Vasileios Chatzaras (Referee)

Dear Authors and Editor,
This manuscript presents a microstructural study of the deformation mechanisms in the basic amphibolites of the metamorphic sole beneath the Oman peridotite. The microstructures were analysed with Electron Backscatter Diffraction (EBSD), and mineral composition was estimated and mapped with Electron Probe MicroAnalysis (EPMA).
The aim of the manuscript is clear. Study the deformation history of the amphibole- bearing rocks of the metamorphic sole, to understand how crustal material of the subducting plate is being accreted to the base of the overlying mantle wedge. The Authors analysed a suite of six samples from three different locations of the Semail ophio- lite. The samples were collected from the HTa and HTb sub-units defined by Soret et al. (2017), and from distances up to 40 m beneath the thrust fault contact with the overlying peridotites. The Authors described and quantified a range of microstructural parameters (e.g., mineral assemblage, microstructural configuration, grain size, shape preferred orientation, grain shape aspect ratio, and crystallographic preferred orientation) and amphibole composition, to understand how they vary with distance from the peridotites, and thus, degree of retrogression. The combination of the microstructural and chemical data led to the interpretation that a range of mechanisms accommodated deformation during the formation of the metamorphic sole. The Authors provide a conceptual model of how the variations in the strength of the basic amphibolites and the overlying peridotites may control the mechanical coupling between the two plates and the accretion of the crustal material at the base of the mantle wedge.

This is a very interesting manuscript, on a topic that is timely and of broad interest, given the long-standing interest of the Earth Sciences community in subduction processes. However, I feel that: 1) some of the interpretations regarding the dominant deformation mechanisms are not fully supported by the data, 2) the manuscript could benefit from a more reader-friendly way of presentation of the results, and 3) this manuscript has significant overlap with the illustrations published in Soret et al. (2017), which reduces the originality of this research article.

The data presented in this work should be published in a revised manuscript, in which the Authors could consider addressing the following points.

We would like to thank Vasileios Chatzaras for his detailed review and comments. Please, find our answers here after.

Specific comments:
1) Figure 1a,e,f, Figure 2 (entire), and Figure 5b,e,f,g have already been published in Soret et al. (2017). I justify the repetition of Figure 1 because it is the intro Figure and summarizes existing knowledge, and Figure 2d because it is used as a base-image for showing the locations of the EBSD maps, however, I find the repetition of the rest field photographs and photomicrographs included in Figures 2 and 5, not "flattering" for an original article. Moreover, I am wondering why the photomicrographs in Fig. 2d, and Fig. 5e,g have been reversed compared to how they have been previously published (I am comparing with Fig. 5a,d,f in Soret et al., 2017).

Indeed these figures were already published in Soret et al. (2017). However, they are also presented herein as we think that they bring crucial and new information for the reader, and not for a "flattering" purpose.

– As mentioned by the reviewer, Figure 1 is useful to introduce in a nutshell both the large-scale problematic and the object of the study. Therefore, at several places in the introduction, the reader is invited to read more details in Soret et al. (2017).
– Fig. 2 re-uses only few but representative figures from Soret et al. (2017) which outline crucial characteristics of the structure of the Semail metamorphic sole.
– Microphotographs presented in Fig. 5 are used to highlight typical microstructures found in the metamorphic sole that were not described in Soret et al. (2017).
However, and as suggested by the editor, the article Soret et al. (2017) is now properly cited in the new captions of the figures.
Some figures have been reversed for more consistency on the apparent sense of shear. This is now detailed in the captions.

2) Following on from (1) above. In page 3, lines 24-29 and Figure 1e, the Authors present data for the Ti-content of amphibole in the metamorphic sole of the Semail ophiolite. However, Figure 1e, which corresponds to Figure 7k of Soret et al. (2017), only includes data from the exposure of the metamorphic sole in Sumeini. Instead, the Authors could compile the data included in Figures 7j, k, l in Soret et al. (2017) to make a new plot that summarizes the Ti-content of amphibole from the three studied areas of the Semail ophiolite.

As mentioned above, Figure 1 is only used to outline some characteristics of the metamorphic sole. As our study specially focuses on the outcrop from Sumeini, we only show the petrological data from this area. A new plot (Ti vs. distance) cannot be make as the units from the sole do not share the exact same thickness along strike. However, in the text we refer to Soret et al. (2017) for more details.

3) I would strongly recommend that the Authors include in the manuscript EBSD maps and/or CPO data from all the samples that they analysed from the three studied lo- cations of the metamorphic sole. The number of samples (six in total) that they have analysed with the EBSD technique, allows them to do so. Particularly, data from the only sample from the HTb zone, which was collected from Khubakhib, should be included in the manuscript rather than the supplementary information. Also, it is not clear to me what complexities the Authors try to overcome by presenting in the current version of the manuscript only data from the Sumeini area (Page 4, Lines 14-16).

The requested figures were already provided in supplementary material (Table 1).

4) I found it difficult to follow how the different microstructural parameters change with distance beneath the contact with the peridotites. My suggestion would be to make a new figure (modified version of Fig. 9c) that will include in the vertical axis the distance from the peridotites, and in the horizontal axis the range of the microstructural parameters (J-index, M-index, grain size, axial ratio, deviation of the mean orientation of the grain long axis from the foliation -SPO-, etc.) that were quantified for each mineral. Data from all six samples should be included in this plot.

We disagree with the reviewer's comment. Changes in microstructures with the distance to the peridotites are already highlighted in every figures of the manuscript (EBSD maps, CPO, J-index, SPO and grain size (see the supplementary material for those two). We made a special effort to present the sample SE13-67 (the closest to the peridotites) always before SE13-69 and SE13-76 (the furthest away from the peridotites) both in the text and in the figures. In every caption, this ordering is clearly specified.

5) The manuscript would benefit from the addition of detailed geological and structural maps of the three sampling areas. The Authors could plot on each map the rock fabric (i.e. foliation and lineation) for each of the analysed samples. Importantly, these maps would allow them to describe the sense of shear in the geographic reference framework, rather than the thin-section framework as they currently do.

Cross-sections are available in Soret et al. (2017). A representative and schematic log of the base of the Oman ophiolite is provided in Fig.1c where it is shown the structural position of the samples from Khubakhib, Sumeini, and Wadi Tayin. The structural maps requested by the reviewer are available in Cowan et al. (2014) or in Gnos (1998).
Such maps are not meaningful in our study as the analyzed samples were not structurally oriented on the field. Therefore, our interpretations can only be based on the thin-section framework. As a result, our study focuses on the mechanical behavior of amphibolites in general, without specific geographic reference framework.

In the new version of the manuscript, it is more clearly highlighted that cross-sections and structural maps can be found in Soret et al. (2017) and Cowan et al. (2014), respectively.

6) Some additional information could be included in the Methods section. Description of the method (e.g., linear intercept, equivalent circular diameter) that was used to estimate grain size should be included. Moreover, the Authors need to explain which mean (arithmetic or geometric) of the grain size distribution they report in Table 1. How were the thin sections, and thus the EBSD maps, produced relative to the rock fabric (i.e. foliation and lineation)? This information should be added in all the captions of Figures with either EBSD maps or photomicrographs. Also, the lower hemisphere projections of CPO data are not in the typical plotting framework with vertical foliation and horizontal lineation. Could the Authors comment why is that? The plots could be rotated so as the CPO to be reported into the usual plotting framework.

The definition for the grain size calculation (i.e. equivalent circular diameter has been added. The mean distribution corresponded to the mean arithmetic. In the new version of the text, however, the median grain size is now provided (instead of the mean) as it is more meaningful (less sensitive to the few large crystals).

The PF are not perfectly oriented since some thin sections were not perfectly made perpendicularly to the foliation and parallelly to the lineation (sometimes hardly visible on the hand specimen). Therefore, we chose to define the lineation on the PF by the amphibole c-axis maxima (point "X").

7) The preferred interpretation for the concentration of low-angle misorientation axes around the [001] crystallographic axis in amphibole, is micro-fracturing along the [001] axis combined with small rigid rotations (Page 12, Lines 10-12). In this case, there should be a spatial correlation between subgrain boundaries and intragrain microfractures, e.g., the healed microfractures shown in Fig. 5h. Although such correlation is implied in Fig. 6c,h, the photomicrograph and the EBSD map are too small to observe such features. The Authors could provide some more detailed EBSD maps that would support their preferred interpretation. It would also be interesting to explore what is the orientation of the misorientation axes associated with the low-angle boundaries in the new EBSD maps, as well as in Figures 6e,h,i. An alternative interpretation for the observed distributions of the misorientation axes, could be the formation of low-angle boundaries with both tilt and twist components, due to operation of more than one slip systems (e.g., Díaz Aspiroz et al., 2007 also cited in the manuscript). Is there anything

to rule out this interpretation? If not, and considering the strong concentrations of low-angle misorientation axes subparallel to the [001] axis in the samples from the HTa sub-unit, what would be the implications on the preferred interpretation that dislocation creep does not contribute significantly to the high temperature deformation of amphibole?

Deformation mechanisms in amphibole appear particularly complex. It is true that based on evidence of cristal plasticity, Diaz Aspiraz et al. (2007) suggested that the observed low angle misorientations resulted from a combination of multiple slip systems (without any other microstructural arguments).

However, amphibole in our study shows only few low-angle misorientations, and even rarer optical evidence for intracrystalline plasticity. Therefore, it is very unlikely that amphibole deformed plastically. On the other hand, amphibole shows numerous micro-fractures and fractures (parallel to (001) and (010) planes as also observed by Diaz Aspiroz et al.). Contrary to the reviewer's comment, it is clear that these brittle deformation features coincide spatially with the low angle misorientations (Fig.6a,e). We therefore suggest that frictional slips on specific planes explain the presence of low misorientation angles and their preferred distribution around the b and c axes.

Fig. 6a has been improved to ease the comparison between two undeformed and deformed amphibole crystals.

8) Following on from (7) above. The Authors attribute the patchy distribution of the Ti-high areas and the crystallization of Ti-medium/low amphibole to dissolution- precipitation creep. One of the main arguments is the spatial correlation between microfractures and Ti-medium/low areas. Microfracturing enhances permeability, fluid circulation and retrograde hydration, promoting dissolution-precipitation creep. Although this is a valid interpretation, the Authors should discuss and exclude alternative interpretations. Specifically, I am thinking the possibility that low-angle boundaries (potentially not associated with microfracturing) have acted as elemental pathways that enhanced in-grain element diffusion (e.g., Chapman et al., 2019). The manuscript would benefit from a more detailed characterization of the spatial relationships between Ti- medium/low areas and subgrain boundaries, which is relevant to comment 7, above, regarding the relationship between microfractures and low-angle boundaries.

This is an interesting point. However, such mechanism is very unlikely since we have demonstrated that low angle boundaries do not result from plastic deformation but from brittle deformation.
Most amphibole crystals show this patchy zonation but only rare show misorientations (as previously explained). It is also clear that the heterogeneous amphibole composition correlates with the fractures cutting across the crystal (Fig. 6c,h,l). Moreover, lobate amphibole boundaries and the crystallization of ilmenite and low Ca-plagioclase after amphibole are additional evidence supporting the dissolution-precipitation creep.

The description of the correlation between Ti amphibole zoning and the microfractures has been improved in the new manuscript.

9) Unless I missed something, I did not find in the supplementary information any figure captions or text describing the data from the samples in Khubakhib and Wadi Tayin areas. The Authors provide only figures. At a minimum, figure captions should be added.

Extended captions have been added. More details are provided in Soret et al. (2017).

More specific comments and technical corrections (on text and figures) are provided on an annotated version of the manuscript.

Suggestions and corrections have been taken into account.

Papers cited:

Chapman, T., Clarke, G. L., Piazolo, S., Robbins, V. A. and Trimby, P. W. (2019), Grain scale dependency of metamorphic reaction on crystal plastic strain. J Metamorph Geol.

Best wishes, Vasilis Chatzaras

Please also note the supplement to this comment: https://www.solid-earth-discuss.net/se-2019-28/se-2019-28-RC1-supplement.pdf

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Marco Herwegh (Referee)

Dear authors, dear editor

This article deals with the microstructural evolution of the metamorphic sole of exhumed mantle in Oman using samples form three different sites. Based on vertical sample transects, the authors investigate microfabric changes as a function of increasing distance to the hanging wall peridotite and attribute these changes to changing deformation processes as a function of progressive exhumation. They excellently document changes in mineral assemblages, phase distributions, mineral chemistry and geometric microstructural (grain sizes, grain aspect ratios) aspects as well as CPOs.

Based on these data they come up with a generalized conceptual model where on the prograde metamorphic path dehydration reactions lead to the formation of amphibole, plag, cpx, grt aggregates where the latter two being rigid inclusions in a weak amphibol-plag matrix. Fluid assisted grain fracturing lead to grain size reduction, where then fine-grained mixed polymineralic aggregates deformed by diffusion creep processes (including grain boundary sliding and mass transfer processes). Cpx and grt clasts reduce their grain size further by fracturing and dynamic recrystallization, respectively. With reducing temperature cpx and grt are strongly altered and a matrix consisting of amphibole and plagioclase dominates. Seeing evidences for subgrain rotation formation in amphiboles, the authors claim a transition to dislocation creep, although still being in a polymineralic system. The formation of shear bands with precipitation of epidote as well as nucleation of new amphiboles indicate an important role of fluids down to these retrogressed conditions. Linking the microfabric evolution to qualitative rheo- logical considerations, inferences about the stability and mechanical coupling across the plate interface are finally made.

The article is of great scientific interest for the subduction zone community particularly when interested in the mechanical coupling and the role of potential grain scale processes. The authors excellently document a nice suite of microfabric transitions giving important insights into the role of grain-scale processes in this environment. Using quantitative microstructural analysis, EBSD as well as microchemistry, they applied state of the art analytical techniques to achieve their aimed goals. The article is very well written and structured as well as excellently illustrated. Despite all these positive aspects, I have some major scientific points which are either not sufficiently presented or, in my opinion even wrongly interpreted, needing a careful re-examination during the revision of this manuscript.

We would like to thank Marco Herwegh for his detailed review and comments. Please, find our answers here after.

These points are:
1) One of the major goals of this manuscript seems the link between microfabric and crustal-scale interplate mechanics. For me the already at the microscale important gaps exist. Despite spreading bits and pieces of rheological terminology in a not very organized manner in results and discussion sections, a proper sequential description of arguments/hints on rheology at the different stages of microfabric evolution and a subsequent thorough discussion is currently missing. For example, already in the re-sults terminology like 'load-bearing framework' etc. is used. Here the authors need first to describe which parts of the polymineralic aggregates show brittle and which ductile processes (what they in parts do well) not going further at that stage. In the discussion, these findings have then to be revisited and thoroughly treated in a rheological point of view. Which are the mechanically weak phases, which ones are strong? Please use for this argumentation the microstructural criteria presented before. See next point.

The result and discussions sections have been thoroughly reworked to better describe, distinguish and discuss the different deformation mechanisms in the amphibolite.

The term "load-bearing framework" has been removed.

2) Currently the discussion dives right away into the deformation behavior of amphibole. This is a big step for a reader. Why not first revisiting the major aspects and goals, discussing then the general rheological aspects of the different aggregates and defining the rheological key players in the system? In this way, the authors could ideally set the scene for the subsequent treatment of the individual mineral phases.

An introduction of the discussion has been added summarizing the microstructures observed each individual phases and their potential explanations in terms of deformation mechanisms. This will allow the reader to better understand the influence of each phase on the overall mechanical behavior of the rock.

3) My next concern is the way how the terms 'recrystallization' and 'dynamic recrystallization' are used or that the terms 'chemically-induced recrystallization' and 'nucleation of grains' (in the sense of precipitation out of a fluid) are missing. For readers experienced with these processes, which in my opinion all occur in the presented samples, the current use/not use of this terminology is somewhat confusing. Here a clear definition in the introduction on all these terms is mandatory. DYNAMIC RECYSTALLIZATION is always associated to deformation and MUST be related to reorganization of dislocation structures.

The terms "recrystallization" and "dynamic recrystallization" were both used to define recrystallization during intracrystalline deformation through reorganization of the dislocations in the crystal lattice. By opposite, the terms "precipitation" and "nucleation" was used to define chemically-driven crystallization (reaction product), either as new grains or as overgrowth rims on existing grains.

In case of cpx, the authors use undulose extinction apply this term to subgrain rotation and the formation of new recrystallized cpx gains in the mantle of cpx cores. These new CPX grains are surrounded by new amphibole grains clearly documenting a chemical reaction/mass transfer and not an individual dynamic recrystallization process. I am also wondering whether really subgrain rotation recrystallization is active or the grains either chemically nucleate completely new or present host cpx fragments disintegrated along cleavage planes and being then subject of rotational reorientations.

The core of clinopyroxene porphyroclasts shows undulose extinction but no subgrain formation. The small clinopyroxene grains in the wings present a quite variable grain size, which is unlikely to occur in a formation by dynamic recrystallization.

New compositional maps have been therefore conducted to better constrain the origin of the small grains around clinopyroxene porphyroclasts. The results are in agreement with the reviewer's comment. They clearly evidence a formation through microfracturing of the host mineral (the porphyroclast rich in NaAl) associated with small grain rotations together with localized dissolution-precipitation of secondary clinopyroxene (poor in NaAl) and amphibole.

This new statement has been thoroughly described and discussed in the new version of the manuscript.
Since EBSD data were made it should be easy to detect the grain refinement/nucleation process and to document this also in the manuscript. Also the changes in the Ti content in the amphiboles make me suspicious. Dynamic recrystallization per se cannot produce chemical changes. Here you need chemical driving forces such as chemically-driven recrystallization or chemically-driven grain boundary migration etc. I listed in the attached document a bunch of literature to this subject one can look at and cite. Last but not least the nucleation of new phases is a very important process. I have the impression that the current version of the manuscript does not highlight this point strong enough, since this process provides the fabric with new, unstrained, chemically equilibrated grains. See next point.

We do not suggest that amphibole dominantly accommodated the deformation in the dislocation creep regime. Rare amphibole show evidence for plastic deformation (undulose extinction mostly) but no spatial correlation have been observed with the chemical zonation. The Ti zonation in amphibole rather documents dissolution precipitation process localized along grain boundaries and microfractures.

4) The authors claim that pinning in the polymineralic fabric keeps the grain size small. I attached some references hoping to help the readers to find relevant references with this respect. Please note that pinning alone cannot keep a grain size small in nature since coupled grain coarsening would led the grains grow. In a dynamic system, such as present in the metamorphic sole of Oman, the presence of grain boundary sliding requests the formation of cavities at grain triple junctions to maintain strain compatibility. Such dilatational domains either are filled by growing neighbor grain (dissolution-precipitation) or new phases nucleate (note both processes are chemically driven, this is why the discriminations/definitions made above are so important). With the nucleation of new grains a steady supply of small grains helps to keep the average grain size small and supports the pinning behavior efficiently.

The pinning effect has been removed from the new version of the manuscript.

5) Transition from diffusion creep to dislocation creep towards lower temperature: dislocation creep is a deformation mechanism in monomineralic materials undergoing crystal plastic deformation. Hence a fabric needs subgrain (low angle) or grain boundaries (high angle) to be able to accommodate for such

creep processes and recover them. If I interpret the microstructures and given statements correctly, there exist nothing in the present samples such as monomineralic layers but they are all polymineralic. Hence you would need interface boundaries between grains to be able to recover dislocations, which in my opinion makes no sense. Hence, dislocation creep cannot be the dominant deformation mechanism in such a polymineralic aggregate. The only statement that can be made is that within a mineral phase, dislocation creep may become more important. This does not mean that the bulk aggregate is deforming by dislocation creep as a whole.

The activation of the dislocation creep regime towards lower temperature was essentially related to the high degree of retrogression leading to the crystallization of monomineralic aggregates of plagioclase (sample SE13-76).

However, the intense plagioclase serecitization did not allow us to correctly quantify the microstructures and crystal orientations in plagioclase. We have therefore decided to moderate our interpretation on the transition from diffusion creep to dislocation creep in the new version of the manuscript.

6) Last but not least, the attached PDF contains a list of further suggestions/corrections as well as few suggestions for adaptations in figures.

Suggestions and corrections have been taken into account.

I hope these comments help during the revision. With kind regards Marco Herwegh
Please also note the supplement to this comment: https://www.solid-earth-discuss.net/se-2019-28/se-2019-28-RC2-supplement.pdf
Interactive comment on Solid Earth Discuss., https://doi.org/10.5194/se-2019-28, 2019.

Deformation mechanisms in mafic amphibolites and granulites: record from the Semail metamorphic sole during subduction infancy

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Abstract. This study sheds light on the deformation mechanisms of subducted mafic rocks metamorphosed at amphibolite and granulite facies conditions, and on their importance for strain accommodation and localization at the top of the slab during subduction infancy. These rocks, namely metamorphic soles, are oceanic slivers stripped from the downgoing slab and accreted below the upper plate mantle wedge during the first million years of intra-oceanic subduction, when the subduction interface is still warm. Their formation and intense deformation (i.e. shear strain ≥ 5) attest to a systematic and transient coupling between the plates over a restricted time span of ~1 My and specific rheological conditions. Combining micro-structural analyses with mineral chemistry constrains grain-scale deformation mechanisms and the rheology of amphibole and amphibolites along the plate interface during early subduction dynamics, as well as the interplay between brittle and ductile deformation, water activity, mineral change, grain size reduction and phase mixing.

Results indicate that increasing pressure-temperature conditions and slab dehydration (from amphibolite to granulite facies) lead to the nucleation of mechanically strong phases (garnet, clinopyroxene and amphibole) and rock hardening. Peak conditions (850°C and 1 GPa) coincide with a pervasive stage of brittle deformation which enables strain localization in the top of the mafic slab and therefore possibly the unit detachment from the slab. In contrast, during early exhumation and cooling (from ~850 down to ~700°C and 0.7 GPa), the garnet-clinopyroxene-bearing amphibolite experiences extensive retrogression (and fluid ingression) and significant strain weakening essentially accommodated in the dissolution-precipitation creep regime including heterogeneous nucleation of fine-grained materials and the activation of grain boundary sliding processes. This deformation mechanism is closely assisted with continuous fluid-driven fracturing throughout the exhumed amphibolite, which contributes to fluid channelization within the amphibolites. These mechanical transitions, coeval with detachment and early exhumation of the HT metamorphic soles, controlled therefore the viscosity contrast and mechanical coupling across the plate interface during subduction infancy, between the top of the slab and the overlying peridotites. Our findings may thus apply to other geodynamic environments where similar temperatures, lithologies, fluid circulation and mechanical coupling between mafic rocks and peridotites prevail, such as in mature warm subduction zones (e.g., Nankai, Cascadia), in lower continental crust shear zones and oceanic detachments.

1 Introduction

Metamorphic soles underlying ophiolites are 10-100 m thick metamorphosed oceanic slivers stripped from the slab during subduction infancy (Hacker, 1990; Dewey and Casey, 2013; Agard et al., 2016; Rioux et al., 2016; Guilmette et al., 2018). Their accretion to the upper plate mantle wedge (i.e., the future ophiolite; Fig. 1a) is indicative of the rheology of the nascent, still warm interface, which favours strong mechanical coupling between the two plates (Agard et al., 2016, 2018; Soret et al., 2016, 2017). Internal changes in lithologies and metamorphic conditions reveal short-lived, stepwise accretion at characteristic pressure-temperature-time (P–T–t) conditions (Wakabayashi and Dilek, 2000, 2003; Plunder et al., 2016; Soret et al., 2017): two major accretion events have been identified in the mafic, high-temperature amphibolite to granulite facies portions of the Semail ophiolite sole (Oman, and United Arab Emirates; UAE), at 850 ± 50°C and 0.9 ± 0.2 GPa and 750 ± 50°C and 0.7 ± 0.2 GPa (Soret et al., 2017). The striking similarity of P–T conditions across the whole ophiolite width (~150 km) also indicates that these slivers experienced shear strains of at least 4–5 gamma during accretion/exhumation (Soret et al., 2017), coeval with large ductile deformation in the banded peridotites above (Boudier et al., 1988; Prigent et al., 2018a,c).

How deformation is accommodated within the amphibole-bearing sole rocks, and how mafic slivers get detached from the top of the subducting slab and accreted to the upper plate at T ≥700°C is so far unknown. To investigate the deformation mechanisms accompanying the progressive change of P–T conditions and mineralogy (i.e., essentially amphibole, with varying amounts of plagioclase, clinopyroxene and garnet), we provide detailed micro-structural and mineral chemistry data from the well-constrained Semail ophiolite sole. In contrast to plagioclase and clinopyroxene (e.g., Bascou et al., 2002; Rybacki and Dresen, 2004; Hier-Majumder et al., 2005; Dimanov et al., 2007), the physical properties and mechanical behaviour of amphibole and amphibole-bearing polymineralic aggregates, commonly found over a large range of P–T and water activity conditions, have been far less studied and remain puzzling (see Getsinger and Hirth, 2014). Understanding their deformation mechanisms is therefore expected to shed light on the plate interface rheology during subduction infancy (Soret et al., 2016, 2017; Prigent et al., 2018b) or beneath warm subduction zones (where similar temperatures, lithologies and mechanical coupling are expected at ~60 km depth; Abers et al., 2017), as well as on the rheological behaviour of amphibole-bearing rocks and strain localization in mid-crustal environments (e.g., continental crust: Imon et al., 2004; Tatham et al., 2008; Getsinger et al., 2013; Giuntoli et al., 2018; oceanic detachment faults or transform faults : Boschi et al., 2006; Escartín et al., 2003).

2 Deformation of amphibolites

Naturally and experimentally deformed amphibolites commonly show well-developed foliation and strong crystallographic–preferred orientation (CPO), regardless of their P–T–water activity conditions and compositional range (e.g., Imon et al., 2004; Tatham et al., 2008; Cao et al., 2010; Getsinger et al., 2013; Ko and Jung, 2015; Marti et al., 2017, 2018; Guintoli et al., 2018). Foliation is usually underlined by the shape–preferred orientations (SPO) of amphibole and plagioclase. Compared to plagioclase and clinopyroxene, the CPO of amphibole is generally stronger (Siegesmund et al., 1994; Imon et al., 2004; Diaz

Aspiroz et al., 2007; Tatham et al., 2008; Cao et al., 2010; Gómez Barreiro et al., 2010; Getsinger et al., 2013; Getsinger and Hirth, 2014; Kim et al., 2015; Ko and Jung, 2015), hence leading several authors to consider that it accounts for seismic anisotropy in the lower/middle crust (Mainprice and Nicolas, 1989; Tatham et al., 2008; Lloyd et al., 2011; Ji et al., 2013) and in subduction zones (Ko and Jung, 2015).

There are different interpretations for the strong CPO of amphibole and its SPO. The presence of a CPO usually hints at dislocation creep as the dominant deformation mechanism (e.g., Wenk and Christie, 1991). Several studies report intra-crystalline deformation in amphibole at high temperature (T ≥ 650–700˚C), compatible with dislocation glide along the most favourable slip systems {hk0}[001] (Berger and Stünitz, 1996; Diaz Aspiroz et al., 2007; Cao et al., 2010; Gomez Barreiro et al., 2010). However, other studies have suggested that amphibole is one of the strongest silicates, with limited ability to deform by dislocation creep (e.g., Brodie and Rutter, 1985). Amphibole would rather behave as a rigid particle, rotating and fracturing (Hacker and Christie, 1990; Ildefonse et al., 1990; Nyman et al, 1992; Shelley, 1994; Berger and Stünitz, 1996; Imon et al., 2004; Ko and Jung, 2015), and/or dissolving and reprecipitating during deformation (Brodie, 1981; Hacker and Christie, 1990; Berger and Stünitz, 1996; Kruse et al., 1999; Imon et al., 2004; Marti et al., 2017, 2018; Guintoli et al., 2018). While variations in P–T conditions, water activity and grain size are known to control the activation of the different deformation mechanisms (e.g., Brodie and Rutter, 1985), their respective roles have not been clearly assessed in the specific case of amphibole.

3 The Semail metamorphic sole

The Semail metamorphic sole is a relatively thin unit (commonly ≤ 100 m thick) found at the base of the ≥ 10 km thick Semail ophiolite (Oman and UAE; Fig. 1a-c). This unit results from the juxtaposition of several slices of oceanic crust (Fig. 1c-d; Soret et al., 2017 and references therein) that were buried, strained and metamorphosed against the hot overlying mantle wedge, from granulite-facies (for the uppermost slice) to upper greenschist facies conditions (for the lowermost one). In practice, it is convenient to distinguish in the field a high-temperature (HT) sole, found directly below the mylonitic basal peridotite, from a low-temperature (LT) sole onto which the HT sole is thrust. This structural organization is found all along the Semail ophiolite (Fig. 1b-c; Gnos, 1998), from Wadi Tayin (Oman) in the south to Sumeini (Oman) and Asimah–Khubakhib (UAE) in the north. These characteristics are common to most metamorphic soles worldwide, regardless of the nature of the overlying ophiolite (see Agard et al., 2016).

The HT sole is composed of two major sub-units (Fig. 1c), being either made of garnet–clinopyroxene amphibolites (HTa, above) or plagioclase-rich amphibolites (HTb, below). The contrasting Ti content of amphibole, which correlates positively with crystallization temperature (Ernst and Liu, 1998) and shows a stepwise decrease from ≥ 0.2 a.p.f.u. (atoms per formula unit) in HTa to ≤ 0.15 a.p.f.u. in HTb (Fig. 1e; Soret et al., 2017), indicates a ~100˚C gap in peak T between the two units. Mapping of the Ti-content is used hereafter to track different amphibole generations (Sect. 5.3).

Peak P–T conditions for the HT sole were estimated at 850 ± 50˚C and 0.9 ± 0.1 GPa for HTa and 725 ± 50°C and 0.8 ± 0.1 GPa for HTb (Fig. 1f; see Soret et al., 2017, for details). The preservation of prograde chemical zoning (over a dT ≥ 100˚C and a dP ≥ 0.1 GPa) suggests fast exhumation of the HT sole (≤ 1–2 Ma) after reaching peak conditions at 95–96 Ma, as supported by radiometric dating (e.g., Hacker, 1990; Rioux et al., 2016).

The underlying LT sole (Fig. 1c) is mainly composed of greenschist facies metacherts, with imbrications of amphibole-bearing metatuffs, and is not considered here. Estimated peak P–T conditions are more loosely constrained at 530 ± 50°C and 0.5 ± 0.1 GPa (Fig. 1f; Soret et al., 2017).

The entire metamorphic sole shows a strong planar fabric with evidence of both pure and simple shear deformation (Figs. 2a-c). In the LT sole, the lattice preferred orientation of quartz in the inter-bedded quartzite is consistent with shear senses observed in the basal banded peridotite (Boudier et al., 1988; Gray et Gregory, 2000; Ambrose et al., 2018). Deformation is less conspicuous in the garnet–clinopyroxene-bearing HTa sole compared to the HTb and LT soles, in which larger lithological heterogeneities exist. HTa amphibolite is indeed homogeneous (Figs. 1c, 2a-b), fine-grained and composed of amphibole + garnet + clinopyroxene ± plagioclase, while HTb amphibolite is coarser-grained and consists of amphibole + plagioclase ± epidote with rare biotite and plagioclase-rich imbricated layers (Figs. 1c, 2c).

4 Methods and sampling strategy

A suite of samples was collected from the two sub-units of the HT sole from three localities where the HT sole is the most complete and best preserved (Khubakhib, Sumeini and Wadi Tayin; Fig. 1b). Six samples (five from HTa and one from HTb; Fig. 1c, Table 1) were analysed using electron back-scattered diffraction (EBSD). For clarity, only microstructures of the most complete and representative section (the three HTa unit samples from Sumeini; see Soret et al., 2017) are detailed here. Microstructural descriptions for the Khubakhib and Wadi Tayin sections are given as supplementary information.

EBSD data were collected using a CamScan X500FE CrystalProbe scanning electron microscope (SEM) at Géosciences Montpellier (France). Measurements were performed on polished thin sections at a 25 mm working distance with an accelerating voltage of 15 kV. For each sample (see map step size in Table 1), amphibole, plagioclase, clinopyroxene, garnet (together with prehnite, epidote and Ti-rich phases such as rutile, titanite and ilmenite) were indexed wherever present. Resulting maps were first filtered using the Channel 5 software suite (Schmidt and Olesen, 1989) to increase the quality of the maps. Isolated pixels were removed, and non-indexed pixels with a minimum of 6 identical neighbours were filled with the same orientation. Maps were then processed using MTEX, a MATLAB toolbox for textural analysis (Hielscher and Schaeben, 2008; Bachmann et al., 2010; Mainprice et al., 2014).

In MTEX, misorientation angles (defined as the lowest rotation angle between two pixels about a common axis that brings two lattices into parallelism; e.g., Lloyd et al., 1997; Wheeler et al., 2001) were used to identify grain boundaries, applying a 10° threshold between adjacent pixels. Grains with a surface smaller than 10 pixels were discarded. Twins in plagioclase were distinguished from grain boundaries by filtering out the 178° to 180° misorientations during grain boundary identification. The grain size for each mineral was calculated using the equivalent circle diameter. Pole figures were calculated using the crystallographic orientation of each grain (i.e., one point per grain). All plots are represented in lower hemisphere projections in the specimen reference frame, with contours as multiples of a uniform distribution. Mineral crystallographic preferred orientation (CPO) strength was characterized using the J index (from 1 in the case of random orientation distribution to infinity in the case of an ideal single crystal; Bunge, 1982), calculated from the orientation distribution function (ODF; Mainprice et al., 2014). The shape preferred orientation (SPO) was calculated from the average orientation of the long axis of the best-fit ellipse of each grain. The aspect ratio (AR) of grains corresponds to the length ratio between the long and short axes of the best-fit ellipse. Kernel Average Misorientation (KAM) analysis was used to map intragranular misorientations in clinopyroxene, plagioclase and amphibole. The KAM is defined as the average misorientation around a measurement point with respect to the 16 nearest neighbour points in a particular grain.

To track nucleation and dissolution-precipitation processes during the deformation of amphibole and clinopyroxene, composition maps (Figs. 6,7) were acquired with 1–3 µm spatial resolution. Major elements were measured at CAMPARIS (Sorbonne Univ.) using a CAMECA SX-5 electron microprobe. Classical analytical conditions were used (200 kV, 40 nA, wavelength-dispersive spectroscopy mode), using Fe2O3 (Fe), MnTiO3 (Mn, Ti), diopside (Mg, Si), orthoclase (Al, K), anorthite (Ca) and albite (Na) as standards. See Soret et al. (2017) for representative point analyses of garnet, amphibole, clinopyroxene, feldspar and epidote in these samples.

Mineral abbreviations used throughout the text and figures are given after Whitney and Evans (2010).

5 Results

5.1 Sample overview

Samples from the Sumeini HTa unit are presented structurally from top to bottom, starting from the highest-grade samples collected near the contact with the overlying peridotite to garnet-free samples away from the contact. Mineral occurrences and proportions are given in Table 1.

Within 2.5 m from the peridotite, the metamorphic sole is composed of a garnet-clinopyroxene bearing amphibolite. Peak metamorphic assemblage and microstructures are well preserved in sample SE13-67 (Fig. 2d; Soret et al., 2017). The garnet-clinopyroxene amphibolite SE13-67 exhibits a mylonitic foliation, locally transected at a relatively low angle (15-25¬∞) by C'-type shear bands indicating a dextral shear sense in the thin-section frame. The foliation comprises fine-grained aggregates of brown amphibole and clinopyroxene, and locally garnet and clinopyroxene porphyroclasts (Fig. 2d). Three disjunctive domains are distinguished in thin-section:

- Area 1 (A1) is dominantly composed of a clinopyroxene aggregate aligned in the foliation, and is cut across at low angle by veins of epidote ¬± prehnite ¬± apatite (Figs. 2d, 3a).
- Area 2 (A2a, b) is composed of amphibole (50-65%) and clinopyroxene (25-35%) (Figs. 2d, 3b,c).
- Area 3 (A3) is composed of amphibole (42%), clinopyroxene (22%) and garnet (12%) (Figs. 2d, 3d).

Plagioclase is either rare or absent in the matrix, and most crystals have not been successfully indexed due to pervasive late sericitization by a minute assemblage of albite + epidote + muscovite. Epidote (≤ 2 vol.%), apatite (≤ 1 vol.%) and prehnite (≤ 5%), commonly found in veins sub-parallel to the foliation (Fig. 2d), testify to a late stage of Ca-rich fluid circulation at low-T conditions (≤ 700°C), which is documented across the entire HT metamorphic sole (Fig. 2b; Soret et al., 2017).

The degree of high-T (700-800°C) retrogression increases steadily towards the base of the HTa unit, and is maximum at the contact with the HTb unit (Soret et al., 2017). Rocks located further away from the sole-peridotite contact therefore mostly record lower temperature associated with post-T-peak deformation. About 8 m beneath the peridotite (sample SE13-69; Fig. 4a), the metamorphic sole exhibits a coarser-grained, more conspicuous foliation characterized by higher proportions of brown amphibole (58%) and plagioclase (14%), partly replacing clinopyroxene (12%) and garnet (3%). About 25 m below the contact (sample SE13-76; Fig. 4b), garnet and clinopyroxene no longer coexist in the metamorphic sole. Amphibole (23%) has a brown to greenish-brown colour and is closely associated with plagioclase (64%), both with coarser grain size. Amphibole grains are more scattered in the plagioclase-rich matrix and do not commonly form aggregates. The amphibolite also evidences precipitation of yellowish epidote (12%) aligned along C'-type shear bands together with fine-grained amphibole (Fig. 4b).

The underlying HTb unit is made of coarse-grained (typically 1 mm in diameter) plagioclase and greenish-brown amphibole aggregates, roughly in equal proportions, with rare ‚â§ 50 cm-thick intercalations of biotite-plagioclase-rich amphibolite (Soret et al., 2017). Plagioclase-rich and darker amphibole-rich layers alternate throughout this unit (Fig. 2c).

5.2 Microstructures

5.2.1 Amphibole

The amphibole median grain size decreases towards the contact with the peridotite (Table 1; Figs. 3a-c), i.e. where peak-metamorphic textures are best-preserved (≤ 2.5 m; SE13-67). In this sample, the median grain size for amphibole associated with clinopyroxene (A2; 56–57 µm) is similar to that for amphibole associated with clinopyroxene and garnet (A3; 55 µm; Figs. 5a,b; Table 1). Most amphibole grains have a subhedral shape. Away from the peridotite, the amphibole median grain size increases with increasing retrogression from 93 µm (at 8 m; SE13-69; Fig. 5c) to 110 µm (at 25 m; SE13-76; Fig. 5d), and the shape becomes more anhedral, commonly characterized by interstitial overgrowths at triple junctions with plagioclase (Fig. 5d).

Large amphibole grains display irregular boundaries in all samples, especially where bounded by -altered- plagioclase or prehnite (Figs. 5c,d, 6a-d). They also show intragranular micro-fractures which are parallel to cleavage planes or perpendicular to the [001] direction (Fig. 6a-d). These micro-fractures locally dissect the large grains, forming smaller grains with straight and sharp intra-phase boundaries (Fig. 6a-d). Later and wider prehnite-filled fractures are also found transecting the amphibolite (Fig. 5b).

The mean aspect ratio of amphibole (1.9 ± 0.6) does not vary with the distance from the peridotite nor with the mineral assemblage (Fig. S2a). Amphibole shape-preferred orientation (SPO), subparallel to the shear plane, is very strong in all samples and its intensity correlates positively with grain size and aspect ratio (Fig. S2a).

In the HTa unit, only rare (< 5%) amphibole grains show microstructural evidence for intra-crystalline plasticity, as undulatory or patchy extinction (Fig. 6a-b) and subgrain boundaries. However, in the sample best-preserved from retrogression (SE13-67) the Kernel Average Misorientation (KAM) maps outline the presence of intracrystalline misorientations in most amphibole grains. Most of these misorientations are associated with significant rotations (up to 6°; Fig. 6e-i). Grains with the high micro-fracture density show the highest misorientation angles or new grain boundaries (red arrows; Fig. 6a,e). In the more retrogressed samples (SE13-69, SE13-76), amphibole grains also show a high density of micro-fractures (Fig. 6c,d) which are associated with high intragranular misorientations (Fig. 6h,i). In both samples, some of these intracrystalline misorientations are spatially correlated with undulatory extinction and subgrain formation (Fig. 6c,h), especially in the largest and/or most elongated amphibole grains (i.e., which can locally show intragranular fractures; Fig. 6d-i).

5.2.2 Garnet

Garnet grains have rounded to ellipsoidal shapes (Figs. 2d, 5a,b) and essentially form σ-type porphyroclasts showing a dextral sense of shear in the thin-section frame (Figs. 2d, 5a). Pressure shadows are composed of fine-grained amphibole and clinopyroxene. Garnet crystals are fractured and, locally, fragmented (Fig. 5b). These fractures cut across their prograde growth zonation (Soret et al., 2017) and are filled with oriented, fine-grained mixtures of amphibole + clinopyroxene ± rare plagioclase (Fig. 5b). Where retrogression is more pervasive (SE13-69), garnet is rimmed by plagioclase (Figs. 4a, 5c) and lacks of pressure shadows.

5.2.3 Clinopyroxene

Clinopyroxene grains have euhedral to ellipsoidal shapes (Figs. 2d, 5e-h). The aspect ratio of clinopyroxene is smaller than that of amphibole (1.6 ± 0.4 on average) and does not vary with grain size, mineral assemblage or with the distance of the samples to the peridotite contact (Fig. S2e). Within mono-mineralic layers (A1 in SE13-67; Figs. 2d, 3a, 5e), clinopyroxene has a median grain size of 31 µm (Fig. S2d). Where associated with amphibole (A2) and/or garnet (A3), the median grain size (51–57 µm) is similar to that of amphibole (Fig. S2d). Yet, clinopyroxene forms in places σ-type porphyroclasts (A2 in SE13-67; Figs. 2d, 3b-c, 5f) with high aspect ratios (≥ 2). They are usually aligned in the foliation plane (Figs. 2d, 5f, S2f) while the SPO for small clinopyroxene grains are more random (Fig. S2f).

The core of clinopyroxene porphyroclasts is characterized by undulose extinction and trails of secondary fluid inclusions representing healed fluid-filled micro-fractures (dashed white arrows; Fig. 5g,h). Minute amphibole is found along the cleavages and the micro-fractures (white arrows; Fig. 5h). These trails are locally cut across by the wider prehnite-filled fractures.

Clinopyroxene mantle also shows elongated fine-grained wings (consistent with dextral sense of shear in the thin-section frame; Fig. 2d) composed of small grains of variable size but with a median value similar to that of the new grains scattered in the matrix and in monomineralic layers (A1). Some of these small grains display undulose extinction (Fig. 5h). However, they rarely contain micro-fractures. Interstitial small amphibole grains (green arrows; Fig. 5g-h), randomly oriented, are typically found in the porphyroclast mantle and wings at the triple junction of the new clinopyroxene grains (Figs. 5g-h).

Where garnet is present (A3 in SE13-67, SE13-69; Figs. 2d, 5a), clinopyroxene grains form fine-grained aggregates embedded in an amphibole-rich matrix. In sample SE13-67, most amphibole grains have a subhedral shape (Fig. 5a). However, the degree of phase mixing with amphibole in the matrix is higher than in Area 2, especially in sample SE13-69 characterized by precipitation of secondary amphibole at the expense of clinopyroxene.

5.2.4 Plagioclase

Plagioclase is rare, even in the best-preserved metamorphic sole samples. The analysis of the crystallographic orientation in plagioclase grains is complicated by retrogression, therefore the results shown below are restricted to the best-preserved grains, and may not be representative of all grains formed at high P–T.

5.3 Mineral composition mapping

5.3.1 Amphibole

Amphibole composition plots within the pargasite to actinolite fields (see Soret et al. (2017) for detailed analyses). Hereafter, amphibole is referred to as Ti-high (≥ 0.2 a.p.f.u.), Ti-medium (0.1–0.2 a.p.f.u.) and Ti-low (≤ 0.1 a.p.f.u.) amphibole.

In sample SE13-67, amphibole grains show an homogeneous Ti-high composition (Fig. 6j-k), confirming that these grains formed at or near peak conditions. Interstitial amphibole grains have a Ti-medium composition, indicating a nucleation during the onset of cooling. The opaque mineral and veins found along amphibole grain boundaries and microfractures correspond to ilmenite (green arrow; Fig. 6a,b,j,k) which also formed at slightly lower P–T conditions (Soret et al., 2017).

In the samples marked by a higher degree of retrogression at amphibolite-facies conditions (SE13-69, SE13-76), amphibole grains evidence a much more complex and patchy zoning pattern including smaller Ti-rich areas than in sample SE13-67. These Ti-rich areas are usually truncated by Ti-medium to Ti-low areas, especially along micro-fractures (red arrows; Figs. 6l-m). In addition to the precipitation of secondary plagioclase and ilmenite at amphibole lobate grain boundaries and/or along the micro-fractures (Fig. 6a-c), these zoning patterns indicate dissolution-precipitation during cooling (i.e., 800–700°C). This also further supports the observation that Ti-medium and Ti-low amphibole grains are not in equilibrium with clinopyroxene and garnet but rather with plagioclase.

5.3.2 Clinopyroxene

Clinopyroxene has a diopside-rich composition with small variations in jadeite content (Na, Al). Hereafter, clinopyroxene is distinguished as jadeite-rich (Al > 0.2 a..p.f.u) and jadeite-poor (Al < 0.2 a..p.f.u) clinopyroxene, recording the peak-pressure condition and the early exhumation conditions, respectively (Soret et al., 2017).

Clinopyroxene porphyroclasts have a jadeite-rich core similar in composition to that of inclusions in garnet, and a thin jadeite-poor rim (Fig.6a-c). The jadeite-rich core is truncated by micro-fractures which are both filled by Ti-rich to Ti-medium amphibole (red arrows; Fig.6a-c). At the edges of the largest microfractures dissecting the porphyroclast core, compositions are jadeite-poor.

Small clinopyroxene grains in mono- and poly-mineralic layers display a zoning pattern similar to that of the clinopyroxene porphyroclasts, with jadeite-rich cores rimmed and locally truncated by jadeite-poor domains (Fig.6a-c). As for clinopyroxene porphyroclasts, some of the small grains exhibit amphibole-bearing micro-fractures in the jadeite-rich core only.

5.4 Crystallographic preferred orientation

5.4.1 Amphibole

In all samples (SE13-67, SE13-69 and SE13-76), amphibole has a very strong CPO, with [001] axes (i.e., shortest Burgers vector; Hacker and Christie, 1990) mostly parallel to the lineation (Figs. 8a, 9a-c). Poles to (100) are subperpendicular to the foliation and poles to (010) are in the foliation, subperpendicular to the lineation (Fig. 8a). Poles to (100) always show the highest density and poles to (010) usually display the weakest preferred orientation.

Amphibole J-index ranges from 2.86 in the sample SE13-76 to 5.27 in the sample SE13-67 (Fig. 10a-b). The CPO strength is slightly positively correlated with the modal proportion of amphibole but no systematic correlation is found with the distance to the peridotite (Fig. 10a-b). In sample SE13-67, the CPO strength is significantly weakened around garnet and clinopyroxene porphyroclasts which show strong foliation deflection. In the more retrogressed sample SE13-69, where garnet and clinopyroxene coexist but do not deflect the foliation plane, amphibole has a strong CPO fabric (J-index = 3.67; Fig. 10a-b) as in the garnet-free layers of SE13-67 (Area 2a). The weakest CPO (J-index=2.87; Fig. 10a-b) is observed away from the contact in the garnet-free sample SE13-76 which has the smallest amphibole modal proportion. Moreover, as highlighted with the SPO, amphibole grains with smaller grain size (< 80 μm) and/or aspect ratio (< 1.5) display a similar CPO pattern but significantly weaker in intensity compared to larger or more elongate grains (Fig. 10c).

The misorientation angle distribution of amphibole in all samples highly differs from the theoretical random distribution (i.e., the "uniform" green curve; Fig. 8b). This is consistent with the strong intensity of amphibole CPO. Small misorientation angles (from 2 to 10°) are largely dominant. They correspond to rotations around the [001] axis, and to a much lesser extent around the [010] axis (Fig. 8c). The [010] axis concentration is slightly higher in sample SE13-76 compared to the other samples.

5.4.2 Clinopyroxene

Clinopyroxene has a moderate to weak CPO. As in amphibole, the [001] maximum is subparallel to the lineation but more dispersed (Fig. 9d-f, 11a, S5b). The majority of CPO patterns has girdle concentrations of both (100) and (010) poles, except in sample SE13-69 where poles to (010) have a maximum normal to the foliation (Fig. 11a). In SE13-67, the strongest CPO (or J-index) is found within monomineralic layers of SE13-67 (J-index=2.61 in A1; Figs. 10a). In poly-mineralic aggregates, clinopyroxene J-index ranges from 1.21 to 1.73 (Fig. 10b). In contrast with amphibole, both the SPO and CPO strength of clinopyroxene appear to be also largely insensitive to grain size and aspect ratio (Fig. 10c).

The misorientation angle distribution of clinopyroxene in all samples does not significantly differ from the theoretical random distribution (i.e., the "uniform" green curve; Fig. 11b), except in the monomineralic layer A1 in sample SE13-67. Small misorientation angles (from 2 to 10˚) largely prevail. They correspond to rotations essentially around the [010] and the [001] axis (Fig. 11c), which corresponds to the mechanical twinning axis, as previously reported for clinopyroxene deformed at high temperature conditions (Frets et al., 2012).

5.4.3 Plagioclase

Plagioclase has a weak CPO (Fig. 12a, S5c-d). Its strength is similar to that of clinopyroxene, with a J-index varying between 1.51 and 2.06 (Fig. 10a). Plagioclase grains display a concentration of (001) poles normal to the foliation plane and [100] axes subparallel to the lineation (Fig. 12a). Poles to (010) show no preferred alignment. The CPO strength and patterns do not vary with the distance from the contact, nor with the mineral assemblage.

The misorientation angle distribution of plagioclase in all samples slightly differs from the theoretical random distribution (i.e., the "uniform" green curve; Fig. 12b). Small misorientation angles (from 2 to 10˚) are largely dominant. They correspond to rotations around the twinning axis [100], and to a much lesser extent around the [001] axis (Fig. 12c). However, the [001] axis becomes the main axis of intracrystalline misorientations in sample (SE13-76), where plagioclase forms monomineralic aggregates (Fig. 12a).

6 Discussion

The HTa metamorphic sole unit is characterized by an intense gradient of syn-kinematic retrogression increasing toward its base. This gradient allows us to constrain the combined deformation mechanisms in amphibolites at peak conditions (~850°C – 1GPa; in sample SE13-67) and during cooler and more hydrated conditions (~800 and ~750°C and 0.7 GPa, in samples SE13-69 and SE13-76, respectively).

Amphibolites recording peak conditions (e.g. SE13-67) show large contrasts in mineral strength and crystallographic fabric. Clinopyroxene forms σ-type porphyroclasts and monomineralic fine-grained aggregates wrapped around by monomineralic aggregates of amphibole or polymineralic aggregates of amphibole + clinopyroxene ± plagioclase (Fig. 2d). Where garnet is present, clinopyroxene forms fine-grained aggregates partially mixed within an amphibole-rich matrix. Clinopyroxene appears therefore to be mechanically stronger than amphibole and the polymineralic matrix, but weaker than garnet. Yet, such a strength contrast disappears in the more retrogressed garnet-clinopyroxene amphibolite (SE13-69) where mineral reactions are more pervasive.

Moreover, clinopyroxene aggregates show ubiquitous plastic deformation (as indicated by the presence of undulose extinction; Fig. 5g-h) but display a weak CPO. By contrast, amphibole aggregates in the amphibolites of the HT metamorphic sole have a very strong CPO (*J*-index ~ 5; Fig. 10) despite showing no or only little evidence for intracrystalline plastic deformation. Extensive phase mixing is observed throughout the rock, especially in more retrogressed samples. Finally, amphibole, clinopyroxene and garnet underwent intense grain size reduction by micro-fracturing, closely associated with fluid-driven mineral reactions.

In the light of our observations (see also Table 2) we discuss below the possible deformation mechanisms and their relative contributions to the mechanical behaviour of the amphibolites of the soles.

6.1 Deformation processes in amphibolite

6.1.1 Dislocation creep

Amphibole SPO and CPO are similar in orientation to what is commonly reported for strained amphibole (Berger and Stünitz, 1996; Cao et al., 2010; Díaz Aspiroz et al., 2007; Elyaszadeh et al., 2018; Getsinger et al., 2013; Gomez Barreiro et al., 2010; Hacker and Christie, 1990; Imon et al., 2004; Tatham et al., 2008). They are also consistent with the extreme tectonic thinning and large shear strain of the HT metamorphic soles ($\gamma \geq 5$; Soret et al., 2017). For amphibole with J-index of ~3 and ~5, shear strains of ≥ 5 and ≥10 have been reported in amphibolite in deformation experiments (Getsinger, 2015) and in continental shear zones (Tatham et al., 2008), respectively (Fig. 10a). As for amphibole in the Semail HT metamorphic sole, those amphibole crystals show no or little evidence for intracrystalline plastic deformation and coexisting phases (plagioclase, clinopyroxene and quartz) have a weak CPO.

If the strong amphibole CPO and the apparent intracrystalline misorientations (Fig. 8) result from plastic deformation, the misorientation axis should be perpendicular to the direction of crystal slip (e.g., Lloyd et al., 1997). In our study, however, intracrystalline misorientations are essentially accommodated around the [001] axis, and only to a lesser extent around the [010] axis (Fig. 8b). Most of the misorientations are therefore incompatible with the activation of the amphibole easy slip system (100)[001] that would account for the observed CPO geometries and intracrystalline misorientations (Fig. 8a). Conversely, the [010] rotation axis (Fig. 8b), lying in the foliation plane perpendicularly to the general shear sense, is compatible with the activation of the amphibole easy slip system. The relatively small number of rotation axes oriented parallel to [010] is also consistent with the fact that only few of the Ti-rich amphibole grains recording peak T conditions (~850°C) show microstructural evidence for plastic deformation (such as subgrain formation; SE13-67; Fig. 9a-c).

Clinopyroxene has a CPO pattern characterized by the [001] axis maximum subparallel to the lineation (Figs. 9d-f, 11a), and girdle concentrations of both (100) and (010) poles perpendicular to the lineation (Figs. 11a). This pattern reflects the dominant activation of the {hk0}[001] glide systems in the dislocation creep regime, as commonly reported in experiments on omphacite and diopside (Bascou et al., 2002; Getsinger and Hirth, 2014; Ingrin et al., 1991). This is consistent with the intracrystalline misorientations accommodated around the [010] axis (Fig. 11c), especially dominant in the fine-grained monomineralic aggregates. However, the CPO strength is low to moderate with some dispersion of the [001] axis even in the fine-grained monomineralic aggregates (Figs. 11a, S5b).

6.1.2 Brittle deformation

The high micro-fracture densities in coarse amphibole grains (Figs. 5a, 6a-b) and the general fine-grained size in the best preserved sample (SE13-67) attest to grain size reduction through extensive brittle deformation starting at or after peak conditions. Healed micro-fracturing in secondary amphibole crystals grown during retrograde P–T conditions (in SE13-69 and SE13-76) indicates that brittle deformation also persisted during cooling. This is further supported by the ubiquitous presence of wider epidote- and prehnite-filled fractures crosscutting the entire HT amphibolite (Fig. 2d).

The brittle behaviour of amphibole within a rock deforming ductilely at high temperature has already been reported (Nyman et al, 1992; Berger and Stunitz, 1996; Imon et al., 2002; Diaz Aspiroz et al., 2007; Gomez Barreiro et al., 2010; Ko and Jung, 2015; Marti et al., 2017; Giuntoli et al., 2018) but ascribed to significantly lower deformation temperatures (≤ 700˚C). Preferential micro-fracturing along planes including the long ([001]) crystallographic axis could explain the similar aspect ratios of fine and coarse amphibole grains (essentially ≤ 2–3, as suggested by Gomez Barreiro et al. (2010). Micro-fracturing along the [001] crystallographic axis together with small rigid rotations (1–3°; Fig. 6e-h) may further explain some of the apparent intracrystalline misorientations in amphibole around the [001] rotation axis (Figs. 6j, 8c)

Intense grain size reduction through brittle deformation in fact affected the whole rock at or near peak conditions as attested by the presence of fractured and rotated garnet and jadeite-rich clinopyroxene porphyroclasts in sample SE13-67. The lack of micro-fractures in the new small clinopyroxene suggests that fracturing preferentially occurred along cleavage planes of the porphyroclasts, and the precipitation of minute amphibole along these cleavage planes has probably facilitated the failure. Moreover, the intense brittle deformation followed by small rigid rotation easily explained the general weak of the CPO of clinopyroxene in the amphibolite.

The strong correlation between the aspect ratio, the CPO and SPO intensities of primary and secondary amphibole in all samples (Fig. 10) also advocates for a component of rigid grain rotation in the strain accommodation from peak to retrograde conditions (as previously reported in other settings; Ildefonse et al. 1990; Shelley 1994; Berger and Stünitz 1996; Díaz Azpiroz et al. 2007; Tatham et al. 2008; Elyaszadeh et al., 2018). Contrary to clinopyroxene, the high aspect ratio of amphibole allowed the preferential alignment of the long axes parallel to the stretching direction. Yet, the strong SPO/CPO parallel to the lineation in secondary amphibole could also be explained by oriented dissolution-precipitation during cooling conditions (e.g., ; Shelley, 1994; Berger and Stünitz, 1996).

6.1.3 Dissolution-precipitation creep and grain boundary sliding

Lobate boundaries and patchy zoning of amphibole defined by Ti-high cores truncated by the precipitation of Ti-medium/low areas reveal that brittle deformation was closely associated with and/or promoted dissolution precipitation (Fig. 6k-m). This is also indicated by the nucleation of Ti-medium amphibole and jadeite-poor clinopyroxene within micro-fractures and cleavages of diopside-rich clinopyroxene (Figs. 5g, 7).

Dissolution-precipitation creep was likely driven by the metastability of the peak assemblage during cooling and hydration, and was further enhanced by the permeability created by the micro-fracturing. Such a positive feedback between viscous and/or brittle deformation and (hydrous) mineral reactions was recently described in shear experiments on amphibolites conducted at 600–800°C and 0.5–1.5 GPa (Marti et al., 2017, 2018). The tight relationship between brittle deformation and dissolution-precipitation creep advocates for transient changes in pore-fluid pressure, either during dehydration (and/or melting) at peak conditions (e.g., Brodie and Rutter, 1985) or during the onset of retrogression (i.e., fluid ingression from adjacent slab dehydration; e.g., in a colder subduction context: Locatelli et al., 2018).

The presence of randomly-oriented minute amphibole at the grain boundaries of mantled clinopyroxene and the general intense phase mixing in the poly-mineralic matrix testify to the activation of grain boundary sliding (GBS) as a dominant mechanism accompanying dissolution precipitation creep syn to post grain size reduction, even in the mono-mineralic layers (A1; SE13-67). The absence, in the retrogressed HTa amphibolite (sample SE13-69; Fig. 3a) of microstructural evidence (e.g. pressure shadows) for any strength contrast between phases known to have different strength further supports the role of GBS.

6.3 Mechanical evolution of the plate interface during subduction infancy

During initial subduction progress, the leading edge of the slab encounters an increasingly warmer, anhydrous mantle wedge acting as a buttress (Fig. 14a; Agard et al., 2016). Accretion of metamorphic soles to the basal peridotites of the future ophiolite reflects this increased mechanical coupling between the plates across a restricted P–T-time window (i.e., when viscosities of the slab crust and overlying mantle are similar; Agard et al., 2016). Our micro-structural data allow to document the evolution of the deformation at the top of the slab (stages A1-A2-B; Figs. 13, 14):

— Approximatively from amphibolite to granulite facies and up to 850 ± 50˚C – 1.0 GPa, the slab crust progressively dehydrates and minerals such as amphibole (Ti-medium/poor) and plagioclase are replaced by mechanically stronger garnet and clinopyroxene in the HTa unit (and Ti-rich amphibole; stage A1; Fig. 13a). The leading edge of the slab thus likely hardens (as shown by the evolution of the strength curve in figure 14). When it reaches the strength of the mantle on top, HTa gets stripped and becomes the first slice accreted to the upper plate peridotite (stage A; Fig. 14). Our observations indicate that a strong amphibole fabric dominates rock anisotropy at the top of the slab. This fabric is controlled by syn-kinematic oriented growth and rigid grain rotation, as shown by the strong correlation between grain size, aspect ratio and fabric intensity. The onset of brittle deformation in the garnet–clinopyroxene amphibolite leads to drastic grain size reduction (GSR; stage A1; Fig. 13a). This brittle deformation, possibly controlled by dehydration embrittlement (Davies, 1999), dehydration-driven stress transfer (Ferrand et al., 2017) and/or fluid ingression from adjacent slab dehydration acts as a precursor for strain localization in the garnet–clinopyroxene amphibolite within the downgoing slab (and therefore detachment of HTa; Fig. 14). Similarly, fluids released at the plate interface during slab burial are thought to trigger early strain softening of the base of the mantle wedge through GSR promoted by fluid/mantle interaction and dissolution/precipitation processes (Fig. 14b; Prigent et al. 2018b; Soret et al., 2016). Overall, these combined processes controlled the onset and location of strong mechanical coupling across the plate interface, between the top of the slab and the base of the nascent mantle wedge (stage A; Fig. 14).

— from 850 down to 750°C and 1 to 0.7 GPa (stage A2 in Fig. 13a), early exhumation and cooling of the garnet–clinopyroxene bearing HTa is associated with strong shearing and pervasive retrogression across the plate interface (Soret et al., 2017; Prigent et al., 2018b). Deformation in HTa is extensively accommodated by dissolution-precipitation assisted by grain boundary sliding (including mineral reactions, heterogeneous nucleation and phase mixing), leading to a second stage of significant strain softening of the exhuming HTa unit. Dissolution-precipitation creep and GBS are closely related to the brittle deformation events observed from peak conditions and operating until late exhumation (see sect. 6.3) which facilitate fluid ingression and thereby enhanced mineral reactions and rock re-equilibration within HTa. Syn-exhumation mechanical softening occurs also in the basal mantle wedge in the diffusion creep regime, as it becomes colder and more metasomatized (Fig. 14; Agard et al., 2016; Prigent et al., 2018a,b; Soret et al., 2016). Similar weakening on both sides of the plate interface maintains a coupling between HTa and the peridotites and explains their coeval early exhumation (from ~1 to 0.7 GPa).

— At temperatures around 750°C (stage B: Fig. 12b; Fig. 14), during later exhumation and cooling of HTa, pervasive fluid-rock interaction transforms the base of HTa into a two-phase matrix composed of syn-kinematic Ti-medium/low amphibole and plagioclase, with only minor amount of biotite and epidote. Meanwhile, the top of the subducting slab (i.e., the future plagioclase-rich HTb unit) consists of a similar mineral assemblage (Fig. 14). Our observations show that GBS is progressively inhibited while dissolution–precipitation creep remains the dominant deformation mechanism, thus behaving potentially like the HTb unit. In the absence of significant GBS, the modal increase in (wet) plagioclase has a major softening effect. Mechanical coupling between HTb and HTa and/or HTb and the weakening at the base of the mantle wedge is responsible for the detachment and accretion of HTb (Fig. 14).

These deformation stages between 850 and 750°C result in the extreme thinning and distribution of similar HT metamorphic soles below the ophiolite (shear strain ≥ 5) and in the thinning of the base of the ophiolite itself (see discussion in Casey and Dewey, 2013).

6.4 Mechanical implications for warm subduction zones and oceanic/continental crustal-scale shear zones

We envision at least three major implications of this record of progressive deformation in metamorphic soles:

— Since pressure is not expected to significantly influence deformation mechanisms in the ductile regime, we argue that deep recoupling mechanisms in mature warm subduction zones (at T ≥ 800°C; e.g., Nankai, Cascadia; Wada and Wang, 2009; Abers et al., 2017) could be controlled, as for HTa metamorphic soles, by the extent of fluid-rock interactions and the degree of stability of high-pressure amphibole.

— Dissolution-precipitation creep and associated amphibole-forming reactions coupled with brittle deformation may also control strain localization at high temperature conditions, and therefore the development of long-lived oceanic detachments and core complexes in slow-spreading environments (Boschi et al., 2006; Escartin et al., 2003; Gülcher et al., 2019), as well as continental crustal-scale shear zones in collisional settings under cooling conditions and exhumation (Getsinger et al., 2013; Giuntoli et al., 2018; Tatham et al., 2008).

— Finally, while many different interpretations have been invoked for the deformation mechanisms of amphibole and amphibolites (e.g., GBS, diffusion creep, dislocation creep; see sect. 2), such diversity could reflect change in P-T conditions, water activity and mineral stability. This study outlines that ongoing metamorphic processes and amphibole stability should be carefully taken into account when interpreting deformation mechanisms in amphibole, especially in shear zones experiencing hydration and cooling during exhumation, as a well-developed CPO in amphibole does not systematically testify to dislocation creep, and does not exclude a component of fracturing and GBS in sheared amphibolites.

7 Conclusions

Based on micro-structural analysis and mineral chemistry, this study highlights the mineral-scale mechanisms controlling the progressive deformation of sheared amphibolites from the Oman metamorphic sole during subduction infancy, and unravels how strain is localized and accommodated in (hydrated) mafic rocks under amphibolite and granulite facies conditions. Metamorphic reactions and pore-fluid pressures driven by changes in P–T conditions and/or water activity exert a key control on the rheology of mafic rocks and the transition between brittle and viscous deformations at high temperature conditions (as noted experimentally; Marti et al., 2017, 2018).

At 850 ± 50°C and 1 GPa, garnet-clinopyroxene amphibolites accommodate large shear strain essentially through fracturing, grain size reduction and grain boundary sliding, confirming that amphibole and amphibolite has only little ability to deform in the dislocation creep regime. The exact driving mechanism for the fracturing remains uncertain. Possible explanations include dehydration embrittlement, dehydration-driven stress transfer and/or fluid ingression.

Lower temperatures (800 – 700°C) and higher hydrated conditions on the return path lead to higher rock disequilibrium and therefore pervasive hydrous reactions. Strain in the exhumed amphibolite is dominantly accommodated in the dissolution-precipitation creep regime assisted and enhanced by a component of brittle deformation. Grain size reduction through fracturing and heterogeneous nucleation enables GBS and significant phase mixing, thereby producing a large mechanical weakening. However, the fabric intensity of amphibole is not significantly affected by the GBS activation (contrary to clinopyroxene and plagioclase) due to its specific high aspect ratio.

These mechanical evolutions, marked by strain hardening during increasing P–T conditions and dehydration and later, large strain softening during cooling and hydration, are respectively coeval with the detachment and early exhumation of the different amphibolitic units of the HT metamorphic sole. They likely control the extent of the viscosity contrast and, therefore, the mechanical coupling between the top of the slab and the peridotites across the plate interface during subduction infancy (Agard et al., 2016; Prigent et al., 2018b).

As amphibole is commonly found with plagioclase, clinopyroxene and/or garnet in high-temperature shear zones, these largely pressure-independent findings may be applied to other geodynamic environments where similar temperatures, lithologies, fluid circulation and mechanical coupling between mafic rocks and peridotites prevail, such as in mature warm subduction zones (e.g., Nankai, Cascadia), in lower continental crust shear zones and oceanic detachments

Author contributions

MS, PA and BD conceived the initial idea of the study. MS, PA, BD and CP participated in the fieldwork. MS conducted EBSD and EMP analyses. MS and BI performed EBSD data processing using MTEX. MS prepared the manuscript with contributions from all co-authors.

Competing interests

The authors declare no competing interests.

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