# Two-stage formation of pallasites and the evolution of their parent bodies revealed by deformation experiments

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## ABSTRACT

Pallasites, stony-iron meteorites predominantly composed of olivine crystals and Fe-Ni metal, are samples of the interior of early solar system bodies and can thus provide valuable insights into the formation of terrestrial planets. However, pallasite origin is controversial, either sampling the core-mantle boundary or the shallower mantle of planetesimals that suffered an impact. We present high strain-rate deformation experiments with the model system olivine + FeS melt ± gold melt to investigate pallasite formation and the evolution of their parent bodies and compare the resulting microstructures to two samples of Seymchan pallasite. Our experiments reproduced the major textural features of pallasites including the different olivine shapes, olivine aggregates, and the distribution of the metal and sulfide phases. These results indicate that pallasites preserve evidence for a two-stage formation process including inefficient core-mantle differentiation and an impact causing disruption, metal melt injection, and fast

cooling within months to years. Olivine aggregates, important constituents of angular pallasites, are reinterpreted as samples of a partially differentiated mantle containing primordial metallic melt not stemming from the impactor. The long-term retention of more than 10 vol% of metal melt in a silicate mantle sampled by olivine aggregates indicates high effective percolation thresholds and inefficient metal-silicate differentiation in planetesimals not experiencing a magma ocean stage.

## 1. Introduction

Pallasites are stony-iron meteorites that are predominantly composed of large olivine crystals embedded in a matrix of iron-nickel and minor amounts of troilite (Fig. 1). Since their first description by Peter Simon Pallas in the late 18$^{th}$ century, researchers have aimed to explain the unusual composition and texture of pallasites, a challenge that can be summarized by three major questions:

1. Why is olivine the dominant and often singular silicate phase in pallasites?
2. Which process led to mixing between the olivine and the metal phase?
3. Why has the large density contrast between the olivines and the presumably molten metallo-sulphidic components not led to a subsequent gravitational separation?

The last question was termed “the pallasite problem” (Wahl, 1965) and received attention as a key constraint for the origin of pallasites, but plausible formation models must also address how the unusual phase mixture formed in the first place. Various models were proposed over time to explain pallasite formation and to reconcile cosmochemical, isotopic, magnetic, and textural data gained from pallasites (see Table 4 in Boesenberg et al. (2012) for a compilation). For the purpose of this study, we group previous models according to the internal or external origin of the metal phases. Most models belong to the former group that explains pallasites as part of a continuous differentiation sequence ranging from chondrites, acapulcoites, lodranites, pallasites to iron meteorites/achondrites (Boesenberg et al., 2012; Ringwood, 1961). In these models both the metal and the silicates stem from a common chondritic precursor that formed a pallasite parent body (PPB). The pallasite problem is often addressed by positioning the rocks at the core-mantle boundary where a lack of gravitational segregation appears plausible (Boesenberg et al., 2012; Wasson and Choi, 2003). These regions have either retained part of the metal during inefficient differentiation (Boesenberg et al., 2012) or core-melt was re-intruded during a deformation event (Scott, 1977; Yang et al., 2010). The wide variety of cooling rates in the temperature interval between ≈700-400 °C determined in pallasites was linked to different burial depths and taken as evidence against a core-mantle origin for pallasites (Yang et al., 2010). This observation led to recent models of (i) a destructive impact forming a "pallasite planetesimal" (Yang et al., 2010) or (ii) of upwards diking of core-metal originating from an inward crystallizing core (Johnson et al., 2019). The dunitic composition of pallasites is either explained as an olivine cumulate layer (Buseck, 1977) or as restitic after high-grade fractional melt removal (Boesenberg et al., 2012).

The second, more recent, group of models assumes an external source of the metal phases that are injected into a dunitic middle to upper mantle of a PPB during the collision with an impactor (Bryson et al., 2015; Tarduno et al., 2012). The external-metal models were devised to explain remanent magnetization in olivine inclusions suggesting an active dynamo while the rocks cooled below the Curie temperature of ≈360 °C. This required a sufficient distance from a hot convecting core (Tarduno et al., 2012). Furthermore, the external-metal models also reconcile the low Ir content of the pallasite metal with the remanent magnetization. The former may suggest a highly evolved melt stemming from a largely crystallized core (e.g. Wasson and Choi, 2003), while the latter requires a largely molten convecting core. In the external models both constraints are fulfilled by the impactor core and the PPB core, respectively (Tarduno et al., 2012).

Since the different pallasite models often imply contradictory answers to the fundamental questions raised above, the use of pallasites as witnesses for the differentiation history of early solar system bodies is hitherto limited. The current study offers new insights into pallasite origins by using deformation experiments of olivine-metal at high temperature to explain the enigmatic textures of pallasites.

## 1.2 Pallasite textures

Pallasite textures denote the spatial distribution and shape of olivine, Fe-Ni metal and troilite in natural samples. When reporting the results of laboratory experiments below we use the term “microstructure” for easy discrimination.

*Olivine shapes.* The olivines are highly variable among different pallasites and have therefore received much attention as an important element in deciphering pallasite formation history (Boesenberg et al., 2012; Buseck, 1977; Ringwood, 1961; Scott, 1977; Solferino et al., 2015; Yang et al., 2010). In some pallasites, such as Brenham, olivines are well-rounded crystals, other pallasites such as Imilac, Admire, or Seymchan contain polygonal crystals (named angular olivine (Scott, 1977)) and smaller olivine fragments that are commonly surrounded by metal (Fig. 1). Angular pallasites also display cohesive aggregates with diameters up to 30 cm (Fig. 1) called olivine masses (Scott, 1977), olivine nodules (Ulff-Møller et al., 1998), or olivine clusters (Boesenberg et al., 2012). Throughout this work, we use the neutral term “olivine aggregates” for its descriptive connotation and apply it to all aggregates with two or more cohesive crystals.

The commonly accepted paradigm for the textural variation of olivines suggests that angular and fragmental olivines are produced by inter- and intragranular fracturing of olivine aggregates, respectively, caused by a deformation event also responsible for the mixing with metal components (Scott, 1977). Angular olivines have also been termed “euhedral” or "anhedral" (Boesenberg et al., 2012), since their outer shape sometimes resemble crystal facets formed in silicate melt. However, since such "crystal facets" are commonly artifacts of former grain boundaries and triple junctions derived from the broken-up aggregates, such generic terminology is avoided here.

During high temperature annealing angular and fragmental olivines are expected to turn into the rounded shape, thereby approaching textural equilibrium determined by the high surface energy of the metal melt (Scott, 1977). Hence, round-type pallasites may conceal a deformation history (Scott, 1977; Solferino and Golabek, 2018). Rounding and grain-growth processes have been investigated by experimental studies that suggested a time between 100 kyr and several Myr at experimental temperatures of 1100 to 1400 °C to create the large round olivine grains found in pallasites (Saiki et al., 2003; Solferino and Golabek, 2018; Solferino et al., 2015). All three olivine shapes—round olivine crystals, angular olivines, and smaller olivine fragments—are found in close proximity in some pallasites such as Seymchan. This observation needs to be reconciled with models to account for the olivine morphology since the rounding and growth process should first affect the smallest grains (e.g. Solferino et al., 2015).

*Fe-Ni metal and troilite textures.* In previous studies the textures of the metallo-sulphidic components have often been treated indirectly as the negative mould of olivine textures. For example, Boesenberg et al. (2012) considered several geometrical closed packing arrangements for olivine assigning the metal the role of filling the interstices, and in the Scott (1977) model metal acts as the passive infill of inter- and intragranular fractures creating the various olivine shapes. This implies a molten state of the metal phase when forming these textures, which appears to be commonly accepted by all authors, thus forming the basis for our experiments.

Compared to the dominant Fe-Ni phase, troilite (FeS) is of minor volumetric importance in pallasites (ca. 0.5 vol% in Esquel (Ulff-Møller et al., 1998) and 4-5 vol% in Brenham (Spinsby et al., 2008)). However, the textures associated with troilite deserve scrutiny, as it is frequently located in fractures that relate to the pallasite deformation history.

The intergrowth of kamacite and taenite lamellae in the form of Widmanstätten pattern or as plessite has been widely used to infer cooling rates for pallasites (Yang et al., 2010); however, in this study we do not consider these textural features as they form at temperatures well below the solidus of all phases and are therefore secondary.

## 2. Materials and Methods

The deformation experiments utilize the model system olivine with FeS ± gold (Au) melt to simulate the effect of high strain-rate deformation during an impact. The goal was to experimentally reproduce the range of pallasite textures summarized in the previous section and thereby better understand their formation. Experiments were performed using the multianvil press of the novel neutron instrument SAPHiR (Six Anvil Press for High Pressure Radiography and Diffraction) based at the FRM II neutron source of the Technical University Munich (TUM) (Fig. 2a). Additionally, three experiments were performed with the previously described Mavo press based at Bayerisches Geoinstitut (BGI) (Manthilake et al., 2012). Both the SAPHiR and the Mavo presses are identical three-axis multianvil apparatuses with a cubic sample geometry that allow controlled deformation experiments at high pressure and temperature conditions (Manthilake et al., 2012).

The samples were prepared using mechanically ground San Carlos olivine that was mixed with 20 wt% of synthetic FeS powder (ChemPur 99.9% purity). The powder was filled and mechanically compacted in un-welded cylindrical rhenium (Re) capsules measuring 3 mm across and 3 mm in height. Previous experimental studies revealed some reaction of FeS melt directly in contact with the capsule, however, it was shown that the capsule remained generally intact and the sample inside was uncontaminated (Cerantola et al., 2015; Walte et al., 2007, 2011). In order to simulate the introduction of additional melt during deformation, several samples contained a small cavity in the centre filled with either pure FeS powder, Au powder, or ≈1x1 mm solid Au pieces (Fig. 2). Under the experimental conditions, Au and FeS form two immiscible melt phases. This allowed for easy discrimination in the recovered samples between melt that had already been situated in the olivine matrix (FeS) before deformation and the intrusion of 'external' melt (Au). The high surface tension of gold melt in contact with olivine (Walte et al., 2011) and slow heating ensured that the gold remained largely separated from the surrounding olivine–FeS aggregate during the initial heating and annealing stage and that it only intruded into the aggregate during deformation.

The cylindrical samples were placed into 12 mm cubic assemblies with pyrophyllite pressure medium and external gaskets (Fig. 2). A Re-foil resistance furnace was used for heating; the temperature was controlled by the heating power following an empirical 'electric power vs. temperature' calibration based on previous experiments. The absolute temperature error is estimated to be ±30 K. No solid–melt phase separation was observed along the capsule axis in any of the experiments despite long static annealing times, indicating that thermal gradients had little effect on phase distribution and the microstructures. Further details on experimental technique and calibration have been described previously (Manthilake et al., 2012).

Heating to the target temperature (1300 or 1350 °C) commenced after reaching the target pressure of 1 GPa. Slow heating ensured the release of residual stresses from the compression before crossing the FeS solidus, thus preventing melt extrusion and furnace damage. After reaching the target temperatures, all samples were statically annealed at constant temperature before performing the deformation part of the experiments (table 1). A relatively long annealing time was chosen to attain a coarser grain-size and to ensure textural equilibrium of the olivine-FeS melt microstructure. Some experiments were heated up to 1350 °C in order to shorten the annealing time, yet, the sample deformation occurred after reducing the temperature to 1300 °C.

After static annealing the samples were deformed either by plane strain (pure shear, abbreviated PS in table 1), extension followed by compression (E-C), or with an oblate strain field (OS). Pure shear and extension-compression deformation was achieved by shortening of one anvil axis and retracting the second anvil axis, while the third axis remained neutral. Oblate strain deformation was conducted by simultaneously retracting two anvil axes, which was accompanied by shortening of the third axis causing a reduction of the mean sample pressure during deformation. The use of different deformation geometries was necessary to simulate the whole range of pallasite textures as described in the results.

The predominantly brittle deformation textures of fragmental and angular pallasites suggest high strain-rates that may occur for example during an impact on the pallasite parent body. One experiment deformed at the highest sample shortening rate allowed by the press control software ($\dot{\varepsilon} \approx 6\times10^{-4}$ $s^{-1}$, M 719), however, showed that these strain-rates are too low to reproduce pallasite-like microstructures (see section 3.1). Hence, in order to achieve strain-rates $>1\times10^{-3}$ $s^{-1}$ the target positions of two anvil axes were manually altered in the control software by several increments of 20-100 μm (corresponding to a compression or stretch of the samples by ca. 0.5 – 3.0 %) until attaining the targeted finite strain. Each increment is implemented by the hydraulic anvil positioning system within ≈2 seconds, which resulted in a series of short deformation steps in the sample with an instantaneous strain rate of up to $1x10^{-2}$ $s^{-1}$. The resulting average strain-rate for the experiments, reported in table 1, was reconstructed from the accumulated anvil displacement and the total deformation time from the first to the last increment, which lasted for 20 to 60 s. The strain and the strain-rate values reported in table 1 assumed that the displacement of the anvil axis is fully accompanied by a length-change of the samples. After reaching the target strain most samples were immediately quenched by shutting off the electric current resulting in a temperature drop below 300 °C within a few seconds. In order to investigate post-deformation annealing, two experiments (SA 178, SA 181) were held at constant temperatures of 1300 or 1350 °C, respectively, for two hours after deformation.

The recovered samples were cut with a diamond wire saw, embedded in epoxy, ground and polished. The deformed pure shear samples were sectioned in the *x-z* plane of the strain ellipsoid, i.e. the section that contains the compression and the extension axis. The samples deformed by oblate strain were sectioned in the *x-y* plane, thereby containing the two extensional axes with a normal orientation of the compression axis. Imaging of the samples was performed using a Zeiss reflected light microscope at TUM, and a LEO Gemini 1530 scanning electron microscope (SEM) at BGI, with an acceleration voltage of 20 or 30 kV and 4 nA beam current in secondary electron (SE) or backscattered electron mode (BSE).

To compare experimental results with natural pallasite textures, two representative samples of the Seymchan meteorite were investigated in detail: (i) a high-resolution image of a large slab of Seymchan (#5168) was provided by the American Museum of Natural History (New York City, NY, USA); and (ii) a freshly prepared slice of Seymchan (#SEY-18-01) was purchased from a commercial dealer (KD Meteorites) and investigated at TUM using Zeiss binoculars, Zeiss reflected light microscopy, and a CCD camera.

The metal fraction in natural olivine aggregates was estimated by determining the area occupied by metal pockets after binarization of optical photographs of polished sections via digital image analysis using the public domain software ImageJ, developed by the National Institutes of Health, USA. Binary images were attained by manual tracing of individual melt pockets; the resulting area fraction is considered to be approximately equal to the volume fraction. In order to gain an approximate value of the metal fraction of pallasites described in previous literature, a threshold value was set adequate to distinguish between the light grey of the metal and the darker colours of the olivine, if high quality images were available (e.g. the Seymchan slab shown in Fig. 2 of (Yang et al., 2010)).

## 3. Results

### 3.1 Static annealing and pure shear deformation experiments

After static annealing only, the FeS melt distribution is characterized by a range of different-sized melt pockets that display dihedral angles above 60° in accordance with previous work (Fig. 3a-b) (Minarik et al., 1996; Walte et al., 2007). Melt pockets that are small compared to the size of adjacent olivine grains are located at grain triple and quadruple junctions; they have an equant shape and commonly display convex boundaries with the olivines (Fig. 3a). Larger pools surrounded by a higher number of olivine grains are more irregularly shaped and the olivine–melt contacts are smoothly curved both concave and convex shaped (Fig. 3b). The bottom panels of figure 3 show details of the interior of olivine aggregates from Seymchan. The textures closely resemble the features produced by the static annealing experiments including the high dihedral angles, the curved olivine metal boundaries and the difference in shape of the smaller and larger metal pockets (Fig. 3c-d).

After shortening by 7 %, small veinlets originating from large melt pockets intrude olivine grain boundaries by intergranular fracturing (Fig. 4a). At higher strains (11% shortening), veinlets locally interconnect adjacent melt pockets and form a network surrounding isolated olivine crystals (Fig. 4b). Similar troilite (FeS) and Fe-Ni metal containing intergranular veinlets are often found inside Seymchan olivine aggregates either isolated or forming an interconnected network between metal pockets (Fig. 4d-e); locally, the olivine aggregates are also cross-cut by transgranular faults (Fig. 4f).

Pure shear deformation at higher strain (13–24 % shortening) causes pervasive melt-aided brittle deformation of the olivine – FeS melt matrix, which created olivine fragments of various sizes by intragranular fracturing (Fig. 4c). In high strain zones the deformation mechanism can be described as melt-aided cataclastic flow producing olivine fragments whose size decreases with increasing strain, while angular grains are produced in lower strain areas and close to larger melt pools that promote intergranular melt intrusion.

In order to investigate the role of strain-rate, one experiment (M 719) was deformed at a strain-rate of $6\times10^{-4}$ $s^{-1}$, nearly one order of magnitude lower than the other experiments. In this experiment, olivines display more internal deformation features such as lattice bending and formation of sub-grain boundaries. Strain is localized into FeS-filled shear zones that are either anastomosing around large olivines or locally cross-cut them (suppl. Fig. 1). These high strain zones often contain micron-sized roundish olivine grains that may have been formed by rounding of small fragments during the longer deformation duration. These brittle-ductile microstructures are not found in pallasites but resemble results of olivine-FeS melt samples deformed at similar strain-rates in a previous study (Walte et al., 2011). Hence, the dominantly brittle structures observed in pallasites suggest high strain rates $>1\times10^{-3}$ $s^{-1}$ supporting olivine – metal mixing caused by an impact (see Appendix A for further discussion).

### 3.2 Extension-compression and oblate strain deformation experiments

Although some pure shear compression experiments contained a central cavity filled with Au or FeS (table 1), the melt remained largely separated from the olivine-FeS aggregate up to the maximum shortening attained (24 %). In order to promote formation of the characteristic olivine–metal mush and to better understand the conditions that facilitate the mixing, several experiments were deformed either by pure shear extension followed by compression or by an oblate strain geometry as described in the methods section.

During extension-compression the central Au reservoir partially collapsed forming melt filled fractures that intruded and mixed with parts of the adjacent olivine aggregate. This locally created olivine–melt mushes with isolated olivine crystals and dislodged coherent olivine aggregates that resemble the olivine aggregates that are observed in pallasites (Fig. 5). In their interior, the experimental olivine aggregates preserve melt pockets that stem from the pre-deformation annealing stage and intergranular veinlets similar to the low strain microstructures described in section 3.1. Hence, olivine aggregates preserve the older pre-deformation history of the experimental samples.

Samples deformed by oblate strain responded to the extension by the most efficient mixing of the Au melt with the adjacent olivine matrix observed in our experiments (suppl. Fig. 2). However, rather than predominantly producing olivine fragments as during high-strain pure shearing, many of the olivines embedded in the Au matrix display an angular shape (Fig. 6a-b). For comparison different areas of Seymchan #5168 are shown that are either dominated by angular olivine or olivine fragments (Fig. 6c-d).

In order to investigate the role of pre-existing melt in the olivine matrix, one oblate strain experiment was performed with a sample containing FeS-melt free olivine surrounding the central Au-filled cavity (SA 176). In this case, the deformation resulted in the formation of large melt-filled fractures originating from the central cavity but did not form an olivine–melt mixture suggesting that pre-existing melt in the olivine matrix is important to facilitate matrix disintegration (suppl. Fig. 2).

### 3.3 FeS–Au microstructures as analogues for troilite textures

Areas of our deformed samples in which Au melt mingled with FeS melt revealed microstructures that closely resemble troilite textures found in our Seymchan samples (Fig. 7) and described previously (Buseck, 1977): (i) Smoothly curved metal-sulphide contacts and a preferable location of troilite in fractures and veinlets, and enclosing groups of small olivines. (ii) The bulging out of troilite from a fracture, forming a drop-like shape at the entrance, or drawing the surrounding Fe-Ni liquid into narrow fractures (Fig. 7a, d, see also Fig. 12 in Buseck (1977)). (iii) If fractures contain both liquids, Fe-Ni generally occupies the wider part and the phase boundary is generally convex towards troilite (Fig. 7b, e). We suggest that these textures can be explained by the lower surface energy of troilite compared to Fe-Ni as discussed in section 4.1.

**3.4 Post-deformation annealing**

Indicators for annealing in angular pallasites such as microscopically rounded olivine edges (Buseck, 1977) and rounding of small olivine fragments (Scott, 1977) can be used to constrain the post-deformational thermal history of pallasites. Two exploratory experiments were conducted to investigate annealing processes. The first experiment (SA 178) reproduced the oblate strain experiment SA 177 but was annealed at 1300 °C for 2 h after deformation, while the second experiment (SA 181) was deformed and annealed at 1350 °C and only contained FeS as the melt phase. The first experiment revealed grain boundaries and healed fractures decorated with small FeS melt droplets and rounding of olivines with a diameter below 10-15 micron (Fig. 8). Pinch-off of veinlets filled with high-dihedral-angle melt is known from previous experiments (Walte et al., 2011) and represents an additional indicator for annealing. The microstructure of the second higher temperature experiment displays an even greater textural equilibration with fully rounded olivines with diameters up to ca. 40 microns (suppl. Fig. 3). For comparison, veinlet pinch-off is rare in Seymchan and is only observed in some intragranular fractures with a diameter below ca. 10 μm (Fig. 8c). On the other hand, rounding is generally observed in small olivines with grain sizes below ca. 300 μm and occurs both in grains surrounded by troilite and Fe-Ni metal (Fig. 8c bottom). Here, we consider the troilite-enclosed grains, because the resulting grain sizes can be directly compared to the grain sizes of rounded olivine within FeS melt pockets of our experiments.

Based on experimental results and theoretical considerations, Saiki et al. (2003) suggested that the timing of olivine rounding is proportional to the cubed grain size. Hence, if grains with a diameter of ca. 10-15 μm are rounded after 2 h annealing at 1300 °C, we expect that olivines with a diameter of 300 µm would be rounded within less than ten years if annealing conditions were similar. At 1350 °C this rounding would only take about three months for grains surrounded by troilitic melt, which may be more realistic, since the temperature after deformation was probably higher than 1300 °C. While more systematic experimental studies employing a more precise temperature control are needed in the future, it is safe to suggest that cooling of the pallasites below the metal solidus temperature occurred on geologically short timescales.

## 4. Discussion

### 4.1 Formation mechanisms of pallasite textures

*Olivine textures.* The mechanisms to form angular and fragmental olivine by inter- and intragranular fracturing of olivine aggregates suggested by Scott (1977) was confirmed by our experiments. Our post-deformation annealing experiments also reproduced the subsequent olivine rounding, which may be fast if high temperatures persisted (≥1350 °C). This implies geologically very rapid cooling of angular and fragmental pallasites after deformation likely within months to years. If high temperatures persisted for longer periods of time, rounding may even be a viable mechanism to form the large rounded olivines in round-type pallasites suggested previously (Scott, 1977; Solferino and Golabek, 2018; Solferino et al., 2015). However, our experiments support previous suggestions that the large olivines with round boundaries found in Seymchan are relicts of the pre-deformation annealing stage rather than a result of post-deformational annealing (Fig. 5) (Yang et al., 2010; Scott, 2017).

*Olivine aggregate fragmentation*. Olivine aggregate disintegration and olivine–metal mixing is the signature process preserved in angular and fragmental pallasites such as Imilac and Admire and mixed-type pallasites such as Seymchan. Pallasite textures show that disintegration is coupled with the influx of metal melt, which leads to a loss of cohesion and inflation of the olivine aggregates. Our experiments simulate the process by oblate strain deformation, and show that the previous existence of metal melt in the olivine aggregates and an additional external source of melt are the key elements of this process. The role of the dispersed metal pockets is likely to weaken the grain boundaries thereby favouring intergranular fractures over intragranular breaking of olivines. It follows that the metal pockets must have been liquid *before* aggregate inflation and further metal-melt influx, which supports the textural evidence for liquid metal pockets presented in section 3.1 and suggests that the impact was not the primary heat source. While angular olivines were formed by oblate strain deformation, olivine fragments were dominantly produced by high strain-rate pure shear deformation. We suggest that the latter simulates the initial deformation caused by an impact, while the former simulates extensional stress and a widespread disintegration of the host rocks driven by the subsequent intrusion of external metal melt from the impactor. The appearance of different pallasites would then be determined by the degree that these processes act at the particular location with respect to the impact site. For example, Seymchan slab #5168 (Fig. 1a) exhibits discrete areas that are dominated by angular olivines and areas dominated by smaller olivine fragments (Fig. 6c-d), which suggests sample-scale deformation localization into the latter areas that was followed by melt influx inflating both regions. Predominantly fragmental pallasites such as Admire and predominantly angular pallasites such as Esquel or Imilac may accordingly sample regional-scale deformation localization within the mantle volume affected by the impact.

*Metal pockets in olivine aggregates.* The olivine–metal pocket textures that are preserved inside olivine aggregates are characteristic of high-dihedral-angle melt-bearing systems undergoing static recrystallization and can be explained as follows: the occurrence of metal pockets of various sizes is energetically favourable for high surface energy melt that promotes an uneven melt distribution (Walte et al., 2007). The equant shape of small melt pockets is determined by the resulting high dihedral angle (von Bargen and Waff, 1986), while the uneven shape of the large pockets is due to their lower surface to volume ratio, making them more susceptible to distortions during ongoing grain growth (Walte et al., 2003). Hence, olivine aggregates preserve a coarse-grained, equilibrated olivine plus metal melt texture, indicating long-term static grain growth at high temperature (Solferino and Golabek, 2018). In order to distinguish these metal pockets from the second generation of metal intruded during the collision we henceforth call them "primordial".

*Troilite textures.* While sulphur is highly soluble in Fe-Ni melt, it does not fit into the crystalline structure of taenite and thus troilite (FeS) is thought to exsolve upon crystallization of the Fe-Ni-S liquid close to 1000 °C. Hence, troilite would only be present as a separate phase after the mixing event between the metal and the olivines, which differs from the experiments where FeS and Au are present as immiscible liquids from the start. However, the resulting textures are surprisingly similar between the experiments and pallasites (Fig. 7), which suggests that many troilite textures are melt-pseudomorphs as previously suggested by Buseck (1977). The textural details can then be understood by considering the lower surface energy of FeS compared to both Au liquid and crystallizing taenite. Hence, the lower wetting angle of FeS in contact with the olivine walls causes the observed bulging of the meniscus of Fe-Ni towards troilite in veinlets and explains that troilite often surrounds groups of small olivine grains and occupies confined spaces such as fractures and veinlets. These locations are all characterized by a high grain boundary area to volume ratio and are thus preferred sites for the lower surface energy liquid. Based on the structural continuity from narrow troilite-bearing fractures inside olivine aggregates to the breakup of the aggregates at their margins we suggest that most troilite textures record the final stage of a single deformation event rather than a later troilite mobilization episode as suggested previously (e.g. Ulff-Møller et al., 1998).

### 4.2 Comparison of Seymchan with other main group pallasites

Seymchan has an unusual classification history, being first classified as an iron meteorite (Scott and Wasson, 1976), later as an ungrouped pallasite (Wasson and Wang, 1986), and finally as a main group pallasite (van Niekerk et al., 2007). Seymchan shares many features with angular and fragmental pallasites such as the occurrence of olivine aggregates surrounded by mush-like regions containing olivine fragments and angular olivines in a metal matrix. The Seymchan olivine aggregates are characterized by a large amount of equilibrated metal-pockets, which is reflected in the description of Seymchan olivine aggregates as "Brenham-like" by Yang et al. (2010). The primordial metal fraction of our two Seymchan samples is 9-13 vol% (Fig. 1), and the olivine aggregates in the large Seymchan slab pictured in Fig. 2 of Yang et al. (2010) contain ca. 15 vol% primordial metal pockets, which appears to be the upper limit found in olivine aggregates of Seymchan. For comparison, Brenham and other round-olivine type pallasites contain a higher metal fraction of ca. 25-30 vol% (Buseck, 1977), setting them apart from Seymchan olivine aggregates, despite the resemblance of some olivine-metal contacts. Primordial metal content of olivine aggregates in other angular pallasites has not been systematically investigated, yet. In fact, to our knowledge a separate source of the metal melt pockets inside olivine aggregates has only been considered in one study that examined a large slab of pallasite Esquel (Ulff-Møller et al., 1998). Olivine aggregates in that sample contain up to 8 vol% primordial metal (Fig. 1 of Ulff-Møller et al. (1998)), which is similar in volume and appearance to our Seymchan sample #SEY-18-01 (Fig. 1b). A preliminary survey of available literature, collections, and online images of samples of other main group pallasites has shown that large olivine aggregates generally contain primordial metal pockets, including Finmarken (suppl. Fig. 4), Imilac (large slab exhibited in the "vault" on the 1st floor of the Natural History Museum, London), Admire (photographs of commercially available slices), Fukang (Figs. 1 and 4 of Dellagiustina et al. (2019)), and Mount Vernon (e.g. Fig. 2 of Scott (1977)). We estimate a range of primordial metal of ca. 5-15 vol% that is preserved in olivine aggregates of the various main group pallasites with Admire at the lower end of the spectrum, Esquel and Imilac in the middle of the range, and Seymchan at the top with the highest percentage of primordial metal. The general presence of pre-existing metal pockets in olivine aggregates of both angular and fragmental pallasites is compatible with our observations that a dispersed melt facilitates matrix breakup.

### 4.3 Formation of pallasites and the evolution of a pallasite parent body

Our results indicate that two generations of metal are present in main group pallasites providing new constraints on pallasite evolution. The first generation is preserved as primordial metal pockets in olivine aggregates and characterized by long-term static annealing and the second generation intruded during a short-lived deformation episode that was followed by freezing within months to years. The timescale of the pre-deformation annealing stage can currently not be quantified, but geological timescales are likely required for attaining cm-scale grains, since the high dihedral angle metal pockets slow down grain growth by a process similar to Zener pinning (Walte et al., 2007).

We present a new evolution model for a pallasite parent body (PPB) that is consistent with these results and previous constraints (Fig. 9): (a) Radiogenic heating of a chondritic PPB precursor by $^{26}Al$ initially producing sulphur-rich melt crossing the Fe-S solidus (≈980 °C (Brett and Bell, 1969)) and triggering the onset of differentiation (Fig. 9a). As the fraction of the newly formed melt crosses a percolation threshold (5–10 vol% (Bagdassarov et al., 2009; Walte et al., 2007; Yoshino et al., 2003)), it becomes mobile thus forming a small core. This stage could be represented by acapulcoite meteorites that show a mobilization of sulphide melt but remained below the silicate solidus (Floss, 2000; McCoy et al., 1996). (b) As heating continues, partial melting of silicates begins at ca. 1050-1100 °C (Mare et al., 2014). This stage in planetesimal evolution may be represented by lodranites, meteorites that are considered to have lost both sulphide and silicate melt components (Floss, 2000; McCoy et al., 1997). Laboratory experiments have shown that the formation of silicate melt causes breakdown of metallo-sulphidic melt-networks, thereby halting further core-mantle differentiation (Cerantola et al., 2015), while allowing for gravity-driven percolation of buoyant silicate liquids (Connolly et al., 2009; Lichtenberg et al., 2019) thereby suggesting that sulphide loss generally predates silicate melt loss (Fig. 9b). Further heating causes temperatures to rise above or close to the Fe-Ni liquidus, which is accompanied by continuous fractional melting removing most non-olivine silicate components from the mantle (Boesenberg et al., 2012; Lichtenberg et al., 2019), while the metal melts remain trapped within the olivine matrix (Cerantola et al., 2015). (c) The high temperatures also facilitate static olivine grain growth (Solferino and Golabek, 2018; Solferino et al., 2015) and textural equilibration of the olivine-metal melt restites, thus creating the features preserved in olivine aggregates (Fig. 9c). (d) A PPB is disturbed by an impact of a differentiated body (Tarduno et al., 2012) that causes intense deformation closely followed by the injection of the impactor's residual core metal into the partially disintegrated mantle (Fig. 9d). (e) Rapid cooling until reaching the Fe-Ni-S solidus preserves the veinlets and prevents rounding of large olivines, likely caused by exhumation in the aftermath of the impact (Fig. 9e). A viable way to achieve this is impact rebound, as demonstrated for impact events on planetesimals (Ciesla et al., 2013; Jutzi et al., 2013). Once the process stalls, pallasite material remains immobile and slower conductive cooling resumes, possibly slowed down by an insulating post-collision regolith layer (Tarduno et al., 2012) allowing for the formation of Widmanstätten patterns (Yang et al., 2010).

Previous pallasite formation models either focussed on fractional melting of chondritic material near the core-mantle boundary (Boesenberg et al., 2012), or considered an already completely differentiated upper mantle that was modified by an impactor (Bryson et al., 2015; Tarduno et al., 2012). While the former model also acknowledged texture alteration by impacts, it does not account for the initially rapid cooling indicated by the preserved veinlets and the position in the shallower mantle during further cooling. On the other hand, the two-body scenario does not explain the olivine–metal melt equilibrium recorded in olivine aggregates. Our model presents a synthesis, including both a differentiation and an impact stage, with two separate generations of metal melt. Thus, it provides a simple explanation for the origin of the primordial melt pockets, since a uniform dispersion of high dihedral angle metal melt is difficult to achieve by other mechanisms (as our melt-free matrix deformation experiment illustrates – section 3.2).

A test of our two-stage model would be to compare the composition of small isolated primordial metal pockets with the outside metal in pallasites. If their origin is distinct, their composition may also differ (Ulff-Møller et al., 1998).

The planned NASA orbiter mission to the asteroid 16 Psyche may present a chance to directly investigate a PPB. The most recent density estimations for the asteroid suggested a metal fraction of 30 – 60 vol%, which is compatible with a pallasitic composition of Psyche rather than an exposed core as previously thought (Elkins-Tanton et al., 2020). If a PPB, the mission might be able to discriminate between the different models: The presence of a core overlain by a pallasitic mantle connected to impact structures or evidence for ferrovolcanism would support external-metal models including our hybrid model or the diking model of Johnson et al. (2019), respectively. The validation of pyroxene at the surface of Psyche (Drummond et al., 2018) would be also compatible with our mechanism of dunite – pyroxenite/basaltic differentiation of the PPB mantle. On the other hand, a gravitational homogenous pallasitic body would confirm the destructive impact model of Yang et al. (2010). Finally, internal-metal formation models that predict a layer of pallasite material at the core mantle boundary could be verified if the rocky mantle of Psyche has been removed.

**4.4 Olivine aggregates as natural laboratories**

Olivine aggregates are natural samples of texturally equilibrated silicate–metal melt aggregates. As such, they present natural laboratories that can be applied to questions of planetary core-mantle differentiation and the distribution of metallic melt in silicate systems. Laboratory experiments have suggested metal melt percolation thresholds of ca. 5 vol% (Yoshino et al., 2003), that may be even further depressed to levels below 1-2 vol% by melt network hysteresis (Ghanbarzadeh et al., 2017) or by deformation (Bruhn et al., 2000), which would allow for efficient core-mantle differentiation without a magma ocean stage. The much higher primordial melt fraction of Seymchan olivine aggregates of ca. 9-15 vol% indicates the contrary, at least for the case of PPBs. We have demonstrated that these primordial melt pockets must have been molten for extended periods of time to promote grain growth and to allow for an efficient fragmentation to form the olivine–metal mixture preserved in pallasites. If these pockets were interconnected during that period of time, the metal melt would have gravitationally segregated due to the large grain sizes (Lichtenberg et al., 2019). However, such high effective percolation thresholds are compatible with our PPB formation model. Here, efficient metal melt percolation is initially hindered by production of silicate melt long before the Fe-Ni-S components are fully molten (Cerantola et al., 2015). Subsequently, the aggregates have sufficient time to undergo textural annealing as the temperature slowly rises towards the metal liquidus. Annealing causes pinch-off of the narrowest tubules in high-dihedral-angle networks increasing the percolation threshold and creating immobile melt pockets (Bagdassarov et al., 2009; Walte et al., 2007).

## 5. Conclusions

In the introduction we posed three questions on pallasite textures and argued that any model for their formation must provide plausible answers. We conclude with our answers for the reader to scrutinize:

*1. Why is olivine the dominant and often singular silicate phase in pallasites?*

Our experiments and observations do not deal directly with the petrological evolution of pallasites. However, our textural interpretations suggest high temperatures >1450 °C for an extended period likely induced by the decay of radiogenic isotopes such as $^{26}Al$. This supports the model of Boesenberg et al. (2012) suggesting that pallasite host rocks are restitic dunites after high-grade fractional melting and silicate melt removal. We suggest that the mantle of the PPB was dominantly of dunitic composition with only minor pyroxenes, while possibly pyroxenitic and basaltic upper mantle and lithosphere layers remained un-sampled.

*2. Which process led to mixing between the olivine and the metal phase?*

Pallasite formation models can be grouped as internal and external according to the source for the metal. Our model is an internal-external hybrid; we suggest that 5-15 vol% of metal in angular pallasites have an internal origin remaining in the mantle after partial differentiation in the form of primordial melt pockets, while the rest of the metal (20-30 vol%) was externally derived from an impactor. The impact resulted in deformation of the mantle followed by expansion caused by the influx of core-metal from the impactor. The primordial melt pockets were instrumental for allowing pervasive intrusion of the external melt into the dunites producing the characteristic olivine–metal mixture.

*3. Why has the large density contrast between the olivines and the presumably molten metallo-sulphide components not led to a subsequent gravitational separation?*

The answer to the "pallasite problem" is twofold: (i) Primordial melt pockets in olivine aggregates prove that a moderate metal melt-fraction of up to 15 vol% can be retained in the mantle for long periods of time. (ii) After further metal melt injection from the impactor, rapid cooling until reaching the Fe-Ni-S solidus prevented gravity-driven separation of metallic phases from the olivine.

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**Appendix A Supplementary Materials**

Supplementary materials can be found online.

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## Figure captions

**Fig. 1.** Photographs of (a) Seymchan slab #5168 of the American Museum of Natural History, New York and of (b) Seymchan slice #SEY-18-01 with textural interpretations. Both samples display zones containing angular and fragmental olivines and olivine aggregates of various sizes. The metal pockets in the aggregates are interpreted to predate the surrounding metal–olivine mush zones, hence termed 'primordial' (see text for discussion).

**Fig. 2.** (a) Inside of the SAPHiR press. Six primary anvils transmit the force on a central stack of secondary anvils that contain the sample assembly (6-6 anvil geometry). (b) Sketch of the assembly used for the experiments. (c) Optical micrograph of a deformed sample with a central cavity filled with gold.

**Fig. 3.** (a, b) Reflected light micrographs of microstructures after 89.5 h static annealing. (c, d) Binocular images of equilibrated Fe-Ni metal pockets in Seymchan #SEY-18-01 indicating textural equilibrium.

**Fig. 4.** Pure shear deformation experiments (top, SEM backscatter images) compared to details of Seymchan olivine aggregates (bottom, optical micrographs). (a-c) Intergranular veinlets originating from melt-pockets after 7% and 11% vertical shortening, respectively, and pervasive cataclastic microstructure after 20 % shortening dominantly creating olivine fragments. (d, e) Veinlets interconnecting equilibrated metal pockets. (f) A fault (dashed orange line) cross-cuts an olivine aggregate. Fault-related olivine fragments 'float' in equilibrated metal pockets (black arrows) indicating that the metal was predominantly molten during the deformation.

**Fig. 5.** Olivine – metal mush in (a) experiments and (c) Seymchan showing adjacent round olivines (red arrows) and smaller olivine fragments. The former olivines are relicts of pre-deformation annealing. (b) Olivine aggregates in experiment (6.5 % extension followed by 13 % shortening) and (d) nature. Note 'primordial' melt pockets (white arrows) that stem from pre-deformation annealing and veinlets produced during deformation (yellow arrow). All images are optical micrographs.

**Fig. 6.** Formation of fragmental and angular olivines by different strain geometries. (a) Pure shear deformation creates olivine fragments by predominantly intracrystalline fracturing. (b) Oblate strain (extension in the image plane) forms angular olivines by intercrystalline fracturing. (c-d) Olivine – metal mush zones in Seymchan are locally dominated by fragmental or angular olivines, respectively, suggesting deformation localization. The high metal fraction suggests that both regions subsequently underwent extension by metal influx.

**Fig. 7.** Optical micrographs of Au – FeS melt microstructures in deformed samples (top) compared to Fe-Ni – troilite textures in Seymchan pallasite (bottom). These textures are best explained by liquid immiscibility  (see text for discussion).

**Fig. 8.** Optical micrographs of (a-b) experimental microstructures and (c) Seymchan textures. (a) Oblate strain inter- and intragranular fracturing in the olivine – FeS melt matrix (top) and angular olivine – Au mixture (bottom). (b) 2 h annealing after deformation causes pinch-off of most FeS melt veinlets and creates round olivines in the mush zone. (c) Seymchan textures indicating annealing. While intergranular veinlets are generally continuous in Seymchan, some narrow intragranular fractures have pinched-off (top). The smallest olivine grains in Seymchan generally display a rounded shape (bottom).

**Fig. 9.** Schematic diagram for the evolution of a PPB and the concurrent texture evolution (magnifications). Colours of magnifications are chosen in order to be comparable with the textural mapping in Fig. 1. (a) Formation of sulphur-rich melts in a chondritic precursor body and partial core differentiation via percolation (wavy arrows). (b) Crossing of the silicate solidus traps remaining metal melt in the matrix while partial melting of the silicates is accompanied by silicate melt ascent (wavy arrows). (c) Completion of partial differentiation without a magma-ocean stage leaves a mantle largely consisting of olivine (+/- orthopyroxene) plus remaining primordial metal melt. (d) An impact causes deformation of the mantle (top magnification) closely followed by intrusion of the impactor's core melt (bottom magnification). (e) The impact rebound causes freezing of the metal melt followed by slow conductive cooling. Credit: Reiner Müller.