Px. Non-typical pyroxenes are also more Mg- and Cr-rich, and when bulk compositions are reconstructed, those are more Ca-rich and Fe-poor than bulk typical symplectites (Wo₂₄₋₂₆En₁₂₋₁₆Fs₅₈₋₆₄). These are also notably distinct from lunar pyroxferroite. In addition, one grain from DOM 18509 preserves a rare example of metastable pyroxferroite, confirmed via optical microscopy: Wo₁₂₋₁₃En₉₋₁₀Fs₇₇₋₇₈.

Both Fa-Px-Si symplectite textural types are derived from metastable precursors in highly fractionated, Fe-rich magmatic systems in which pyroxene chemical evolution trends enter the forbidden region. However, only typical symplectites are consistent with a pyroxferroite precursor and subsequent subsolidus breakdown into uniform Fa-Px-Si components. In contrast, non-typical symplectites are derived from subsolidus decomposition of a Ca-rich, augitic precursor. The typical symplectites formed by the breakdown of pyroxferroite (a pyroxenoid), which decomposes directly (Rost et al., 2009) into a three-phase intergrowth of olivine, pyroxene, and a silica phase. In contrast, the non-typical symplectites formed from the breakdown of a metastable pyroxene precursor through a multistep process. The metastable pyroxene first exsolves into high-Ca pyroxene and low-Ca, Fe-rich pyroxene. Subsequently, the low-Ca, Fe-rich pyroxene breaks down to form olivine and a silica phase, producing the observed host-pyroxene texture with olivine and silica blebs.

The preservation of Ca-rich, augitic pyroxene and pyroxferroite in the same grain, both of which are accompanied by the development of non-typical and typical symplectites textures, respectively, captures this progressive relationship. This supports fractionation of metastable pyroxene during late-stage differentiation of basaltic magmas, and the eventual crystallization of Fe-rich pyroxferroite. This is followed by subsolidus breakdown to Fa-Px-Si components during slow cooling. The preservation of both textures, in addition to metastable pyroxferroite, within DOM 18509 and 18543, exemplifies the reduced nature of lunar magmas.

CRedit authorship contribution statement

A. Sedaghat: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **C.L. McLeod:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Formal analysis. **M. Loocke:** Writing – review & editing, Visualization, Methodology, Formal analysis. **B.J. Shaulis:** Writing – review & editing, Visualization, Project administration, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.icarus.2026.117331>.

Data availability

Data will be made available on request.

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