Wet magmatic processes during the accretion of the deep crust of the Oman Ophiolite paleoridge: Phase diagrams and petrological records

DOI:
10.1016/j.tecto.2021.229051

Citation for published version (APA):
Koepke, J., Feig, S. T., Berndt, J., & Neave, D. (2021). Wet magmatic processes during the accretion of the deep crust of the Oman Ophiolite paleoridge: Phase diagrams and petrological records. *Tectonophysics*, [229051]. https://doi.org/10.1016/j.tecto.2021.229051

Published in:
Tectonophysics

Wet magmatic processes during the accretion of the deep crust of the Oman Ophiolite paleoridge: Phase diagrams and petrological records

Revised Version

J. Koepke[1*], S.T. Feig[2], J. Berndt[3], D.A. Neave[4], and the Oman Drilling Project Science Team[5]

[1]Institut für Mineralogie, Leibniz Universität Hannover, Callinstrasse 3, 30167 Hannover, Germany

[2]University of Tasmania, Hobart TAS 7001, Australia

[3]University Muenster, Corrensstraße 24, 48149 Münster, Germany

[4]Department of Earth and Environmental Sciences, The University of Manchester, Oxford Road, Manchester, M13 9PL, UK

[5]Since we present data in this manuscript from the Oman Drilling Project which are not officially published in the related proceedings (http://publications.iodp.org/other/Oman/OmanDP.html) it is necessary to include the OmanDP Science team as author.

Corresponding author: Jürgen Koepke (koepke@mineralogie.uni-hannover.de)

Highlights:

- Magmatic accretion of the deep crust of the Oman Ophiolite paleoridge was wet
- Water in Oman parental melts enables the formation of crustal wehrlites
- Phase diagrams for hydrous crust formation during subduction zone initiation
- Construction of phase diagrams for the axial melt lens at 50 MPa in a wet system
- importance of in-situ crystallization during the accretion of the Oman paleocrust

Keywords:

- Experimental study
- Hydrous MORB-systems
- Oman Drilling Project
- Oman ophiolite
- Fast-spreading oceanic crust
- Wehrlites

Abstract

The Oman Ophiolite is regarded as an analogue to modern fast-spreading ocean ridge systems in an environment of subduction zone initiation. In contrast to recent mid-ocean ridge basalts from the East Pacific Rise, parental melts at the Oman paleoridge are assumed to be hydrous in nature. In order to constrain the role of water during magmatic accretion processes in the deep crust at the Oman paleoridge, we evaluated several experimental studies in hydrous tholeiitic systems performed at shallow pressures. We concluded that the wehrlitic phase assemblage (olivine coexisting with clinopyroxene but without plagioclase) is the most significant feature indicative of high prevailing water activities. The stability of the wehrlitic assemblage decreases with decreasing pressure (not stable in the upper plutonic crust) and depends on the chemical system (only stable in primitive MORB systems).

We applied these results to plutonic rocks from cores drilled as part of the Oman Drilling Project (OmanDP). A key observation is the presence of coherent wehrlitic layers within the layered gabbro series, which are frequent in the lowermost gabbros (20%), relative sparse in the mid-crust (6%), and absent from the top of the plutonic crust at the dike/gabbro transition. Based on the combined phase relations for hydrous MORB-type systems at shallow pressures, we interpret this as a direct consequence of the presence of a significant water activity during the accretion of the plutonic crust of the Oman paleoridge, and not as a local phenomenon related to variations in temperature or bulk chemistry. These findings have implications for the mechanism of accretion of the lower crust at the Oman paleoridge, supporting a model that significant parts of the plutonic crust were produced by in-situ crystallization of primitive melt sills.

1 Introduction

The accretion and growth of oceanic crust at mid-ocean ridges generated by seafloor spreading is one of the dominant processes in the chemical differentiation and physical evolution of the Earth. Nearly 70% of the surface of our planet was built in this way. Oceanic crust from fast-spreading ridge systems shows a relatively homogeneous, layered stratigraphy (e.g., Canales et al., 2003). Here, the basic processes responsible for the generation of oceanic crust are ascent, differentiation, and solidification of Mid Ocean Ridge Basalts (MORB), which are mainly delivered from the axial melt lens (AML), sandwiched between the plutonic gabbroic layer and the volcanic sheeted dike sequence. The melt lens, which is filled with nearly pure melt, is underlain by crystal/melt mush that is in turn laterally surrounded by a transition zone of mostly solidified material that grades into a completely crystalline zone of solidified gabbros (e.g., Vera et al., 1990). The role of the AML during crustal accretion is still debated: either, this melt reservoir is the source for the complete lower, gabbroic crust, formed by the suspension of crystal mush formed here (the "gabbro glacier model", e.g., Henstock et al., 1993), or significant parts of the plutonic crust originate from in situ crystallization in the deep crust (the "sheeted sill model"; e.g., Kelemen et al., 1997). However, current consensus now favors “hybrid” models that combine the two endmember models mentioned above (e.g., Mock et al., 2021b). The in-situ crystallization in the lower crust is also supported from recent seismic experiments that indicate the presence of deep melt sills under recent fast/intermediate-spreading ridges (see Carbotte et al., 2021 and references herein). Since outcrops of the lower oceanic crust in modern fast-spread crust are very rare and difficult to access, it is necessary to undertake corresponding studies on ophiolites and on the Oman ophiolite in particular, which is regarded as the best example of fast-spreading oceanic lithosphere thrusted on land, and which has played a key role in establishing fundamental principles in the geodynamics of mid-ocean ridges (e.g., Nicolas et al., 2000). The Oman Ophiolite is also the target of the multi-national Oman Drilling Project (OmanDP, https://www.omandrilling.ac.uk/) within ICDP (International Continental Scientific Drilling Program) that addresses a diverse range of scientific questions relating to the formation, hydrothermal alteration and weathering of oceanic lithosphere. Sections from drill cores obtained within the OmanDP are the key samples used in this study.

In the present study we focus on the hydrous nature of the parental melts forming the Oman ophiolite paleoridge, which is in contrast with the relatively dry nature of primary MORB melts from the East Pacific Rise (EPR) that represents modern fast-spreading oceanic crust. We first evaluate several experimental studies in wet tholeiitic systems performed at shallow crustal pressures, in order to constrain the influence of water on the stabilities of the phases of the deep crystal mush. Secondly, we apply the experimental results to gabbroic sequences from the OmanDP drill cores, focusing on those features which can be regarded as resulting from the hydrous nature of the parental melts. While the assessment that the parental melts at the Oman paleoridge have been hydrous, is mainly based on the composition of the Oman lavas (MacLeod et al., 2013), we focus in this paper on the plutonic foundation of the crust. We provide evidence that characteristic phase relations recorded within the gabbroic crust could be interpreted as a consequence of the presence of elevated water activities (aH_2O) in the parental melts.

The Cretaceous Oman Ophiolite in the Sultanate of Oman shows complete and intact sequences of fast-spreading oceanic crust in many locations. Basic descriptions of the ophiolite and a geological map can be found in Nicolas et al. (2000). Zircon dating has revealed that the paleocrust formed ~95 Ma ago under fast-spreading conditions with a half-spreading rate of 50 – 100 mm/yr (Rioux et al., 2012). In contrast with the contemporary fast-spreading mid-ocean ridges such as the EPR, field relations and geochemical results suggest a polygenetic origin for the Oman ophiolite (e.g., de Graaff et al., 2019). The first magmatic phase produced the so-called V1 lavas and related gabbros that are very similar to the modern EPR, except that the parental MORB melts show enhanced water contents due to the influence of the regional subduction initiation (e.g., MacLeod et al., 2013). The lithologies formed by the phase-1 magmatism build the classical "Penrose" crust (Anonymous, 1972) consisting of, from the bottom to the top, the Moho transition zone, layered gabbros, foliated gabbros, isotropic gabbros, sheeted dikes and pillow basalts. A schematic section through this type of crust and images from outcrops from rocks formed by phase-1 magmatism are shown in Fig. 1 and 2 a-d, respectively. The parental melts for the phase-1 magmatism are of MORB-type, the so called "Geotimes" basalts (e.g., Godard et al., 2003), but with trace element characteristics similar to Eocene forearc basalts (FAB) from the Izu-Bonin-Mariana (IBM) islands (MacLeod et al., 2013), and are thus interpreted as typical basalts generated by decompression peridotite melting during the initiation of an intraoceanic subduction zone (e.g., Agard et al., 2020). By applying MELTS modeling (Ghiorso and Sack, 1995) to the Oman "Geotimes" lava distributed all over the ophiolite, MacLeod et al. (2013) estimated initial water contents in the range 0.2 to > 1 wt% H_2O, which are significantly higher than modern EPR MORB (~0.2 wt% H_2O, le Roux et al., 2006). MELTS calculations related to varitextured gabbros from the southernmost part of the ophiolite generated during accretion phase 1 reveal water contents of 0.4 to 0.8 wt% (Müller et al., 2017).

A second magmatic phase based on flux-induced peridotite melting, normally intruding into the rocks of the first magmatic phase, formed characteristic lithologies like andesitic and boninitic basalts, as well as clinopyroxene-phyric lavas (V2 basalts: see Godard et al. 2003) in the volcanic crust. The corresponding rocks in the plutonic crust, often named "late-stage intrusives" (e.g., Lippard et al., 1986) are wehrlites, gabbronorites, and felsic intrusions (so-called plagiogranites). A schematic section through this type of crust is shown in Fig. 1, and images from outcrops from rocks formed by phase-2 magmatism are shown in Fig. 2 e-h. Such lithologies are unknown from recent fast- and intermediate spreading systems, underlining the difficulties faced when comparing the Oman ophiolite with modern EPR crust. The two-stage magmatic origin of the Oman ophiolite is in accord with models on subduction zone initiation (e.g., Stern, 2004), with an initial phase of spreading in a forearc regime producing typical FAB basalts by decompression mantle melting comparable with the Oman Geotimes basalts (MacLeod et al., 2013), and a second magmatic phase characterized by flux mantle melting. Concerning the tectonic setting of the Oman ophiolite most scientists favor a model on subduction zone initiation (e.g., MacLeod et al., 2013, Rioux et al., 2013; Agard et al., 2020). The strongest arguments for this are the recorded ages in the metamorphic sole (Guilmette et al., 2018) and the high pressures estimated for its formation (up to 1.3 GPa, Cowan et al., 2014).

In spite of the inferred subduction initiation setting of the Oman ophiolite, the following observations related to the first magmatic phase nevertheless demonstrate a close similarity with the modern, fast-spreading EPR: (1) a continuous layered crustal structure with a typical crustal thickness of ~ 6 km, including a coherent plutonic section consisting of typical layered gabbros with a layering parallel to the crust/mantle boundary; (2) the absence of amagmatic spreading that is common at slow-spreading ridges; (3) a very narrow range of zircon crystallization ages across the width of the ophiolite (max ~100 km) sampled normal to the ridge direction; (4) spinel compositions that overlap with those for peridotites from modern ridges (Python et al., 2008); and (5) a well-developed sheeted dike sequence, orientated perpendicular to the Moho.

Many experimental studies conducted in tholeiitic systems under dry conditions in order to understand the evolution of MORB (see reviews in Elthon, 1991, and Grove et al., 1992). These studies are extremely helpful for evaluating details of crystallization processes in dry MORBs, such as those from the modern EPR, but they fail to predict phase relations and phase compositions in hydrous MORB melts, like those "Geotimes" basalts with FAB characteristics forming the main part of the basalts accreted at the Oman paleo ridge. For this, experimental studies in hydrous systems performed under shallow pressures are necessary.

The main effect of water in basaltic systems is the delay in plagioclase in favor of clinopyroxene saturation (e.g., Feig et al., 2006; Gaetani et al., 1993; Neave et al., 2019), with a dramatic effect both on phase relations and phase compositions. The presence of water may stabilize the paragenesis of olivine and clinopyroxene without plagioclase, thus producing a wehrlitic crystallizing assemblage (Feig et al., 2006; Koepke et al., 2009) with the potential to form wehrlites, if these crystals accumulate and segregate. A further effect of suppressing plagioclase crystallization is that the melts get enriched in plagioclase component resulting in melts in which Al_2O_3 is significantly enhanced, which is well known from calc-alkaline basaltic series typically for subduction-zone environments (i.e. High Alumina basalts, Kuno, 1960; Crawford et al., 1987). Another effect of water in basaltic melts is that the liquidus and temperatures of mineral saturations are lowered (e.g., Almeev et al., 2007; Danyushevsky, 2001), and that crystallizing plagioclases are strongly enriched in anorthite content compared to dry conditions (e.g., Botcharnikov et al., 2008; Sisson and Grove, 1993).

Considering the differentiation of MORB within oceanic magma chambers, likely pressures of crystallization can be evaluated quite precisely. Pressures around ~ 200 MPa can be expected for the crystallization processes at the bottom of the crust, corresponding to ~ 6 km depth below sea floor. Lowest pressures of ~ 50 MPa can be expected for crystallization processes within the AML, which is sandwiched between the gabbro and the sheeted dike sequence at about 1.5 km below the seafloor. In dry systems, such a pressure range would have only a small effect on phase relations. However, this is not the case in hydrous systems because water activity strongly depends on water solubility, which varies significantly with pressure, especially at pressures less than 500 MPa (Berndt et al., 2002).

Experiments performed at both dry and at hydrous conditions show that the basic process responsible for the generation of oceanic crust is fractional crystallization of a MORB-type parental melt formed by decompression melting in the shallow mantle beneath the ridge at 1 to 2 GPa (see review in Elthon, 1991). The main stage of crust accretion is manifested by cotectic crystallization in MORB magmas with the characteristic phase assemblage olivine–plagioclase–clinopyroxene which, after accumulation, form mushes that produce typical olivine gabbros. Berndt et al. (2005), Feig et al. (2006; 2010), and Koepke et al. (2018) systematically investigated experimental phase equilibria in primitive and evolved MORB-type basaltic systems as a function of oxygen fugacity (fO_2) and aH_2O. Their combined experimental data enable a profound insight into the main and late stage of crystallization processes within magma chambers at mid-ocean ridges. It is our attempt to integrate the results of these studies, which are perfect suited for highlighting the role of water during crystallization/differentiation, with field and petrographic observations related to the Oman phase-1 gabbros, in order to get new insight into the role of water during the magmatic accretion at the Oman paleoridge. All of these experimental studies used a very similar methodical approach and have been performed by the same working group in the same, highly specialized high-pressure facility. Thus they are well-suited for a global discussion on the relations and stabilities of the phases in MORBs from spreading systems in which elevated water activities play a significant role.

2 Materials and Methods

2.1 Experimental studies used

In this paper we use results from Berndt et al. (2005), Feig et al. (2006; 2010), and Koepke et al. (2018), which were performed at shallow crustal pressures in different hydrous MORB-type systems, in order to evaluate phase relations applicable to magmatic accretion of the deep crust at the Oman paleoridge. These studies report crystallization experiments with glassy starting materials that were performed in the same internally heated pressure vessel (IHPV) at the University of Hannover. Details of the experimental approaches and the starting materials used, pressures and temperatures applied, prevailing water activities and redox conditions can be obtained from Table 1 and from the individual papers. The apparatus used, a vertically oriented IHPV pressured with Ar as pressure medium, is described in detail in Berndt et al. (2002). Under intrinsic conditions (pure Ar) this equipment is fairly oxidizing with fO_2 varying between QFM+3.2 and QFM+4.2 (QFM corresponds to the quartz-magnetite-fayalite oxygen buffer) under water-saturated conditions. In order to perform experiments at more reducing conditions, Ar-H_2 gas mixtures were used as the pressure medium to attain the required fH_2 . The fH_2 prevailing in the IHPV at high P and T was monitored with a Shaw-membrane made of platinum (Berndt et al., 2002). The fH_2 applied in the experiments considered here maintained redox conditions corresponding to fO_2 values between QFM and QFM+2 under water-saturated conditions. Within the sample capsule, fH_2 was fixed due to the inward diffusion of hydrogen controlling the fO_2 inside the capsule through the equilibrium reaction of water formation (H_2 + 1/2 $O_2 \leftrightarrow H_2O$). Thus, in the capsules with $aH_2O < 1$, the redox conditions were more reducing than in the experiments with $aH_2O = 1$ (for details see Botcharnikov et al., 2005). Since aH_2O was varied between < 0.1 and 1 (Table 1), the overall variation in fO_2 in all experimental series was in the range between ~ QFM-3 and ~ QFM+4.2, thus covering the range of oxygen fugacities prevailing in natural MORB magmas (Bézos and Humler, 2005; Zhang et al., 2018; O'Neill et al., 2018).

2.2 Samples from the ICDP OmanDP

The phase relations obtained from experimental studies described above have been applied to rocks drilled within the ICDP OmanDP to address the influence of a water activity on phase-1 magmatic processes operating during the accretion of the deep crust at the Oman paleoridge in an environment of subduction zone initiation. For this, we used samples with characteristic phase parageneses thought to represent a record of hydrous processes. We used samples of drill cores penetrating crustal series from five sites: CM1 and CM2 – traverses through the crust/mantle transition; GT1 – a traverse through the layered gabbro (deep gabbro traverse); GT2 – a traverse through the transition between the layered and foliated gabbro (shallow gabbro traverse); GT3 – a traverse through the gabbro/dike transition. The absolute heights of the CM drill sites within a crustal profile can be obtained directly from the cores (in meters above mantle harzburgite): CM1 - 300 m; CM2 - 130 m. For the GT1 and GT2 cores, the absolute crustal heights of the sites can be obtained from site surveys performed before the drillings: GT1 ~ 1170 m; GT2 ~ 2700 m (see OmanDP, https://www.omandrilling.ac.uk/). The crustal height of site GT3 can be estimated as ~ 4500m, corresponding to an average from Nicolas and Boudier (2000).

These sites are located in the Southernmost massifs of the Oman ophiolite, where the influence of the phase-2 magmatism is low. All these drill sites have been carefully selected by the multi-national working groups within the frame of the OmanDP to ensure that crosscutting lithologies from the phase-2 magmatism don't play any role. This attempt was confirmed during the phase of detailed core characterization, which was performed on the Japanese drill ship Chikyu. Background information, details on the aims of the project, documented in the original ICDP proposal, as well as information of the operational part can be found on the OmanDP home page https://www.omandrilling.ac.uk/. Core characterization followed the methodical guidelines of IODP (International Ocean Discovery Program), and, due to close cooperation with IODP, the scientific results of the OmanDP obtained so far are published under the umbrella of the IODP publishing platform (Kelemen et al., 2020).

3 Results

3.1 Phase diagrams for hydrous magmatism within the oceanic crust

The best approach to evaluate phase relations in hydrous MORB-type system to investigate crystallization processes related to phase-1 magmatism in the axial magma chambers of the Oman paleoridge is to use phase diagrams based on experiments in corresponding hydrous systems performed at shallow crustal pressures. For this, we used four experimental phase equilibria studies initiated to investigate relations and compositions of minerals and melts in MORB systems (Berndt et al., 2005; Feig et al., 2006, 2010; Koepke et al., 2018). Fig. 3 shows the combined results of these studies, where the upper three diagrams address variations in the chemical system performed at identical pressure (200 MPa), while the lower panels focus on the effect of pressure (100, 200, and 500 MPa) in a single chemical system.

Fig. 3a shows phase relations in a primitive natural MORB system from Feig et al. (2010), derived from a re-melted microgabbro from the IODP (International Ocean Drilling Program) Hole 735B drilled at the Southwest Indian Ridge. Fig. 3b presents experiments performed with an average MORB composition from Berndt et al. (2005) obtained from the data base PetDB, synthesized from oxides. Fig. 3c is based on experiments performed in a late-stage MORB system from Koepke et al. (2018), derived with a statistical approach using evolved fresh MORB glasses from the database PETDB highest in FeO and TiO_2 ("FeTi basalt"), which are assumed to represent the last frozen liquids erupted at the seafloor generated by extensive differentiation of MORB. This composition includes P_2O_5 (and sulfur in some experiments). Fig. 3d-f present phase relations from Feig et al. (2006), who used the same system as that from Feig et al. (2010), but applied different pressures (100, 200, 500 MPa) under more oxidizing conditions. The compositions of the systems used are presented in Table 1.

Due to the buffering of fH_2 in the experiments, fO_2 varies in a given experimental series by about three orders of magnitude, depending on the prevailing water activity in the individual runs (see section 2.1). This is demonstrated in the experiments shown in Fig. 3d-f, by the dotted vertical lines, where fO_2 varies between QFM+1 for the runs with lowest water activity, and QFM+4.2 for the runs at water saturation. A similar range in fO_2 is given for the diagrams in Fig. 3a-c, where this effect is not explicitly included in the diagrams. Since basalts from forearcs are more oxidized than basalts from normal ridges (see review in Cottrell et al., 2021 in press), we present in Fig. 3a-c phase diagrams from experiments that were performed under elevated oxygen fugacities at values for QFM > 1 at water saturation, except for Fig. 3b, where the corresponding experiments were performed close to the QFM buffer.

With the help of the combined phase diagrams shown in Fig. 3, we are able to constrain phase relations in hydrous systems within the axial magma chambers beneath ocean spreading centers. Key observations are the crossing saturation curves for plagioclase and clinopyroxene with increasing water content, shown in Fig. 3a, e, f. These phase relations predict a near liquidus phase assemblage of only olivine and clinopyroxene, if a relatively high amount of water is present in the melt. If these crystals segregate and accumulate, wehrlitic mushes could be produced, from which crustal wehrlites would form following the extraction of residual melts (yellow fields in Fig. 3). Thus, the presence of wehrlites instead of troctolites as early cumulates is strongly indicative of a hydrous magmatic environment. The combined phase diagrams highlight further features related to the potential of the system to produce wehrlites. Specifically, the effect depends strongly on the chemical system and the pressure; the wehrlite assemblage is only stable in the most primitive system, (primitive MORB-type system, Table 1), and the potential for forming the wehrlite assemblage decreases with pressure. In the primitive MORB system considered, the wehrlite field shrinks considerably from 500 to 200 MP (Fig. 3e and f) and disappears entirely at 100 MPa (Fig. 3d). We discuss aspects on wehrlite formation further in section 4.1, highlighting phase relations observed in Oman magmatic phase-1 gabbros.

Although the phase diagram compilation in Fig. 3 is designed for hydrous magmatic processes that operated during the accretion of the Oman paleocrust, we note that they can also generally be applied to MORB-type basalts of similar shallow spreading settings. The Oman ophiolite stands for a typical example of fore-arc spreading environment, and we expect to see similar features in other ophiolites with similar geotectonic setting or in fore-arc systems of the actual oceans (i.e., the archetypal Izu-Bonin-Mariana intra-oceanic arc, Arculus et al., 2019).

3.2 Phase diagrams for melts residing in the AML of fast-spreading mid-ocean ridges

At fast- (and intermediate-) spreading ridges, the AML, sandwiched between the gabbro and sheeted dike sequences at about 1.5 km below the seafloor, corresponding to a lithostatic pressure of 50 MPa, are regarded as key reservoirs where crystallization/differentiation takes place (e.g., Coogan, 2014; Wanless and Shaw, 2012). Interestingly, in spite of the importance of these melt reservoirs that are responsible for the accretion of large parts of the Earth's crust, no phase diagrams exist for MORB-type systems at a pressure of 50 MPa. Of course, 1 atm experiments can be used for completely dry systems (e.g., Tormey et al., 1987), since the pressure dependence of phase relations in dry systems is insignificant, at least over the low pressure range considered here. However, this is not the case for hydrous systems, since water activity, which has a significant influence on phase relations and phase composition, varies considerably with pressure due to the strong dependence of water solubility in silicate melts on pressure (Berndt et al., 2002). In Fig. 4, we present two phase diagrams constructed for a hydrous MORB-type system at 50 MPa derived from Feig et al. 2006 and Koepke et al 2018, suitable for predicting phase relations in the AML from fast-spreading mid-ocean ridge systems.

Fig. 4a shows the phase relations in a primitive natural MORB corresponding to an early stage of differentiation from Feig et al. (2006), who studied the role of water and oxygen fugacity on the phase equilibria and differentiation. Under oxidizing conditions, these authors also studied the pressure dependence (100, 200, and 500 MPa), which enable us to construct a phase diagram for 50 MPa by extrapolating Fig. 4 of Feig et al. (2006), where the saturation temperatures of the occurring mineral phases as a function of pressure under water-saturated conditions are shown. Since the pressure influence was only investigated at relatively high oxygen fugacities, the redox conditions for the 50 MPa phase diagram are also relatively oxidizing, ranging from QFM+1 for less hydrous conditions to QFM+4.2 at water-saturation. Feig et al. (2006) showed that common petrological models for evaluating differentiation trends in MORB like MELTS (Ghiorso and Sack, 1995) and COMAGMAT (Ariskin, 1999) failed to predict the experimental phase relations under hydrous conditions at shallow crustal pressures. Therefore, the extrapolation of experimental results to 50 MPa is the best available way to estimate reliable trends of magma evolution in a primitive hydrous tholeiitic system at the magmatic conditions prevailing in the AML of mid-oceanic ridges.

Fig. 4b shows the phase relations at 50 MPa for a typical MORB late-stage system, which was investigated by Koepke et al. (2018) at a pressure of 200 MPa. This system corresponds to a highly evolved MORB, where FeO and TiO_2 are strongly enriched due to extended differentiation under reducing conditions before Fe-Ti oxide saturation is reached. Such compositions are well-known from glasses erupted at the seafloor (Fe-Ti basalts), implying that such evolved melts exist within some AMLs. The pressure dependence of the mineral saturation temperatures at water-saturation was taken from Feig et al. (2006; see above) to construct this diagram.

3.3 Petrographic records of hydrous magmatism within the lower crust

The presence of wehrlitic assemblages within the phase-1 plutonics is a key indicator of hydrous magmatic processes in MORB-type systems. Wehrlites are indeed observed within all OmanDP cores penetrating the lower crust (CM1, CM2, GT1, GT2), but not in in the core through the dike/gabbro transition (GT3). Fig. 5 shows images from cores drilled through the lower crust, showing wehrlitic layers alternating with olivine gabbros or olivine-bearing gabbros within the layered series. Careful macroscopic and microscopic observations of the relevant sections revealed that most of these layers are fully coherent with foliations in the gabbros of the layered series (Kelemen et al., 2020), and are thus clearly not of crosscutting character, as is the case for the magmatic phase-2 wehrlites – typically meter- to decimeter-thick bodies that intrude into the layered series. Massive wehrlites with a maximal thicknesses of ~ 3 meter only occur in the Moho transition zone drilled by CM1 and CM2, while true wehrlite layers in the GT1 and GT2 cores only occur in the cm-scale (see on-site core descriptions for cores GT1 and GT2 available as electronic supplement in Kelemen et al., 2020). From the detailed characterization of the CM cores it is a clear that all wehrlites are associated with the gabbroic series, and never with the mantle sequence, indicating that these wehrlites are of crustal origin.

Thin sections of wehrlites in the four cores reveal different textures as shown in Fig. 6. Pure wehrlites consisting exclusively of olivine and clinopyroxene (plus Cr-spinel) are typical for the crust/mantle cores CM1 and CM2 (Fig. 6a, b). Here, wehrlites occur with poikilitic clinopyroxene bearing small olivine chadacrysts (Fig. 6a), evidencing the crystallization order olivine before clinopyroxene. In the gabbro cores GT1 and GT2 wehrlites occur in coherent, maximally cm-thick layers with interstitial plagioclases (Fig. 6c), implying co-crystallization of olivine and clinopyroxene before plagioclase. Thin sections showing contacts between gabbro and wehrlitic layers reveal smooth, sutured contacts without discontinuities (Fig. 6d). Macroscopic characterization of these contacts reveal planar interfaces that are characterized as modally gradational or sharp and planar (Kelemen et al., 2020). Since many of these wehrlitic rocks in the GT1 and GT2 cores bear more than 5 % plagioclase in the mode, the requirement for naming such lithologies as "wehrlite" is not fulfilled (rock of olivine + clinopyroxene with plagioclase < 5 mode%). Therefore, the scientific teams that described the cores on the Chikyu named these rocks olivine melagabbro (Kelemen et al., 2020). However, in 97% of the characterized intervals of melagabbro in core GT1, and 91% in GT2, the amount of clinopyroxene is significantly higher than that of plagioclase, such that these gabbros clearly show a wehrlitic character. Nevertheless, such wehrlitic gabbros, bearing prismatic olivine and clinopyroxene and interstitial plagioclase, can also be regarded as indicators for hydrous differentiation, since the order of crystallization obtained from the texture (olivine crystallized together with clinopyroxene before plagioclase, Fig. 6c) clearly requires a relatively high prevailing water activities during crystallization. It should be noted that true wehrlites are also present in the crustal cores GT1 and GT2, as demonstrated by Fig. 6d. although not explicitly noted in the corresponding proceedings (Kelemen et al., 2020).

A noteworthy occurrence of wehrlite was observed in the CM1 core, as demonstrated in Fig. 7. Here, within a several decimeter-long core section, a dunite host rock bears both clusters of wehrlitic (only olivine and clinopyroxene) and troctolitic (only olivine and plagioclase) parageneses. This case is discussed in detail in the section 4.2.

Within the GT3 core penetrating the dike/gabbro transition, neither wehrlites nor wehrlitic assemblages have been recorded during core description (Kelemen et al., 2020). Here, an elevated prevailing water activity is expressed by the presence of magmatic amphibole in most gabbros, especially in the so-called varitextured gabbros, which are characterized by the presence of irregular domains/patches with significant variations in grain size, texture, and mineral mode (for details on this term see MacLeod and Yaouancq, 2000). A typical example of a varitextured gabbro from the GT3 core is presented in Fig. 8., where a granular textural domain with magmatic amphibole enclosing plagioclase crystals is shown. In the poikilitic domains of varitextured gabbros, plagioclase forms chadacrysts within poikilitic clinopyroxene, demonstrating the crystallization order plagioclase before clinopyroxene. Later, interstitial amphibole and Fe-Ti oxide crystallized in the granular domains in the interstices between the poikilitic domains. The skeletal structure of clinopyroxene and the needle-like structure of plagioclase often displaying skeletal morphology imply rapid growth (e.g., Holness, 2014), as it is often observed in gabbros regarded to present the frozen filling of an AML (e.g., from EPR at IODP Site 1256, Koepke et al., 2011; Koepke and Zhang, 2021). We discuss the phase relations observed in these rocks considering the phase diagrams extrapolated for the prevailing pressure of 50 MPa in section 4.5.

4 Discussion

4.1 Evidence for wet differentiation of gabbroic rocks from the OmanDP drill cores: formation of wehrlites

Wehrlites are often interpreted as records of melt accumulation or as products of melt/peridotite interaction in the deeper lithospheric mantle at pressures below plagioclase stability. Such rocks have been reported from the sub-continent mantle (e.g., Beard et al., 2007; Shaw et al., 2005), in mantle from convergent margins (e.g., Parkinson et al., 2003; Peslier et al., 2002), and from the sub-ocean mantle (Arai and Takemoto, 2007). These wehrlites often have textures and fabrics typical of mantle rocks (e.g., porphyroclastic or protogranular textures), and show the depleted phase compositions typical for mantle minerals (i.e., high Mg# in olivine and clinopyroxene, very low TiO_2 in spinels). The formation of such "deep" wehrlite has also been confirmed experimentally by reactive crystallization experiments involving lherzolite and basaltic melts at typical mantle pressures (1 to 0.7 GPa) under nominally anhydrous conditions (Saper and Liang, 2014). Since these wehrlites are restricted to a formation with mantle involvement, such a genesis cannot be considered as model of formation of the crustal wehrlites within the Oman ophiolite. For such rocks located at the crust/mantel boundary, Koga et al. (2001) reported a trace element equilibrium with MORB-like liquids, thus disproving a model that the crustal wehrlites are cumulates from an unusual parental melt. Based on an experimental study, Koepke et al. (2009) concluded for discordant crustal wehrlites of the Wadi Haymiliyah in (Haylan massif), which have been formed during magmatic phase 2 at the Oman paleo ridge, an origin due to an advanced amount of water in a MORB system, enabling the he suppression of plagioclase crystallization.

For the wehrlites from the OmanDP drill cores investigated in this study, we suggest a model of early crystallization and accumulation of olivine and clinopyroxene under a high water activity within axial magma chambers of the Oman paleoridge (see section 3.1). In summary, arguments for this are: (1) wehrlites form coherent layers within the layered gabbro series; (2) olivine and clinopyroxene at least from one investigated wehrlite sample, show Mg# significantly lower as those expected for mantle involvement (see section 4.2); (3) the poikilitic structure of some clinopyroxene in wehrlites imply crystallization from a melt and not reaction between mantle and MORB melts (Fig. 6a); (4) the observed wehrlitic assemblages are in fully accordance with predictions from phase relations in hydrous MORB-type systems (see section

3.1); (5) textures of wehrlites are identical to those of the layered gabbros in terms of mineral structures and foliation, and mantle textures are absent. The driving force for this is the well-known feature that water suppresses plagioclase stability in favor of clinopyroxene, thus expanding the "wehrlite field" to higher water activities in the phase diagrams of Fig. 3. For a better understanding, we present a part of the phase diagram of Fig. 3e from Feig et al. (2006) in Fig. 9, which focuses on main-stage crystallization where olivine, plagioclase and clinopyroxene are considered, and other phases are ignored. The lithologies described in Fig. 9 correspond to cumulate rocks which could be formed by accumulation of the crystal phases stable in each field of the diagram.

Path #1 in Fig. 9 points to an evolution by "dry" differentiation, as typical for MORBs from modern EPR. Under dry conditions, it is predicted that the first crystal mush to be formed from two silicate phases is troctolitic, in agreement with predictions from (dry) 1-atm experiments. Indeed, troctolites are well-known from the deep gabbro cores drilled by IODP Expedition 345 at Hess Deep at EPR, where several decameter-thick sections of layered troctolites have been recovered (Gillis et al., 2014). IODP Expedition 345 drilled 16 different holes into the deep gabbros of Hess Deep, but none of them recovered wehrlites or a wehrlitic gabbro. It should be also noted that troctolites are also very common in the lowermost Oman gabbros, especially from the crust/mantle boundary. Since these are regarded to be derived from hydrous melts in an environment of subduction zone initiation, this seems contradictory on a first view. But, this is not the case, as we will see below. Path #2 in Fig. 9 shows a potential differentiation path under high water activities, leading to the formation of wehrlitic mushes, which may evolve into coherent layers of cumulate wehrlite typical for the lowermost crust formed at the Oman paleoridge. Special differentiation conditions are indicated by path #3 in Fig. 9, touching both the troctolite and wehrlite fields, which explains a peculiar phase situation discussed in section 4.2 and shown in Fig. 7, where both wehrlitic and troctolitic domains coexist within one thin section.

Fig. 9 shows that typical olivine gabbros, which are by far the most common rocks in the gabbro series of the Oman lower crust, followed a differentiation path between paths #1 and #3, resulting in the following succession: dunite – troctolite – olivine gabbros. It should be noted that for these gabbro types it is not possible to predict from the phase diagram in Fig. 3a alone, whether differentiation processes took place under dry conditions (like EPR gabbros) or with an elevated water activity (environment of subduction zone initiation). However, for this, the plagioclase composition can be used, as we discuss in the section 4.2 and more detailed in section 4.4.

Many of the wehrlitic rocks from the OmanDP cores GT1 and GT2 bear late plagioclase ("melagabbros", see section 3.3 and Fig. 6c), clearly indicating that crystallization/differentiation did not end in the wehrlite field of Fig. 9, but continued with the saturation of plagioclase. Considering Fig. 9, this can be occur in two ways:

(1) The system simply continues cooling and oversteps the plagioclase saturation curve, following path #2 to the end of the blue arrow in Fig. 9, enabling the crystallization of plagioclase and leading to the evolution of plagioclase-bearing wehrlites. For these "melagabbros" one would predict more evolved mineral compositions, since they correspond to a more advanced differentiation state. However, due to the high water activity in these systems, the plagioclases are extreme An-rich, with An contents very similar as in the earlier crystallized wehrlites (see compositions in Feig et al., 2006). Moreover, since the high water activities also cause higher oxygen fugacities, the systems evolves to higher Fe_2O_3/FeO (Botcharnikov et al., 2005), which drives the systems to high Mg# of olivine and clinopyroxene (Feig et al. 2006, Berndt et al., 2005). The more the melt differentiates and moves away from the wehrlite field, the more plagioclase is produced. This in turn favors the production of olivine gabbros, which are effectively impossible to distinguish from olivine gabbros formed under drier conditions in the field or under the microscope.

(2) Alternatively the system behaves isothermally but the water activity decreases (a horizontal path from the wehrlite field to the left in Fig. 9). In this scenario the water activity may be lowered by magma recharge and replenishment processes analogous to those responsible for the creation of geochemically variable melt inclusion suites in diverse oceanic settings (e.g., Maclennan, 2008), enabling water-poor melts to mix with those water-enhanced residual melts associated with the wehrlitic assemblage. The consequence of this is that the bulk water activity is lowered, enabling the precipitation of plagioclase in a previously wehrlitic assemblage.

It should be noted that beside the water activity other factors like pressure and chemical composition of the system are also important, whether the wehrlitic phase assemblage is stable or not (see section 3.1). Further factors influencing wehrlite stability are variations in redox conditions, and disequilibrium processes (e.g., melt/rock interaction, magma mixing), which are not reflected in the phase diagrams of Fig. 3, since the corresponding experiments were performed under equilibrium conditions.

4.2 Wehrlitic and troctolitic parageneses within the same thin section

One section of the gabbroic part of the OmanDP drill core CM1, which represents a transect through the crust/mantle boundary, records a key phase relationship that affords interesting perspectives on the formation of early cumulates, i.e. wehrlites and troctolites (Fig. 7). In spite of these rocks being very strongly serpentinized, the thin section of interest still shows relics of primary phases, which enables us to investigate the petrogenesis of this rock. The background rock is a dunite which contains circular to oval clusters of either wehrlitic (only olivine and clinopyroxene) and troctolitic (only olivine and plagioclase) assemblages. It is important to note that these clusters coexist over a cm-scale (Fig. 7d). Considering the interpretation of the phase relations shown in Fig. 9, this special phase situation can be explained by differentiation along path #3 in Fig. 9. This path first crossed the dunitic phase domain (formation of the dunitic matrix) and ended at the point where the saturation curves for plagioclase and clinopyroxene are crossing, where both the troctolitic and the wehrlitic phase assemblage are stable (marked in Fig. 9). At that point very minor changes of bulk composition of water activity could then drag the assemblage into either the wehrlite or troctolite field. If the composition landed exactly on the crossing point the system ends up with a three phase assemblage, which is a bit different from the two distinct lithologies observed in the corresponding sample.

Mineral compositions in both the individual clusters and the dunitic matrix in the thin section have been analyzed by electron microprobe. The results are presented in Fig. 7d. Mg# (MgO/(MgO+FeO); molar) for olivine in the dunite in the groundmass (83.7), in the wehrlitic domains (83.4), and in the troctolitic domain (83.9) are relatively low, comparable to values from typical Oman gabbros (e.g., MacLeod and Yaouancq, 2000), thus excluding any formation model for wehrlites within this section that involves typical mantle processes. The An content of the plagioclase of the troctolitic domains is very high (89.4 mol%), in agreement with experimental results from hydrous tholeiitic systems. For instance, Feig et al. (2006) recorded a shift in An from nominally dry to water-saturated conditions of > 20 mol% at a given temperature in their experiments. Thus, the very high An content in the troctolitic domains can be used as a strong argument that they formed under high water activities.

4.3 The amount of wehrlite and wehrlitic gabbro in OmanDP drill cores

One important question relating to the importance of hydrous magmatic processes at the Oman paleoridge is how common wehrlitic assemblages are within the OmanDP drill cores. Amounts of wehrlite and wehrlitic gabbro (i.e. melagabbro) for the different cores are listed (in % of units) in the proceedings of the OmanDP (Kelemen et al., 2020): CM1: 11.7%, CM2: 28.6%, GT1: 3.9%, GT2: 7.9%, GT3: no wehrlites. For CM1 and CM2, the amount of the recorded wehrlite corresponds only to the crustal (gabbroic) part. Thus, the overall amount of wehrlitic rocks within the layered gabbro series is significant, and even in reality higher when the millimeter- to cm-thin wehrlitic layers in layered gabbros series that have been assigned to olivine gabbro units are also considered. From this, it can be concluded that the record of wehrlites all over the drilled transects from the crust/mantle boundary up to the mid-crust where the foliated gabbros become dominant, can be regarded as a clear indication for accretion of the full thickness of the Oman paleocrust under hydrous conditions.

Concerning the evolution of wehrlites with crustal height, three observations are significant: (1) The overall amount of wehrlite decreases with crustal height, (2) the thickness of coherent wehrlite layers decreases with crustal height, and (3) wehrlites disappear in the uppermost part of the plutonic crust (in a crustal level between the GT2 and GT3 cores). This can be explained by a decrease in pressure, since the experimentally derived phase relations show a decrease in the stability of the wehrlite assemblage with pressure (Fig. 3d-f). Another possibility could be that compositions develop to more differentiated compositions with crustal height, as shown for gabbros from the EPR (Lissenberg et al., 2013), which also reduces the stability of the wehrlitic phase domain.

4.4 Further evidence for wet differentiation during the accretion of the Oman paleoridge: elevated An contents in plagioclase

Differentiation paths expressed by An content in plagioclase versus Mg# in clinopyroxenes from gabbros both from the Oman ophiolite and from modern EPR crust are plotted in Fig. 10. In spite of the data's broad scatter, different evolution trends for both areas are visible, as shown in Fig. 10. While the EPR sample suites follow straight evolution trends similar to those from other modern mid-oceanic ridges (Coogan, 2014), the trend for the Oman gabbro shows a clear evolution towards enhanced An contents in plagioclase, which can be interpreted as a consequence of higher water activities in the parental melts forming the Oman paleo ridge. However, the Oman trend is significantly different from evolution trends of typical arc gabbros, where the enrichment in An content is much stronger, as shown by the differentiation path for arc gabbros in Fig. 10 (data from Kvassnes et al., 2004). This emphasizes that the magmatic processes which formed the Oman paleo ridge share more similarities with those active at modern fast-spreading mid-ocean ridges like EPR, than with those related to modern arc crust formation.

4.5 Phase diagrams for the AML and application to the gabbros from OmanDP drill core GT3 penetrating the dike/gabbro transition

The phase diagrams for hydrous MORB systems at 50 MPa allow us to predict crystallization orders for melts freezing in the AML to produce gabbro, i.e., the type of varitextured gabbros (see section 3.3). The phase diagram in 4a is based on pressure dependent experiments in the primitive MORB system performed at fairly oxidizing conditions (varying between QFM~1 at low water activities and QFM+4.2 at water-saturated conditions). A consequence is that this system shows relatively early magnetite saturation, which appears in the diagram of 4a shortly after clinopyroxene, but distinctly before orthopyroxene and amphibole. Since it can be expected that the redox conditions in the real AMLs are lower, the magnetite saturation curve can be significantly lowered or even disappear (Fig. 3a), depending on the prevailing redox conditions and on the composition. On the other hand, when considering more differentiated systems, the magnetite saturation curve will be shifted to higher temperatures, and in that composition, representing a MORB late stage melt, magnetite is even liquidus phase (Fig. 3c, 4b), at redox conditions spanning oxygen fugacities from QFM+1 ($aH_2O = 1$) to QFM-1 ($aH_2O < 1$) (Koepke et al., 2018).

From the phase diagram for a primitive system at 50 MPa (Fig. 4a) the order of main stage crystallization is olivine – plagioclase – clinopyroxene (ignoring magnetite, see above). The corresponding phase assemblage can been observed in some of the varitextured gabbros of the GT3 cores (e.g., Fig. F27 in the proceedings of GT3 in Kelemen et al., 2020), with olivines being totally serpentinized. It is noteworthy that wehrlitic assemblages have not been observed in the GT3 core, in fully concordance with the corresponding phase diagrams (Fig. 3d-f). Varitextured gabbros without olivine are however much more common, as shown in Fig. 8. The petrographic record shows that plagioclase crystallized before clinopyroxene, followed by the late stage crystallization of interstitial amphibole and Fe-Ti oxide, which does not agree with the phase diagram in 4a, because of the missing olivine. There are at least two possible explanations for this.

One explanation is that the system did not crystallize under equilibrium conditions, as was the case for the experiments. Arguments for this are indications for fast crystal growth that can be observed in thin sections (i.e., olivine shows skeletal amoeboid shape; see Fig. F27 in the proceedings of GT3, Kelemen et al., 2020, clinopyroxene shows skeletal structure, and plagioclase forms extreme long crystals often with skeletal morphology). Further arguments for disequilibrium crystallization include reactions observed in thin sections producing amphibole from primary clinopyroxene (see red arrow in Fig. 8), as well as strong plagioclase zoning.

Another reason why olivine is only rarely observed in the gabbros from the AML horizon is that the chemistry of the varitextured gabbro shows evolution towards highly differentiated compositions, such that the phase diagram in Fig. 4b for a hydrous late stage MORB system is more relevant than that in Fig. 4a. Here, the crystallization takes place at much lower temperatures, without olivine as liquidus phase. Instead, magnetite is the first phase which crystallizes, which is in agreement with observations of highly differentiated compositions in varitextured gabbros (ferrogabbros; e.g., Müller et al., 2017; MacLeod and Yaouancq, 2000). According to the proceedings for the core GT3 in Kelemen et al. (2020), the varitextured gabbros span a large compositional field, from fairly primitive (bulk Mg# = 75) to highly differentiated ferrogabbros (bulk Mg# ~36). The phase relations observed in the ferrogabbros of the GT3 core fit quite well with the phase diagram in Fig. 4b: the recorded mineral assemblage consists of magnetite, ilmenite, clinopyroxene and plagioclase produced in the main crystallization stage; orthopyroxene is widely absent; up to 2% apatite is present as late stage phase, as well as high amounts of magmatic interstitial hornblende (see proceedings of GT3 in Kelemen et al., 2020).

4.6 Implications for the accretion of the lower crust at the Oman paleoridge

The frequency of wehrlitic layers within the deep crust recorded in the OmanDP drill cores prominently reflects the hydrous nature of lower crustal Oman phase-1 magmatism. Here, wehrlites and wehrlitic gabbros document special conditions, where local water activities have been significantly increased, with the consequence that plagioclase crystallization was suppressed. These findings have implications for the mechanism of accretion of the lower crust at the Oman paleoridge.

In the gabbro glacier model (see section 1.1) primitive MORB melts are delivered from the mantle to the AML, where differentiation takes place, producing crystals that accumulate in crystal mushes, which fed as crystal-liquid suspension currents the whole lower crust. This model cannot explain wehrlite production within the lower crust according to the model of wehrlite formation established above. Provided a hydrous MORB melt within the axial melt reservoir is water-saturated (aH_2O = 1), then its maximum water content at a pressure of 50 MPa would be ~ 2.2 wt% (Berndt et al., 2002). When according to the gabbro glacier model crystal-liquid suspension currents starts to move downwards towards higher pressure, the water activity decreases because of the strong dependence of water solubility with depth. At a pressure of 100 MPa (the mid-crust) the activity of water in the same melt containing ~2.2wt% water is significantly lower (aH_2O ~ 0.5). At a pressure of 200 MPa (the lowermost crust), water activity is lowered further (aH_2O ~ 0.3), which drastically reduces the potential for crystallizing the wehrlite paragenesis (according to Fig. 3 and 9), at a crustal level where the record of wehrlite within the layered gabbro series is greatest. This simple consideration makes it highly unlikely that the gabbro glacier process played a significant role during the accretion of the Oman deep paleocrust.

Quite different is the evaluation concerning the other endmember model for fast-spread ocean crust accretion, the sheeted sill model, where the deep crust is formed by in-situ crystallization within relatively small melt sills, injected into the crystal mushes of the lower crust (see section 1.1). When considering that intruding melt volumes have different water contents, wehrlite formation in the deep crust is promoted when the water contents of injected melts are particularly high (Fig. 3 and 9). For most injected melts the water contents were lower, i.e., below the threshold for generating the wehrlite stability, so that "normal" olivine gabbros were produced. Recent results on the isotope geochemistry of sub-nano gram samples from the modern lower oceanic crust revealed that individual melts may have derived from distinct mantle components delivered to the lower crust on a cm scale (Lambart et al., 2019). Hence, it is very probable that individual melt batches also could differ in water contents given the close correlation between water and incompatible trace element contents in MORB-like systems (e.g., Michael, 1995; Saal et al., 2002).

According to the sheeted sill mechanism of Kelemen et al. (1997), residual melts with relatively high water activities (i.e., after precipitating the wehrlitic assemblage) may percolate upwards into the overlying mush stockwork and interact with minerals of olivine gabbro mushes residing there. Since these crystals are then in contact with melts enriched in water, reverse mineral zoning in plagioclase would be expected due to the well-known effect of water activity on plagioclase composition (e.g., Botcharnikow et al., 2018; Feig et al., 2006). Indeed, such a zonation trend in plagioclase towards An-richer rims is common for Oman phase-1 layered gabbros (Browning, 1982; MacLeod and Yaouancq, 2000; Mueller, 2016), supporting this model. It should however be noted that such an inverse zonation of plagioclase is not observed in gabbros recovered from the EPR, which further highlights the hydrous nature of the Oman paleocrust with respect to modern fast-spreading mid-ocean ridges. In principle, a further upward percolation would drive water-rich melts towards water saturation, leading to increasing wehrlite formation with crustal height. However, this is not observed, which we attribute (1) to the mixing of such melts with relatively primitive melts, with lower water contents, and (2) to the lower stability of the wehrlite assemblage with upwards decreasing pressure.

In Fig. 11 we present a sketch of our model highlighting the formation of the lower crust in a hydrous MORB system, with focus on wehrlite formation. Central to this is the mode of layer formation in oceanic layered gabbros, which remains poorly understood. The basis for our model is a recent study on layer formation in oceanic gabbros by Mock et al. (2021a), who investigated a two-meter-thick section of a well-known gabbro outcrop in the Wadi Somerah (Sumail massif) that shows decimeter-scale modal layering with olivine abundances gradually decreasing from layer bases to tops, which is the most common type of layering in the Oman lower gabbros. This section was investigated with a high spatial resolution (centimeter-scale) by applying different techniques (EPMA, LA-ICPMS, EBSD, cooling rate speedometry).

Overall, Mock et al. (2020a) suggested that layers were deposited by density currents of crystal-laden magma within a melt sill. Crystallization occurred at the cooler margins of the melt reservoirs, before slumping downward to their bases, establishing layering typical for the lower Oman gabbros. The dynamics within such a current might prevent clear trends in grain size and phase density within a layer, as would be expected in an environment of undisturbed crystal settling. Marked changes of the recorded signals, especially in terms of mineral chemistry and microstructures, even within one layer, emphasizes the importance of replenishment during layer formation. Considering this formation model, we assume that replenishments can also include primary melts with elevated water concentrations, which then may increase the water activity of the system, which in turn could result in the formation of pure wehrlite layers. This would be the case if a differentiation path left of arrow #3 shown in Fig 9 jumps to a path right of arrow #3, due to an abrupt increase of water activity in the system. Such processes operating within an individual melt reservoir are shown in Fig. 11b. An overview through crust and uppermost mantle, highlighting the formation of wehrlitic layers in the lower part of the crust is shown in Fig. 11b.

4.7 Hydration of the lower crust via deep hydrothermal activity

In the model explained above we assume that the water in Oman parental melts responsible for the formation of coherent wehrlite layers and general enrichment of plagioclase An contents is primary in nature, originating from MORB genesis in an setting of subduction zone initiation transiting between decompression and flux melting of mantle (e.g., Stern, 2004; Agard et al., 2020). However, there are alternative explanations for the involvement of water during the magmatic phase 1 at the Oman paleoridge, which are related to hydrothermal processes operating under very high and even magmatic temperatures. Nicolas et al. (2003) observed a thermally induced microcrack network cutting deep layered gabbros in which very high mineral formation temperatures have been recorded. Isotope investigations on the mineralogical fillings of these cracks revealed seawater-derived hydrothermal fluids (Bosch et al., 2004). Other observations from the lower crust of the Oman ophiolite focus on hydrothermal fault zones, cutting the layered gabbro at several places in the southern massifs of the Oman ophiolite, which have the potential to feed the lower crust with seawater-derived fluids (Coogan et al., 2003; Ziehlman et al., 2018). Results of structural and petrological studies in the Wadi Maharam (Sumail massif) revealed that hydrothermally derived water-rich fluids were introduced via normal faults deep into the lower crust within the magmatic regime, producing hydrous cumulate gabbros with anomalously high An contents in plagioclase (An 90%–95%). Benoit et al. (1999) provided isotopic evidence for the correlation between the high An content of plagioclase and Sr isotopes evidencing the sea-water origin of hydrothermal water-rich fluids involved in the petrogenesis of some depleted gabbroic rocks from dikes in the "Maqsad" mantle diapir (Sumail massif). Moreover, Koepke et al. (2014) showed that gabbros from the Wadi Rajmi in the Northern Oman experienced an invasion of seawater-derived fluids along grain boundaries, which triggered partial melting in these rocks. Finally, Rospabe et al. (2019) present evidence showing that hydrothermal water penetration down to the crust/mantle transition along early faults triggered hydrous rock-forming processes at the base of the crust.

All these examples highlight that seawater-derived hydrothermal fluids had the potential to locally penetrate deeply into the plutonic crust during the Oman paleo ridge accretion, catalyzing hydrous magmatism that produced gabbroic rocks anomalous rich in An content of plagioclase. These processes have the potential to remove latent heat of crystallization, which is necessary for enabling in-situ crystallization, following the injection of melt sills into the lower oceanic crust. However, these processes are local phenomena, which cannot account for the widespread enrichment of An content in plagioclases from Oman gabbros (Fig. 10), which is a consequence of elevated primary water contents in the parental melts forming the Oman paleo ridge, due to the tectonic environment of subduction zone initiation.

5 Conclusions

Based on the combined phase relations for hydrous MORB-type systems at shallow pressures and on the petrological record of coherent wehrlites or wehrlitic layers in layered gabbros from phase-1-plutonics recovered by the OmanDP, we draw the following conclusions:

- From the experimentally derived phase relations we conclude that the wehrlitic phase assemblage (olivine coexist with clinopyroxene without plagioclase) is the most significant feature indicative of high prevailing water activities.
- The phase relations imply that the stability of the wehrlitic assemblage decreases with decreasing pressure (not stable in the upper part of the lower crust) and is depending on the chemical system (only stable in primitive MORB systems).
- The application of the results of the evaluation of the phase diagrams in hydrous tholeiitic systems at shallow pressures to the natural gabbroic sequences recovered by the OmanDP provide overwhelming evidence that the magmatic accretion of the lower crust of the Oman Ophiolite paleoridge was wet, as consequence of an origin within an environment of subduction zone initiation.
- While the key petrographic features indicative for the hydrous differentiation at the Oman paleoridge in the lower and mid-crust is the mineral assemblage olivine-clinopyroxene

(without plagioclase), it is interstitial amphibole, often in coexistence with Fe-Ti oxides, in the uppermost plutonic crust (dike/gabbro transition).

- The evaluation of the phase relations in hydrous tholeiitic systems at shallow pressures enable us, to construct phase diagrams for the AML at 50 MPa in a wet system, in order to predict the phase relation in this important melts reservoir.
- Our results shed light on the detailed mechanism of wehrlite formation within the deep crust as a consequence of the prevailing water activity, highlighting the importance of in-situ crystallization in deep sills during crust accretion.

Acknowledgement

This work is dedicated to Prof. Adolphe Nicolas, who inspired JK 20 years ago to perform experiments in hydrous systems in order to understand better the magmatic processes at the Oman paleoridge. In the following years, he and Francoise Boudier, introduced JK into the Oman mountains, performing marvelous, unforgettable field campaigns, often together with friends and students from all over the world.

Many thanks to the reviewers Georges Ceuleneer and Tomo Morishita, and to the editor Philippe Agard for their comments and suggestions which significantly improved this manuscript.

This research used samples and/or data provided by the Oman Drilling Project. The Oman Drilling Project (OmanDP) has been possible through co-mingled funds from the International Continental Scientific Drilling Project (ICDP; Kelemen, Matter, Teagle Lead PIs), the Sloan Foundation – Deep Carbon Observatory (Grant 2014-3-01, Kelemen PI), the National Science Foundation (NSF-EAR-1516300, Kelemen lead PI), NASA – Astrobiology Institute (NNA15BB02A, Templeton PI), the German Research Foundation (DFG: KO 1723/21-1, Koepke PI), the Japanese Society for the Promotion of Science (JSPS no:16H06347, Michibayashi PI; and KAKENHI 16H02742, Takazawa PI), the European Research Council (Adv: no.669972; Jamveit PI), the Swiss National Science Foundation (SNF:20FI21_163073, Früh-Green PI), JAMSTEC, the TAMU-JR Science Operator, and contributions from the Sultanate of Oman Ministry of Regional Municipalities and Water Resources, the Oman Public Authority of Mining, Sultan Qaboos University, CNRS-Univ. Montpellier, Columbia University of New York, and the University of Southampton. This study was funded by DFG projects KO 1723/16-1, 21-1, 25-1, and 27-1. DAN acknowledges support from the Natural Environment Research Council (NE/T011106/1).

Data Availability

In this paper we compiled the results from four experimental phase equilibria studies, which were all published: Berndt et al. (2005), Feig et al. (2006, 2010) and Koepke et al. (2018). All details to the experiments can be found in these papers. The used rocks are personal samples from J.K. of the drill cores CM1, CM2, GT1, GT2, and GT3 recovered in the frame of the ICDP Oman Drilling Project (OmanDP, https://www.omandrilling.ac.uk/). The corresponding cores are stored in the American Museum of Natural History (New York). Samples can be requested from individual researchers via the OmanDP webpage. The core photos are from the supplemental material published on the IODP platform (Kelemen et al., 2020).

References

Abily, B., Ceuleneer, G., Launeau, P., 2011. Synmagmatic normal faulting in the lower oceanic crust: Evidence from the Oman ophiolite. Geology 39, 391-394.

Agard, P, Prigent, C., Soret, M., Dubacq, B., Guillot, S., Deldicque, D., 2020. Slabitization: Mechanisms controlling subduction development and viscous coupling. Earth-Science Reviews 208, https://doi.org/10.1016/j.earscirev.2020.103259

Almeev, R., Holtz, F., Koepke, J., Parat, F., Botcharnikov, R., 2007. The effect of H2O on olivine crystallization in MORB: Experimental calibration at 200 MPa. American Mineralogist 92, 670-674.

Anonymous, 1972. Penrose Field Conference: Ophiolites. Geotimes 17, 24–25.

Arai, S., Takemoto, Y., 2007. Mantle wehrlite from Hess Deep as a crystal cumulate from an ultra-depleted primary melt in East Pacific Rise. Geophysical Research Letters 34, doi:10.1029/2006GL029198.

Arculus, R.J., Gurnis, M., Ishizuka, O., Reagan, M.K., Pearce, J.A., Sutherland, R., 2019. How to create new subduction zones. A Global Perspective. Oceanography 32, 160-174.

Ariskin, A.A., 1999. Phase equilibria modeling in igneous petrology: use of COMAGMAT model for simulating fractionation of ferro-basaltic magmas and the genesis of high-alumina basalt. Journal of Volcanology and Geothermal Research 90, 115-162.

Beard, A.D., Downes, H., Mason, P.R.D., Vetrin, V.R., 2007. Depletion and enrichment processes in the lithospheric mantle beneath the Kola Peninsula (Russia): Evidence from spinel lherzolite and wehrlite xenoliths. Lithos 94, 1-24.

Benoit, M., Ceuleneer, G., Polve, M., 1999. The remelting of hydrothermally altered peridotite at mid-ocean ridges by intruding mantle diapirs. Nature 402, 514-518.

Berndt, J., Koepke, J., Holtz, F., 2005. An experimental investigation of the influence of water and oxygen fugacity on differentiation of MORB at 200 MPa. Journal of Petrology 46, 135-167.

Berndt, J., Liebske, C., Holtz, F., Freise, M., Nowak, M., Ziegenbein, D., Hurkuck, D., Koepke, J., 2002. A combined rapid-quench and H2-membrane setup for internally heated pressure vessels: Description and application for water solubility in basaltic melts. American Mineralogist 87, 1717-1726.

Bézos, A., Humler, E., 2005. The Fe3+/ΣFe ratios of MORB glasses and their implications for mantle melting. Geochimica et Cosmochimica Acta 69, 711-725.

Bosch, D., Jamais, M., Boudier, F., Nicolas, A., Dautria, J-M., Agrinier, P., 2004. Deep and high-temperature hydrothermal circulation in the Oman ophiolite - Petrological and isotopic evidence. Journal of Petrology 451,181-1200.

Botcharnikov, R.E., Almeev, R., Koepke, J., Holtz, F., 2008. Phase relations and liquid lines of descent in hydrous ferrobasalt - Implications for the Skaergaard Intrusion and Columbia River Flood Basalts. Journal of Petrology 49, 1687-1727.

Botcharnikov, R.E., Koepke, J., Holtz, F., McCammon, C., Wilke, M., 2005. The effect of water activity on the oxidation and structural state of Fe in a ferro-basaltic melt. Geochimica et Cosmochimica Acta 69, 5071-5085.

Browning, P., 1982. The petrology, geochemistry, and the structure of the plutonic rocks of the Oman ophiolite. Open University, p. 404.

Canales, J.P., Detrick, R.S., Toomey, D.R., Wilcock, W.S.D., 2003. Segment-scale variations in the crustal structure of 150-300 kyr old fast spreading oceanic crust (East Pacific Rise, 8 degrees 15 ' N-10 degrees 5 ' N) from wide-angle seismic refraction profiles. Geophys. J. Int. 152, 766-794.

Canales, J.P., Nedimovic, M.R., Kent, G.M., Carbotte, S.M., Detrick, R.S., 2009. Seismic reflection images of a near-axis melt sill within the lower crust at the Juan de Fuca ridge. Nature 460, 89-U100.

Carbotte, S. M., Marjanović, M., Arnulf, A. F., Nedimović, M. R., Canales, J. P., Arnoux, G. M., 2021. Stacked Magma Lenses Beneath Mid-Ocean Ridges: Insights From New Seismic Observations and Synthesis With Prior Geophysical and Geologic Findings. Journal of Geophysical Research: Solid Earth 126, e2020JB021434.

Constantin, M., Hékinian, R., Bideau, D., Hébert, R. j. (1996). Construction of the oceanic lithosphere by magmatic intrusions: Petrological evidence from plutonic rocks formed along the fast-spreading East Pacific Rise. Geology 24, 731-734.

Coogan, L. A., Howard, K. A., Gillis, K. M., Bickle, M. J., Chapman, H., Boyce, A. J., . . . Wilson, R. N., 2006. Chemical and thermal constraints on focussed fluid flow in the lower oceanic crust. American Journal of Science 306, 389-427, doi:10.2475/06.2006.01

Coogan, L.A., 2014. The lower oceanic crust; 2nd Edition, in: Turekian, K., Holland, H.D. (Eds.), Treatise on Geochemistry. Elsevier, Amsterdam, pp. 497-541.

Cottrell, E., Birner, S., Brounce, M., Davis, F.A., Waters, L.E., Kelley, K.A., 2021 in press. Oxygen Fugacity Across Tectonic Settings. AGU Geophysical Monograph, in: Neuville, D.R., Moretti, R. (Eds.), Redox variables and mechanisms in magmatism and volcanism. Wiley, p. DOI: 10.1002/essoar.10502445.10502441.

Cowan, R.J., Searle, M.P., Waters, D.J., 2014. Structure of the metamorphic sole to the Oman Ophiolite, Sumeini Window and Wadi Tayyin: implications for ophiolite obduction processes, in: Rollinson, H.R., Searle, M.P., Abbasi, I.A., Al-Lazki, A., Al-Kindi, M.H. (Eds.), Tectonic Evolution of the Oman Mountains. Geological Society of London, Special Publication, Vol. 392, London, pp. 155-175, doi: 110.1144/SP1392.1148.

Crawford, A.J., Falloon, T.J., Eggins, S., 1987. The origin of island-arc High-Alumina basalts. Contributions to Mineralogy and Petrology 97, 417-430.

Danyushevsky, L.V., 2001. The effect of small amounts of H2O crystallisation of mid-ocean ridge and backarc basin magmas. Journal of Volcanology and Geothermal Research 110, 265-280.

de Graaff, S.J., Goodenough, K.M., Klaver, M., Lissenberg, C.J., Jansen, M.N., Millar, I., Davies, G.R., 2019. Evidence for a Moist to Wet Source Transition Throughout the Oman-

UAE Ophiolite, and Implications for the Geodynamic History. Geochemistry Geophysics Geosystems 20, 651-672.

Dick, H. J. B., Natland, J. H. (1996). Late-stage melt evolution and transport in the shallow mantle beneath the East Pacific Rise. Proc. ODP, Sci. Results 147, 103 -134.

Elthon, D., 1991. Experimental phase petrology of mid-ocean ridge basalts, in: Floyd, P.A. (Ed.), Oceanic basalts. Blackie, New York, pp. 94-115.

Ernst, W.G., Liu, J., 1998. Experimental phase-equilibrium study of Al- and Ti-contents of calcic amphibole in MORB - a semiquantitative thermobarometer. American Mineralogist 83, 952-969.

Feig, S., Koepke, J., Snow, J., 2006. Effect of water on tholeiitic basalt phase equilibria: An experimental study under oxidizing conditions. Contributions to Mineralogy and Petrology 152, 611-638.

Feig, S., Koepke, J., Snow, J.E., 2010. Effect of oxygen fugacity and water on phase equilibria of a hydrous tholeiitic basalt. Contributions to Mineralogy and Petrology 159, doi: 10.1007/s00410-00010-00493-00413.

Gaetani, G.A., Grove, T.L., Bryan, W.B., 1993. The influence of water on the petrogenesis of subduction-related igeneous rocks. Nature 365, 332-334.

Ghiorso, M.S., Sack, R.O., 1995. Chemical mass transfer in magmatic processes. IV. A revised and internally consistent thermodynamic model for the interpolation and extrapolation of liquid-solid equilibria in magmatic systems at elevated temperatures and pressures. Contributions to Mineralogy and Petrology 84, 107-145.

Gillis, K.M., Snow, J.E., Klaus, A., and the Expedition 345 Scientists, 2014. Expedition 345. Proceedings of the Integrated Ocean Drilling Program 345.

Godard, M., Dautria, J.-M., Perrin, M., 2003. Geochemical variability of the Oman ophiolite lavas: Relationship with spatial distribution and paleomagnetic directions. Geochemistry Geophysics Geosystems 4, 2002GC000452.

Grove, T. L., Kinzler, R. J., Bryan, W. B., 1992. Fractionation of Midoceanic Ridge Basalt (MORB). in Morgan, J. P., Blackman, D. K., Sinton, J. M. (eds.): Mantle Flow and Melt Generation at Mid-Ocean Ridges, Geophysical Monograph Series 71, 281-310.

Guilmette, C., Smit, M.A., van Hinsbergen, D.J.J., Gurer, D., Corfu, F., Charette, B., Maffione, M., Rabeau, O., Savard, D., 2018. Forced subduction initiation recorded in the sole and crust of the Semail Ophiolite of Oman. Nature Geoscience 11, 688-+.

Henstock, T.J., Woods, A.W., White, R.S., 1993. The accretion of oceanic-crust by episodic sill Intrusion. Journal of Geophysical Research-Solid Earth 98, 4143-4161.

Holness, M.B., 2014. The effect of crystallization time on plagioclase grain shape in dolerites. Contributions to Mineralogy and Petrology 168.

Kelemen, P.B., Koga, K., Shimizu, N., 1997. Geochemistry of gabbro sills in the crust-mantle transition zone of the Oman ophiolite: Implications for the origin of the oceanic lower crust. Earth and Planetary Science Letters 146, 475-488.

Kelemen, P.B., Matter, J.M., Teagle, D.A.H., Coggon, J.A., and the Oman Drilling Project Science Team, 2020. Proceedings of the Oman Drilling Project: College Station, TX (International Ocean Discovery Program), https://doi.org/10.14379/OmanDP.proc.12020.

Koepke, J., Botcharnikov, R., Natland, J.H., 2018. Crystallization of late-stage MORB under varying water activities and redox conditions: Implications for the formation of highly evolved lavas and oxide gabbro in the ocean crust. Lithos https://doi.org/10.1016/j.lithos.2018.10.001.

Koepke, J., France, L., Müller, T., Faure, F., Goetze, N., Dziony, W., Ildefonse, B., 2011. Gabbros from IODP Site 1256 (Equatorial Pacific): Insight into axial magma chamber processes at fast-spreading ocean ridges Geochemistry Geophysics Geosystems 12, doi:10.1029/2011GC003655.

Koepke, J., Berndt, J., Horn, I., Fahle, J., Wolff, P.E., 2014. Partial melting of oceanic gabbro triggered by propagating water-rich fluids: a prime example from the Oman ophiolite. In: H.R. Rollinson, M.P. Searle, I.A. Abbasi, A. Al-Lazki and M.H. Al-Kindi (Editors), Tectonic Evolution of the Oman Mountains. Geological Society of London, Special Publication 392, London, 187-204.

Koepke, J., Schoenborn, S., Oelze, M., Wittmann, H., Feig, S., Hellebrand, E., Boudier, F., Schoenberg, R., 2009. Petrogenesis of crustal wehrlites in the Oman ophiolite: Experiments and natural rocks. Geochemistry Geophysics Geosystems 10, doi:10.1029/2009GC002488.

Koepke, J., Zhang, C., 2021. Axial melt lens dynamics at fast-spreading mid-ocean ridges, in: Vetere, F. (Ed.), Dynamic Magma Evolution. AGU Geophysical Monograph, Vol. 254. Wiley, pp. ISBN: 978-971-119-52113-52116.

Koga, K.T., Kelemen, P.B., Shimizu, N., 2001. Petrogenesis of the crust-mantle transition zone and the origin of lower crustal wehrlite in the Oman ophiolite. Geochemistry Geophysics Geosystems 2, 2000GC000132.

Kuno, H., 1960. High-alumina Basalt. Journal of Petrology 1, 121–145, https://doi.org/10.1093/petrology/1.2.121.

Kvassnes, A. J. S., Strand, A. H., Moen-Eikeland, H., Pedersen, R. (2004). The Lyngen Gabbro: The lower crust of an Ordovician Incipient Arc. Contributions to Mineralogy and Petrology 148, 358-379.

Lambart, S., Koornneef, J.M., Millet, M.-A., Davies, G.R., Cook, M., Lissenberg, C.J., 2019. Highly heterogeneous depleted mantle recorded in the lower oceanic crust. Nature Geoscience 12, 482-+.

le Roux, P.J., Shirey, S.B., Hauri, E.H., Perfit, M.R., Bender, J.F., 2006. The effects of variable sources, processes and contaminants on the composition of northern EPR MORB (8-10 degrees N and 12-14 degrees N): Evidence from volatiles (H2O, CO2, S) and halogens (F, Cl). Earth and Planetary Science Letters 251, 209-231.

Lippard, S.J., Shelton, A.W., Gass, I.G., 1986. The ophiolite of Northern Oman. Blackwell Scientific Publ., Oxford.

Lissenberg, C. J., MacLeod, C. J., Howard, K. A., Godard, M. (2013). Pervasive reactive melt migration through fast-spreading lower oceanic crust (Hess Deep, equatorial Pacific Ocean). Earth and Planetary Science Letters 361, 436-447. doi:10.1016/j.epsl.2012.11.012

MacLennan, J., 2008. Concurrent Mixing and Cooling of Melts under Iceland. Journal of Petrology 49, 1931-1953.

MacLeod, C.J., Lissenberg, C.J., Bibby, L.E., 2013. "Moist MORB" axial magmatism in the Oman ophiolite: The evidence against a mid-ocean ridge origin. Geology 41, 459-462.

MacLeod, C.J., Yaouancq, G., 2000. A fossil melt lens in the Oman ophiolite: Implications for magma chamber processes at fast spreading ridges. Earth and Planetary Sciences Letters 176, 357-373.

Michael, P.J., 1995. Evidence from trace elements and H2O for regionally distinctive sources of depleted MORB: Implications for evolution of the depleted mantle. Earth and Planetary Science Letters, 131, 301–320; doi:10.1180/minmag.1994.58A.2.52.

Miller, D. J., Iturrino, G. J., Christensen, N. I. (1996). Geochemical and petrological constraints on velocity behavior of lower crustal and upper mantle rocks from the fast-spreading ridge at Hess Deep. Proc. ODP, Sci. Results 147, 477-490.

Mock, D., Neave, D.A., Muller, S., Garbe-Schonberg, D., Namur, O., Ildefonse, B. and Koepke, J., 2021a. Formation of Igneous Layering in the Lower Oceanic Crust From the Samail Ophiolite, Sultanate of Oman. J. Geophys. Res.-Solid Earth, 126(1): 29.

Mock, D., Ildefonse, B., Muller, T., Koepke, J., 2021b. A Reference Section Through Fast-Spread Lower Oceanic Crust, Wadi Gideah, Samail Ophiolite (Sultanate of Oman): Insights From Crystallographic Preferred Orientations. J. Geophys. Res.-Solid Earth 126(6): 27.

Müller, T., 2016. A petrological and geochemical cross section of lower crust at the Wadi Gideah (Samail ophiolite): Implications for the crustal accretion at fast-spreading mid-ocean ridges. University of Hannover, p. 199.

Müller, T., Koepke, J., Garbe-Schonberg, C.D., Dietrich, M., Bauer, U., Wolff, P.B., 2017. Anatomy of a frozen axial melt lens from a fast-spreading paleo-ridge (Wadi Gideah, Oman ophiolite). Lithos 272, 31-45.

Natland, J. H., Dick, H. J. B. (1996). Melt migration through high-level gabbroic cumulates of the East Pacific Rise at Hess Deep: the origin of magma lenses and the deep crustal structure of fast-spreading ridges. Proc. ODP, Sci. Results 147, 21-58.

Neave, D.A., Namur, O., Shorttle, O., Holtz, F., 2019. Magmatic evolution biases basaltic records of mantle chemistry towards melts from recycled sources. Earth and Planetary Science Letters 520, 199-211.

Nicolas, A., Boudier, F., 2000. Large mantle upwellings and related variations in crustal thickness in the Oman ophiolite. Geological Society of America Special Paper 349, 67–73.

Nicolas, A., Boudier, F., Ildefonse, B., Ball, E., 2000. Accretion of Oman and United Arab Emirates ophiolite - Discussion of a new structural map. Marine Geophysical Researches 21, 147-179.

Nicolas, A., Mainprice, D., Boudier, F., 2003. High temperature seawater circulation throughout crust of oceanic ridges. A model derived from the Oman ophiolite. Journal of Geophysical Research 108, No. B8.

O'Neill, H.S.C., Berry, A.J., and Mallmann, G., 2018. The oxidation state of iron in Mid-Ocean Ridge Basaltic (MORB) glasses: Implications for their petrogenesis and oxygen fugacities. Earth and Planetary Science Letters, 504, 152–162, doi:10.1016/j.epsl.2018.10.002.

Pallister, J. S., Hopson, C. A. (1981). Samail Ophiolite plutonic suite: Field relations, phase variation, cryptic variation and layering, and a model of a spreading ridge magma chamber.

Journal of Geophysical Research: Solid Earth 86(B4), 2593-2644. doi:10.1029/JB086iB04p02593

Parkinson, I.J., Arculus, R.J., Eggins, S.M., 2003. Peridotite xenoliths from Grenada, Lesser Antilles Island Arc. Contributions to Mineralogy and Petrology 146, 241-262.

Perk, N. W., Coogan, L. A., Karson, J. A., Klein, E. M., Hanna, H. D. (2007). Petrology and geochemistry of primitive lower oceanic crust from Pito Deep: implications for the accretion of the lower crust at the Southern East Pacific Rise. Contributions to Mineralogy and Petrology 154, 575-590. doi:10.1007/s00410-007-0210-z

Peslier, A.H., Francis, D., Ludden, J., 2002. The lithospheric mantle beneath continental margins: Melting and melt-rock reaction in Canadian Cordillera xenoliths. Journal of Petrology 43, 2013-2047.

Python, M., Ceuleneer, G., Arai, S. 2008. Chromian spinels in mafic–ultramafic mantle dykes: Evidence for a two-stage melt production during the evolution of the Oman ophiolite. Lithos 106, 137–154.

Rospabe, M., Benoit, M., Ceuleneer, G., Kaczmarek, M.A., Hodel, F., 2019. Melt hybridization and metasomatism triggered by syn-magmatic faults within the Oman ophiolite: A clue to understand the genesis of the dunitic mantle-crust transition zone. Earth Planet. Sci. Lett. 516, 108-121.

Rioux, M., Bowring, S., Kelemen, P., Gordon, S., Dudas, F., Miller, R., 2012. Rapid crustal accretion and magma assimilation in the Oman-UAE ophiolite: High precision U-Pb zircon geochronology of the gabbroic crust. Journal of Geophysical Research-Solid Earth 117.

Rioux, M., Bowring, S., Kelemen, P., Gordon, S., Miller, R., Dudas, F., 2013. Tectonic development of the Samail ophiolite: High-precision U-Pb zircon geochronology and Sm-Nd isotopic constraints on crustal growth and emplacement. Journal of Geophysical Research-Solid Earth 118, 2085-2101.

Saal, A.E., Hauri, E.H., Langmuir, C.H., Perfit, M.R., 2002. Vapour undersaturation in primitive mid-ocean-ridge basalt and the volatile content of Earth's upper mantle. Nature 419, 451-455.

Saper, L., Liang, Y., 2014. Formation of plagioclase-bearing peridotite and plagioclase-bearing wehrlite and gabbro suite through reactive crystallization: an experimental study. Contributions to Mineralogy and Petrology 167, doi:10.1007/s00410-014-0985-7

Shaw, C.S.J., Eyzaguirre, J., Fryer, B., Gagnon, J., 2005. Regional variations in the mineralogy of metasomatic assemblages in mantle xenoliths from the West Eifel Volcanic Field, Germany. Journal of Petrology 46, 945-972.

Sisson, T.W., Grove, T.L., 1993. Experimental investigations of the role of H2O in calc-alkaline differentiation and subduction zone magmatism. Contributions to Mineralogy and Petrology 113, 143-166.

Stern, R.J., 2004. Subduction initiation: spontaneous and induced. Earth and Planetary Science Letters 226, 275-292.

Tormey, D.R., Grove, T.L., Bryan, W.B., 1987. Experimental petrology of normal MORB near the Kane Fracture Zone: 22°-25° N, Mid-Atlantic Ridge. Contributions to Mineralogy and Petrology 96, 121-139.

VanTongeren, J. A. (2021). The composition of the lower oceanic crust in the Wadi Khafifah section of the southern Samail (Oman) ophiolite. Retrieved from: https://doi.org/10.5061/dryad.c59zw3r6v.

Vera, E.E., Mutter, J.C., Buhl, P., Orcutt, J.A., Harding, A.J., Kappus, M.E., Detrick, R.S., Brocher, T.M., 1990. The structure of 0-my to 0.2-my old oceanic crust at 9° N on the East Pacific Rise from expanded spread profiles. Journal of Geophysical Research-Solid Earth and Planets 95, 15529-15556.

Wanless, V.D., Shaw, A.M., 2012. Lower crustal crystallization and melt evolution at mid-ocean ridges. Nature Geoscience 5(9), 651-655.

Zihlmann, B., Müller, S., Coggon, R. M., Koepke, J., Garbe-Schönberg, D., & Teagle, D. A. H., 2018. Hydrothermal fault zones in the lower oceanic crust: An example from Wadi Gideah, Samail ophiolite, Oman. Lithos 323, 103-124. doi:10.1016/j.lithos.2018.09.008

Zhang, H.L., Cottrell, E., Solheid, P.A., Kelley, K.A., and Hirschmann, M.M., 2018. Determination of $Fe^{3+}/\Sigma Fe$ of XANES basaltic glass standards by Mössbauer spectroscopy and its application to the oxidation state of iron in MORB. Chemical Geology. 479, 166–175, doi:10.1016/j.chemgeo.2018.01.006.

Figures captions

Fig. 1. Schematic section through the Oman ophiolite showing the products of phase-1 magmatism (left) and phase-2 magmatism, the late-stage intrusives (right). "Melt lens" stands for

frozen AML lithologies which are mostly represented by isotropic gabbros (varitextured). "Moho TZ" stands for Moho Transition Zone.

Fig. 2. Images from outcrops in the Oman Ophiolite related to the magmatic phase 1 (a – d) and phase 2 (e – h) during ocean crust accretion. (a) Layered gabbro in the Wadi Haylayn. (b) Isotropic gabbro with cm-long hornblende needles in the Wadi Haymiliyah. (c) Sheeted dikes in the Wadi Scheik. (d) Pillow basalts in the Wadi Jizzi. (e) Black wehrlites crosscutting layered gabbros in the Wadi Haylan. (f) Gabbronorite (left) crosscutting layered gabbro with steep layering (right) in the Wadi Haymiliyah. (g) Large plagiogranite intrusion within upper gabbros near the Somerah oasis. (h) V2 lava flow showing columnar jointing with clinopyroxene-phyric basalts in the Wadi Jizzi.

Fig. 3. Phase diagrams for different hydrous MORB-type systems performed at shallow pressures addressing the phase relations in axial magma chambers from the Oman paleoridge and from other spreading centers in a similar geotectonic setting in an environment of subduction zone initiation. (a) to (c): results of experiments in different MORB-type systems performed at 200 MPa. (a) Primitive natural MORB from Feig et al. (2010). (b) Model MORB from Berndt et al. (2005). (c) MORB late stage system (Fe-Ti basalt) from Koepke et al. (2018). (b) and (c) are redrawn with water content in the melt on the x-axis. (d) to (f): Primitive natural MORB from Feig et al. (2006) performed at different pressures (100, 200, 500 MPa). Due to the fH_2 buffering of the experiments in the used experimental equipment (IHPV), fO_2 varies in the experiments, depending on the prevailing water activity in the individual runs. This is demonstrated in the experiments shown in (d) to (f), by the dotted vertical lines, where fO_2 varies between QFM+1 for the more dry, and QFM+4.2 for the runs at water saturation. A similar range is given for the diagrams (a) to (c), which are performed under more reducing conditions (maximum fO_2 of QFM+2). The phase saturation curves correspond to the appearance (+) and disappearance (-, dotted) of phases in the corresponding experiments. Abbreviations: Ol - olivine, Cr-sp - chromium-rich spinel, Cpx - clinopyroxene, Opx - orthopyroxene, Plag - plagioclase, Mag - magnetite, Amph - amphibole, Ap - apatite, Ilm -ilmenite. The yellow field marks the stability of the wehrlite assemblage (olivine coexist with clinopyroxene without plagioclase). For details see text.

Fig. 4. Phase diagrams for hydrous MORB-type systems in the axial melt lens of fast-spreading mid-ocean ridges (50 MPa). Two chemical systems are shown: (a) Primitive natural MORB from Feig et al. (2006) corresponding to an early stage of differentiation; (b) MORB late stage system from Koepke et al. (2018) corresponding to a highly evolved MORB system (Fe-Ti basalt). For explanation of the curves and for abbreviations see Fig. 3. The dashed lines with arrows correspond to typical differentiation paths. For details see text.

Fig. 5. Images from cores drilled within the ICDP OmanDP program showing wehrlite layers within series of layered gabbroic host rocks. The drill cores are from transects through the crust/mantle boundary (CM1, a, b), through the layered gabbros (GT1, c), and through the transition between layered and foliated gabbro (GT2, d). Olivine is in all sections strongly serpentinized leading to blackish colors. (a) Layered series with alternating layers of olivine gabbro and wehrlite. (b) Boundary between wehrlite (top) and olivine gabbro (bottom). Note that the clinopyroxenes in the wehrlite show poikilitic structures, with small olivine chadacrysts. From such a lithology is thin section image shown in Fig. 6 a. (c) Coarser grained coherent wehrlite layers within finer grained olivine gabbro showing serpentinite veins parallel to the direction of layering. (d) Boundary between wehrlitic gabbro (top) and olivine-bearing gabbro (bottom), with smooth, sutured contact. The scale can be derived from the sample name presented below the images, where the last numbers indicate the length of the shown section in cm (code for sample name: Hole#_core#_section#, cm top – cm bottom). The core fotos are from the supplemental material published on the IODP platform (Kelemen et al., 2020).

Fig. 6. Microphotographs from thin section showing wehrlites in the cores recovered in the frame of the ICDP OmanDP program, from the crust mantle boundary (cores CM1 and CM2), the deep crust (GT1, representing layered gabbros), and the mid crust (GT2, representing the transition between layered and foliated gabbros). (a) Wehrlite of drill core CM1 consisting of exclusively olivine and clinopyroxene. Note the poikilitic structure of the clinopyroxenes, bearing chadacrysts of small olivines (mostly serpentinized); the interstitial areas with whitish color correspond to serpentinite. Sample CM1_58_4, 47-51 cm. (b) Massive layered wehrlites of drill core CM2 with coherent wehrlite layers. The sample is moderately altered. Sample CM2_104_3, 0-2 cm. (c) Coherent wehrlite layer in layered gabbros of the drill core GT1. This rock consists of prismatic olivine and clinopyroxene with a few percent of interstitial plagioclase

in the mode, implying a crystallization order of co-crystallization of olivine and clinopyroxene and late crystallization of plagioclase. Sample GT1_38_4, 36-40 cm. (d) Coherent layers of wehrlite (upper part) and olivine-bearing gabbro (lower part) in layered gabbros of drill core GT2, which penetrated the transition between layered and foliated gabbro in the mid-crust. The wehrlite consists of clinopyroxene and olivine, which is totally altered to iddingsite. A late serpentinite vein crosscuts both lithologies. Abbreviations: ol - olivine, cpx - clinopyroxene, plag - plagioclase. Sample GT2_81_4, 38-43 cm.

Fig. 7. Images from a section of the OmanDP drill core CM1 (transect through the crust/mantle boundary) and related microphotographs. (a) Section CM1_18_2, 6-26 cm showing the evolution from olivine gabbro to a dunitic zone with co-existing circular to oval clusters of wehrlitic and troctolitic assemblages highlighted in the microphotographs in (b) to (d). (b, c) microphotographs from clusters with troctolitic (b) and wehrlitic (c) parageneses shown in (d). (d) Thin section foto from the dunitic zone with troctolitic and wehrlitic clusters shown in (a). Averages of mineral compositions for individual clusters and for the dunitic matrix are shown (Mg# for olivine, ol, and clinopyroxene, cpx; An content for plagioclase, pl). Note the extremely high An content of 89.4 mol% which is typical for hydrous systems. The thin section is from a deeper area (CM1_18_2, 62-67 cm) not shown in (a). The core foto in (a) and the whole thins section foto in (d) are modified images from the supplemental material published on the IODP platform (Kelemen et al., 2020).

Fig. 8. Microphotograph of a varitextured gabbro from Oman DP drill core GT3 (transect through dike-gabbro transition); parallel (a) and crossed (b) polarizers. Shown is an example of a domain with granular texture with late magmatic brown poikilitic amphibole enclosing small plagioclase crystals. The brown amphibole is of magnesiohastingsitic composition, which is in the outer parts hydrothermally altered to green hornblende and actinolite. As formation temperature, 970 °C has been estimated with the Ti-in-amphibole geothermometer of Ernst and Liu (1998). The red arrow points to a relic of clinopyroxene within the amphibole. Abbreviations like in Fig. 6 plus am – amphibole. Sample GT3_130-2,12-18 cm.

Fig. 9. Detail of the phase diagram shown in Fig. 3 e, for a hydrous primitive natural MORB system based on crystallization experiments performed by Feig et al. (2006) at 200 MPa with

focus on the main stage crystallization, ignoring the saturation curves of spinel, orthopyroxene, amphibole, and magnetite. The included lithologies correspond to potential cumulate rocks which could be formed by phase accumulation according to the stability fields of the phases. Possible differentiation paths are included: Paths #1 for "dry" parental melts; path #2 for a condition with a high water concentration, enabling a high water activity; path #3 touches both the troctolite and the wehrlite field, and explains the phase situation shown in Fig. 7 (both wehrlitic and troctolitic domains are stable). For details see text.

Fig. 10. Chemical mineral evolution expressed by An content in plagioclase versus Mg# in clinopyroxenes for gabbros from the Oman ophiolite and from EPR crust. The data for Oman are from Müller (2016, Wadi Gideah), VanTongeren (2021, Wadi Kafifah), Browning (1982, Wadi Abyad), and Pallister and Hopson (1981, Ibra area). The data for Hess Deep are from Dick and Natland (1996), Miller et al. (1996), Natland and Dick (1996), and Lissenberg et al. (2013); those from Pito Deep are from Perk et al. (2007), and Constantin et al. (1996). Data from IODP Hole 1256D are from Koepke et al. (2011). Included are also evolution paths for gabbros from Oman and EPR, as well as for typical arc gabbros which is based on data presented in Kvassnes et al. (2004). For details see text.

Fig. 11. Sketch of our model highlighting the magmatic formation of the lower crust at the Oman paleo ridge in a hydrous MORB system, with focus on wehrlite formation. (a) Overview through the plutonic crust and uppermost mantle, highlighting the formation of wehrlitic layers in the lower two third of the crust, which are formed by injected melt sills after the model of Kelemen et al. (1997). In this model, differentiated melt within an individual sill is pressed out due to compaction and moves upward, resulting in an upward differentiation trend for the lower crust. Due to the dependence on pressure and composition, the wehrlite formation is strongest at the base of the crust fading out upward. Deep gabbro sills injected into the mantle are also included, which may contain layers of wehrlite (Koga et al, 2001). The upper third of the plutonic crust follows a different mode of emplacement by crystal mush suspensions originating from the axial melt lens, according to recent results of Mock et al. (2021b), which are based on microstructural data obtained from rock samples of a profile through the whole lower crust in the Wadi Gideah (Wadi Tayin massif, Oman ophiolite). The AML is fed with primitive melt delivered from the upper mantle by a central melt channel. From here, the upper third of the crust is accreted by

downward crystal mush flows (white dashed arrows). According to Mock et al. (2021b) the lower gabbros consists of layered gabbros and a the lower part of the foliated gabbros, and the upper gabbros of the upper part of the foliated gabbros and varitextured gabbros. The arrows left show the lithostatic pressure and the pressure dependent water solubility according to Berndt et al. (2002). Size of the sills is out of scale; km b.s.: km below seafloor. (b) Detail of the mechanism of the formation of coherent wehrlite layers within one melt sill, based on the model for layer formation within deep oceanic gabbros of Mock et al. (2020a), suggesting that individual layers are deposited by density currents of crystal-laden magma within a melt sill. Crystallization occurred at the cooler margins of the melt reservoirs, before slumping downward to their bases, establishing the layering typical for deep gabbros accreted at fast-spreading ridge systems. At the initial time t = 0, a layer of olivine gabbro is produced by crystallization of hydrous parental MORB left of path #3 in Fig. 9. At t = 1, through replenishment, a MORB melt significantly enriched in water enters the system, which then increases the water activity of the system, which in turn result in the formation of pure wehrlite layers according to a differentiation path right of path #3 in Fig. 9. At t = 2, a further replenishment set the system back to the "normal" mode with differentiation left of path #3 in Fig. 9, producing layers of typical olivine gabbro with plagioclase enriched in An content, due to the elevated water contents in these melts.

Table captions

Table 1. Details of the experimental studies on hydrous MORB-type systems performed at shallow pressures used in this paper.

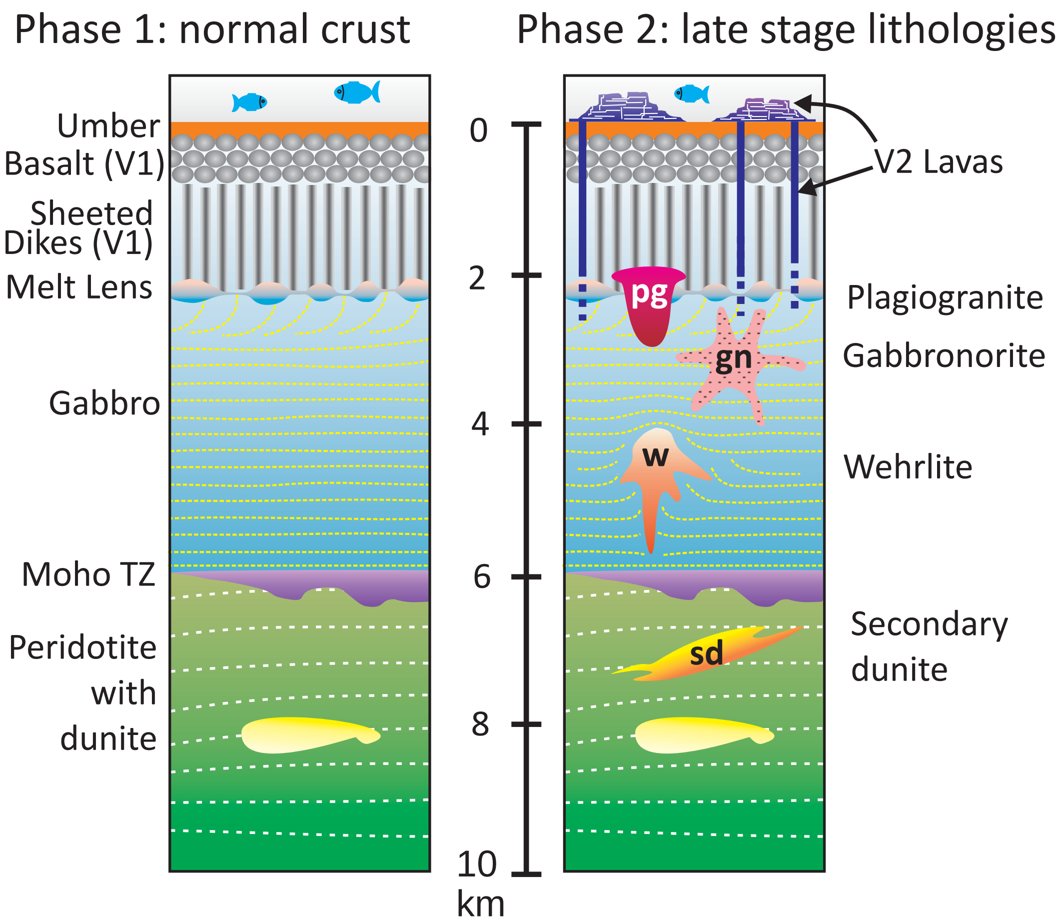
Table 1. Details of the experimental studies on hydrous MORB-type systems performed at shallow pressures used in this paper

Study	System	Pressure	Temperature	Redox	Water addition	Water activity	Duration
Feig et al. (2006)	primitive MORB (natural system)	100, 200, 500 MPa	940 to 1220°C	QFM+1.0 to QFM+4.2	mixes of water and silver oxalate	0.04 - 1	22-91 hours
Feig et al. (2010)	primitive MORB (natural system)	200 MPa	940 to 1220°C	QFM-3.0 to QFM+2.1	mixes of water and silver oxalate	0.02 - 1	2-115 hours
Berndt et al. (2005)	model MORB	200 MPa	950 to 1150°C	QFM-3.4 to QFM+4.2	use of pre-hydrated glasses	0.02 - 1	2-72 hours
Koepke et al. (2018)	late-stage system (FeTi basalt)	200 MPa	850 to 1050°C	QFM-1.1 to QFM+3.2	mixes of water and silver oxalate	0.07 - 1	48-170 hours

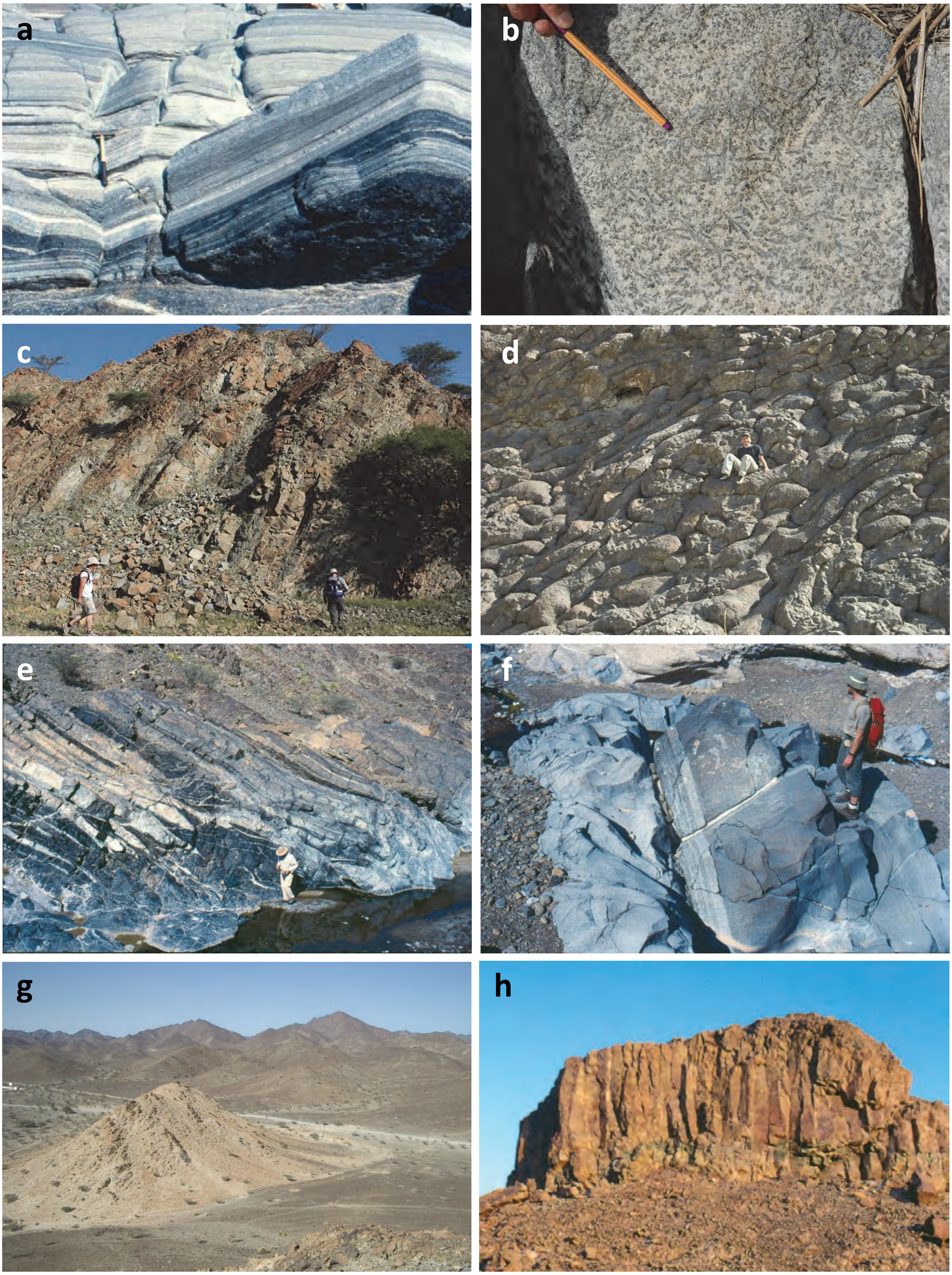
Chemical compositions

Study	SiO_2	TiO_2	Al_2O_3	FeO_{tot}	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total
Feig et al. (2006, 2010)	50.43	0.35	17.18	6.50	0.16	10.12	11.54	2.84	0.04	< 0.03	99.16
Berndt et al. (2005)	49.64	0.87	16.07	8.63	0.15	9.77	12.44	2.28	0.08	0.08	100.0
Koepke et al. (2018	49.56	3.73	11.42	17.92	0.31	3.89	8.93	2.85	0.28	0.65	99.66

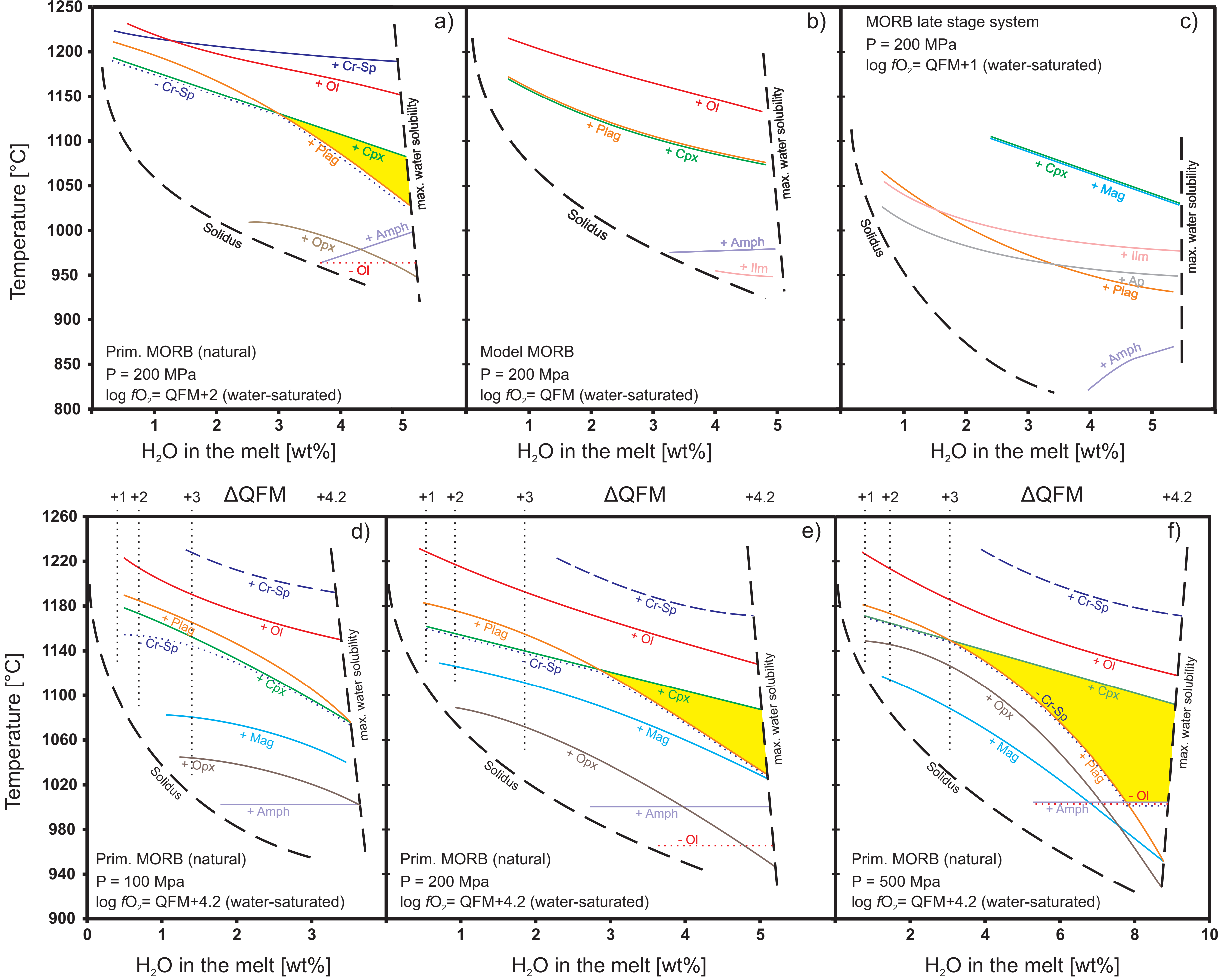
Koepke et al., Table 1



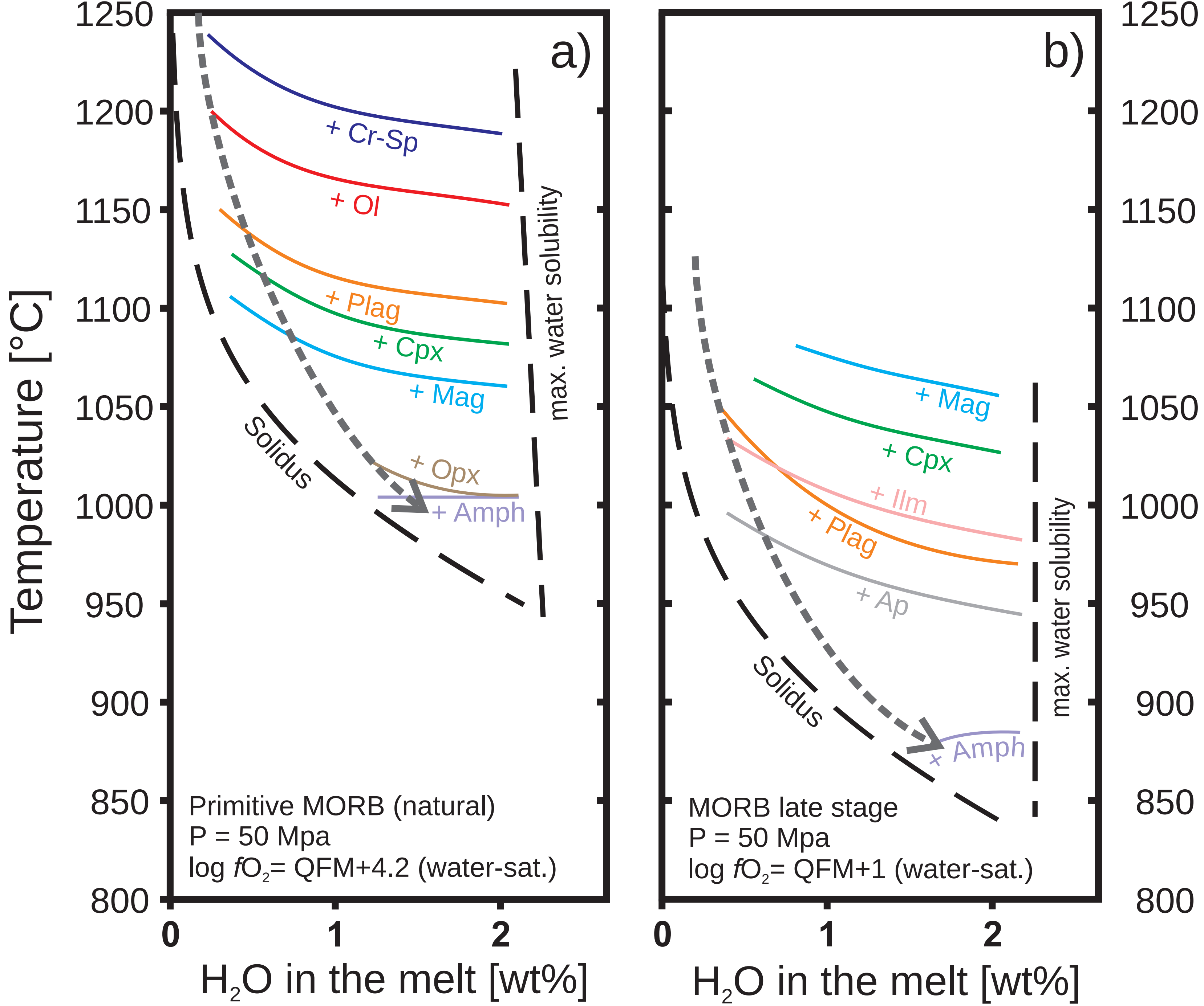
Koepke et al., Fig. 1



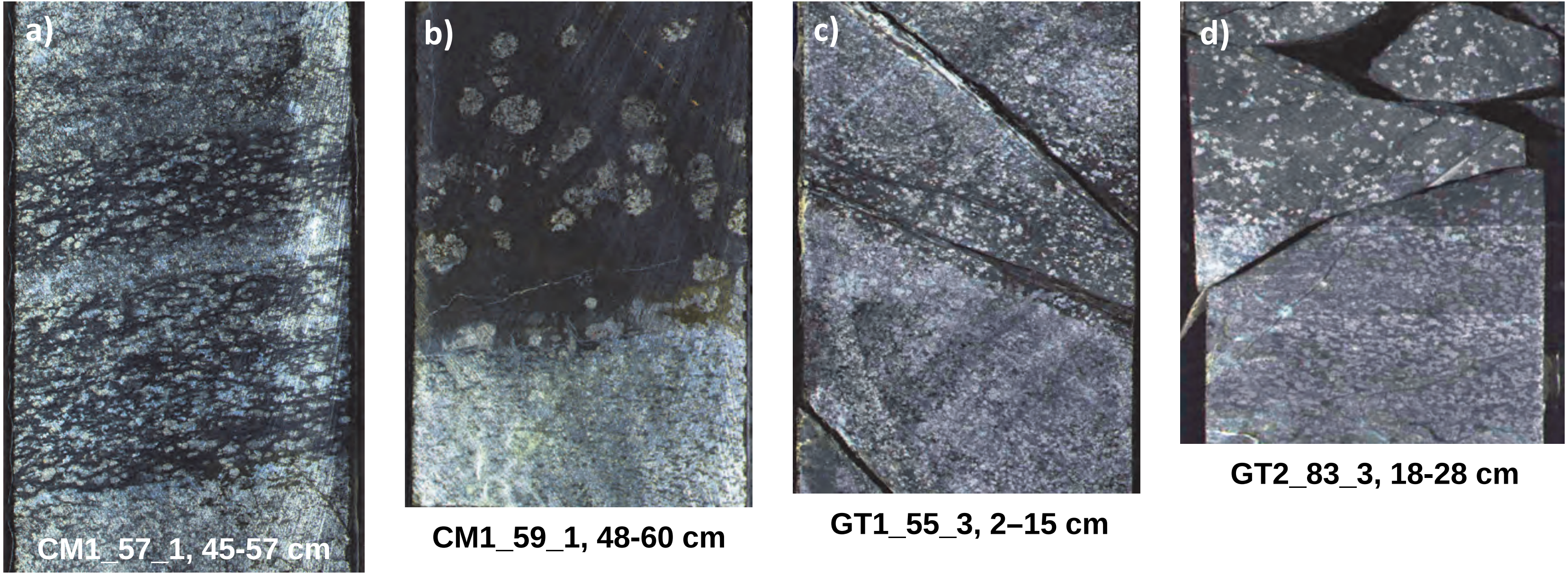
Koepke et al., Fig. 2



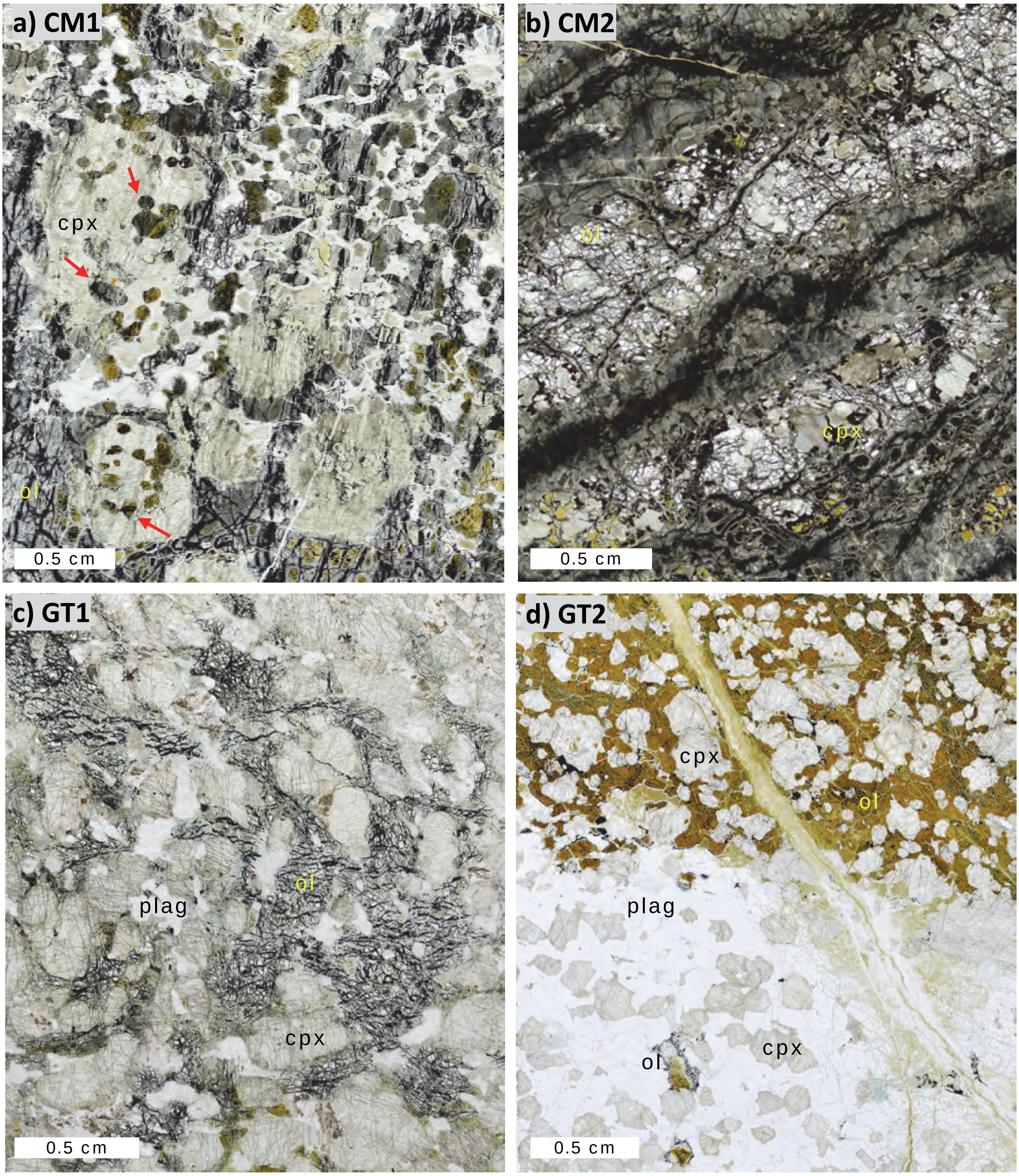
Koepke et al., Fig. 3



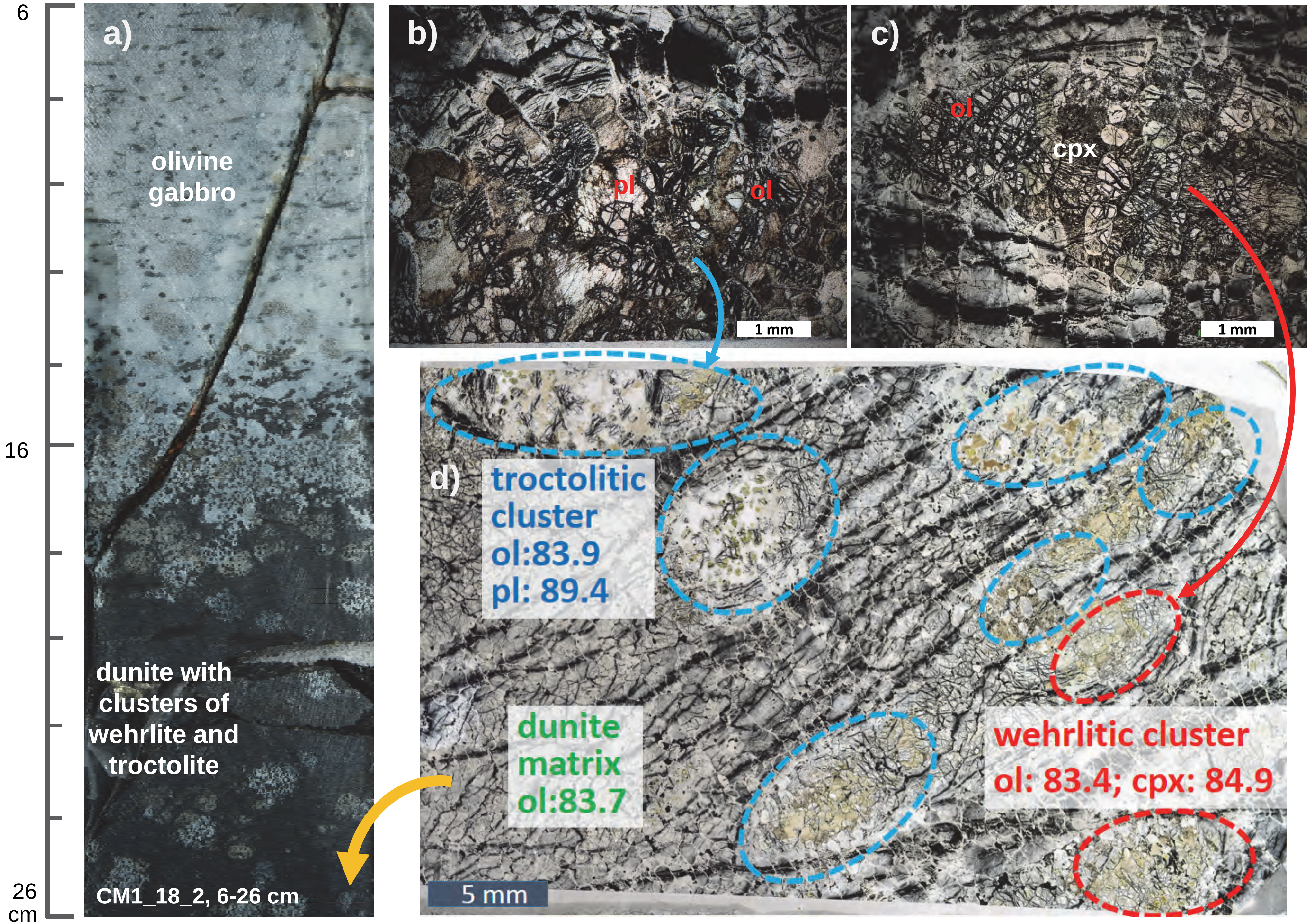
Koepke et al., Fig. 4



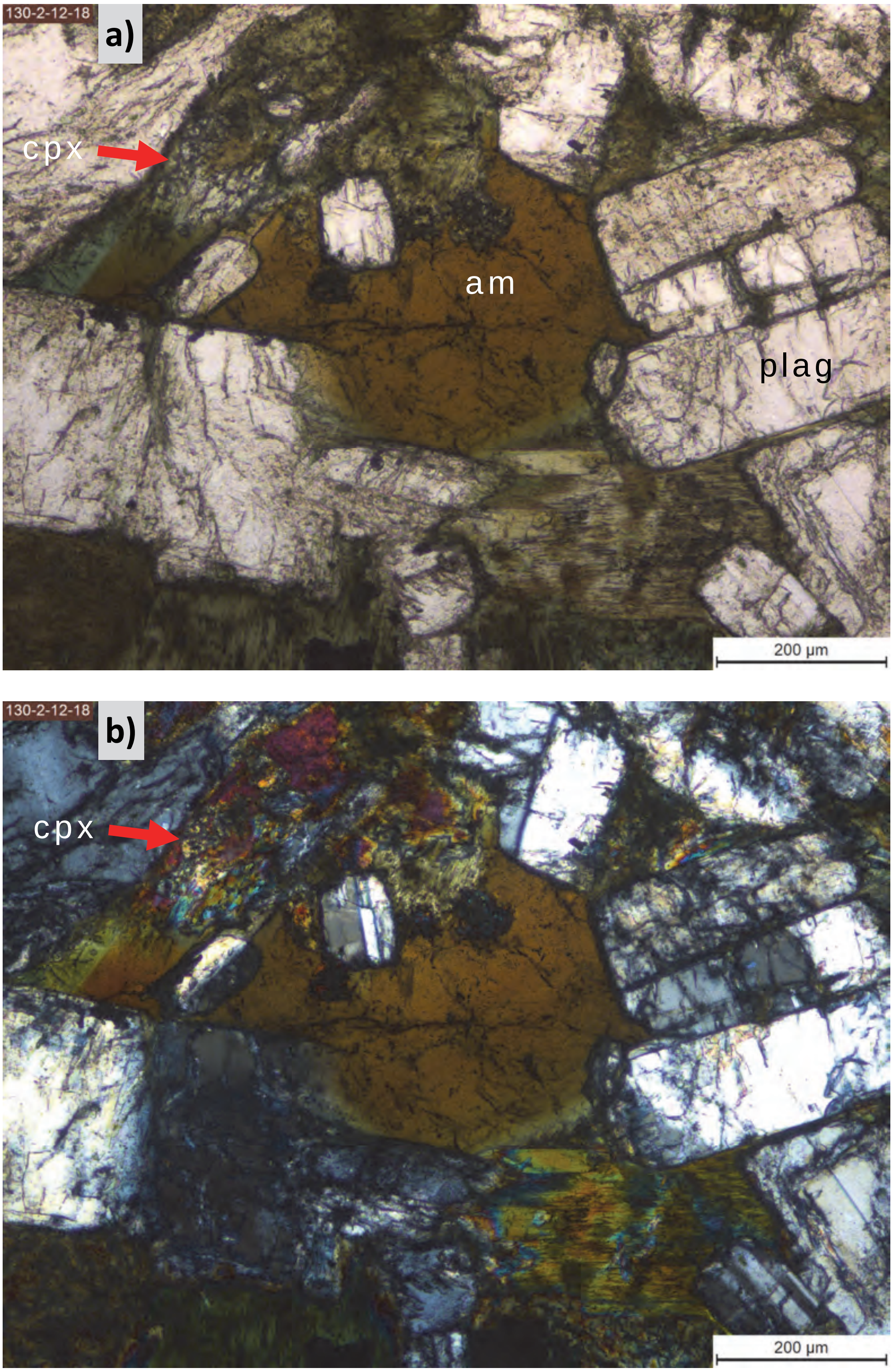
Koepke et al., Fig. 5



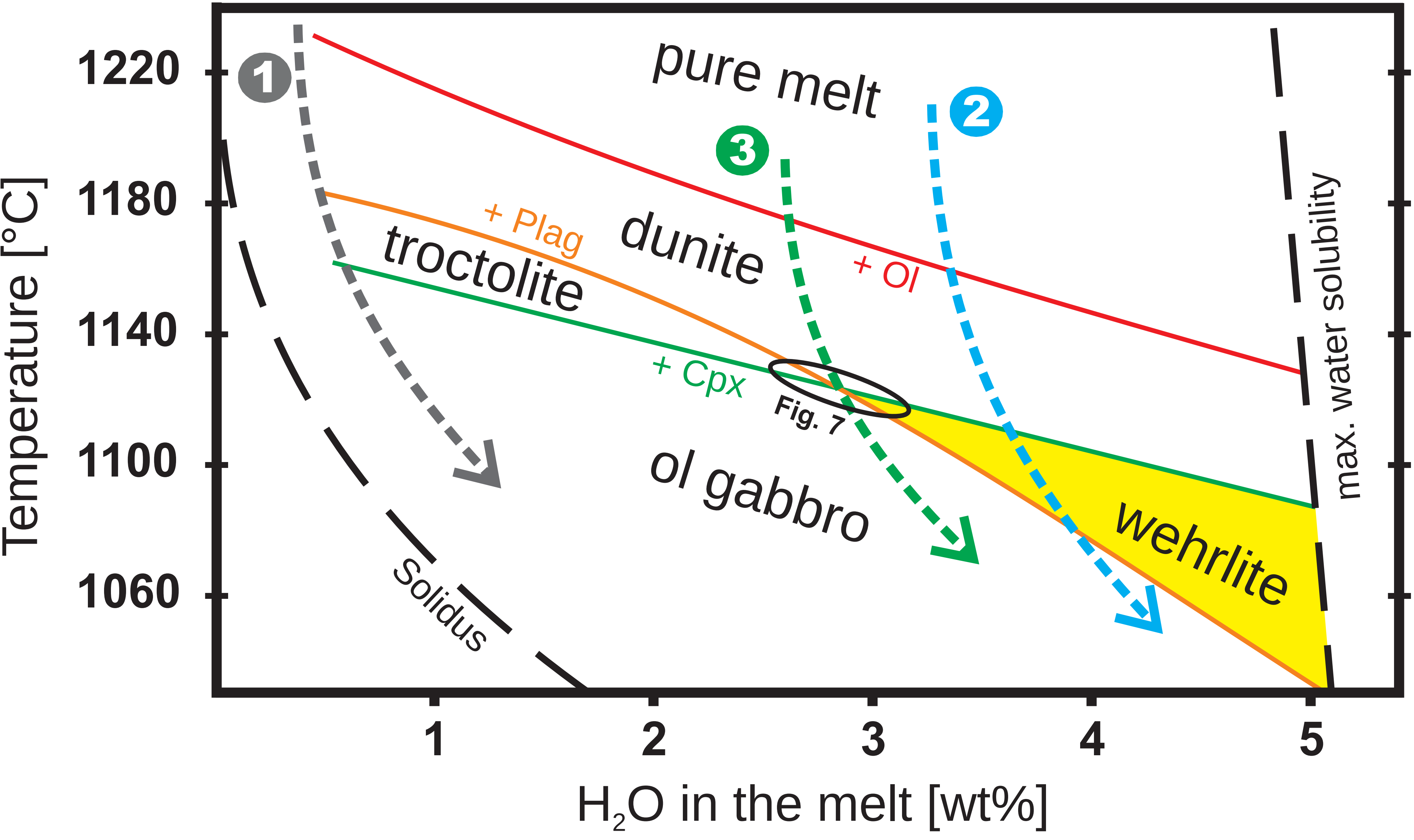
Koepke et al., Fig. 6



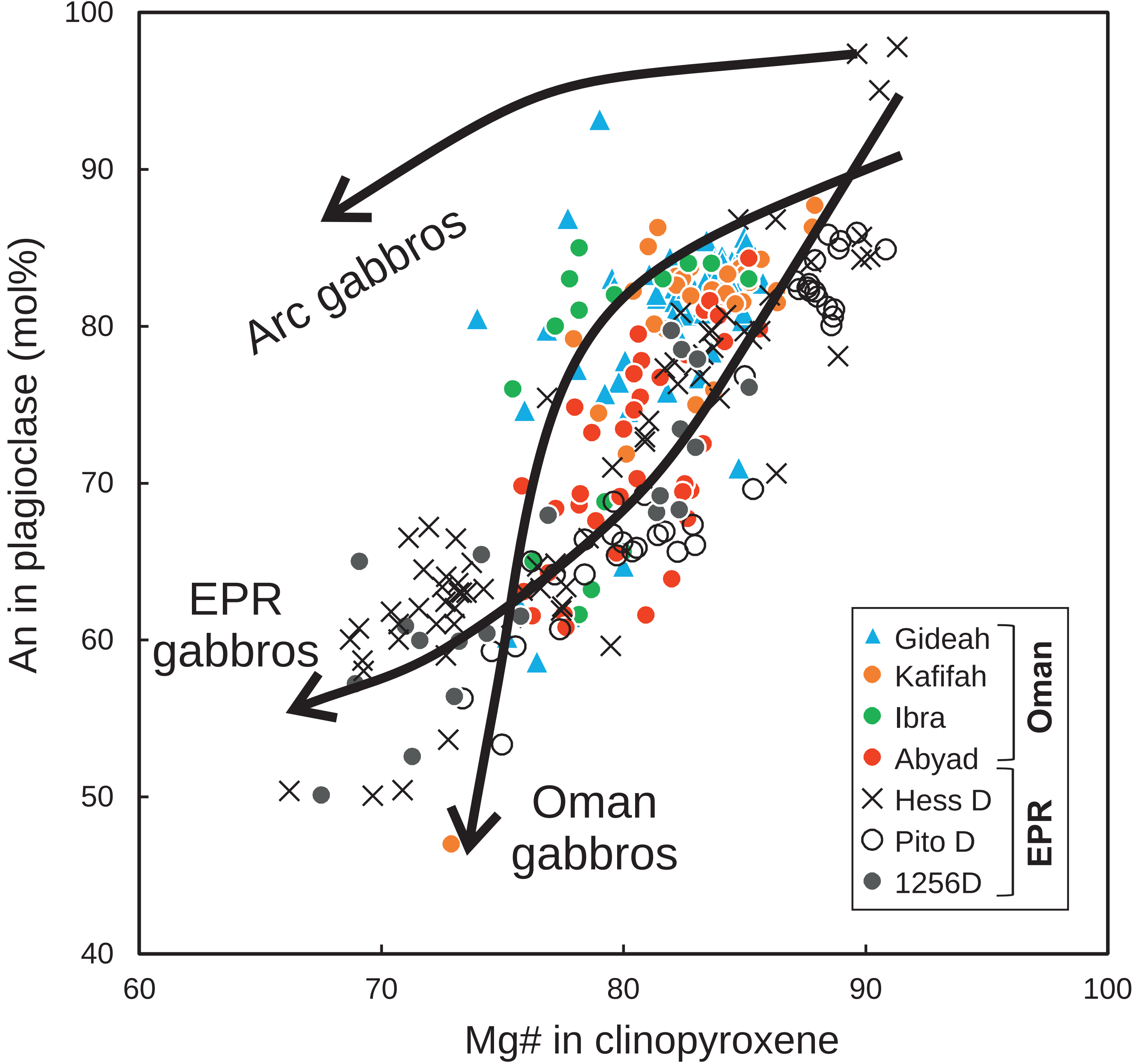
Koepke et al., Fig. 7



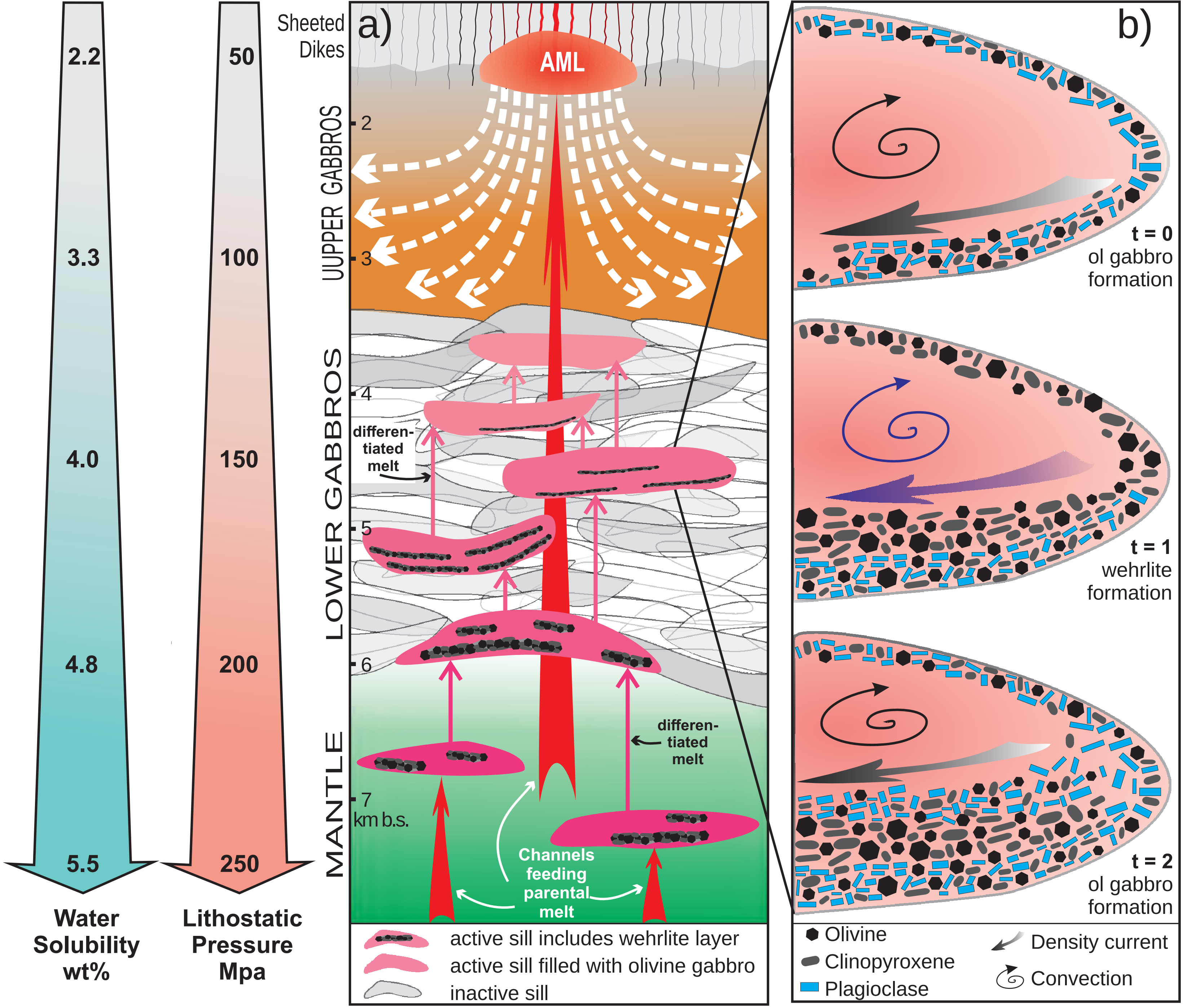
Koepke et al., Fig. 8



Koepke et al., Fig. 9



Koepke et al., Fig. 10



Koepke et al., Fig. 11