Formation and preservation of fresh lawsonite: Geothermobarometry of the North Makran Blueschists, southeast Iran

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17 Short Title:

18 Lawsonite-blueschists in North Makran, Iran

19 Abstract

20 A low-grade metamorphic “Coloured Mélange” in North Makran (SE Iran) contains lenses and a
21 large klippe of low temperature, lawsonite-bearing blueschists formed during the Cretaceous
22 closure of the Tethys Ocean. The largest blueschist outcrop is a >1000 m thick coherent unit with
23 metagabbros overlain by interlayered metabasalts and metavolcanoclastic rocks. Blueschist
24 metamorphism is only incipient in coarse grained rocks whereas finer grained, foliated samples
25 show thorough metamorphic recrystallization. The low variance blueschist peak assemblage is
26 glaucophane, lawsonite, titanite, jadeite $\pm$ phengitic mica. Investigated phase-diagram sections of
27 three blueschists with different protoliths yield peak conditions of $\sim$ 300-380°C at 9-14 kbar.
28 Magnesio-hornblende and rutile cores indicate early amphibolite-facies metamorphism at
29 $>460^{\circ}\text{C}$ and 2-4kbar. Later conditions at slightly higher pressures of 6-9 kbar at 350-450°C are
30 recorded by barroisite, omphacite and rutile assemblages before entering into the blueschist
31 facies and finally following a retrograde path through the pumpellyite-actinolite facies across the
32 lawsonite stability field. Assuming that metamorphic pressure is lithostatic pressure, the
33 corresponding counterclockwise P-T path is explained by burial along a warm geothermal
34 gradient ($\sim 15^{\circ}\text{C}/\text{km}$) in a young subduction system, followed by exhumation along a cold
35 gradient ($\sim 8^{\circ}\text{C}/\text{km}$); a specific setting that allows preservation of fresh undecomposed lawsonite
36 in glaucophane-bearing rocks.

37 Key words: *lawsonite blueschists, Deyader Complex, North Makran, HP/LT metamorphism,*
38 *counterclockwise P-T path*

INTRODUCTION

Blueschist-facies rocks are markers of fossil subduction zones and preserve information on the pre-collisional history of convergent plate boundaries (e.g. Ernst, 1972; Maruyama *et al.*, 1996). Peak mineral assemblages record high pressure/low temperature conditions and elucidate parts of the tectonometamorphic evolution of the rocks in the subduction channel. Yet, precise and accurate determination of peak pressure and temperature (P-T) conditions is often challenging, especially in metabasites whose low-variance mineral assemblages have extensive stability fields. For instance, the relatively rare lawsonite is stable over a large range of pressure, temperature and fluid composition P-T-X(CO₂/O₂) (e.g. Liou, 1971; Nitsch, 1974; Chatterjee *et al.*, 1984; Heinrich & Althaus, 1988; Schmidt & Poli, 1994; Poli & Schmidt, 2002). Lawsonite usually marks the prograde P-T path during burial and is commonly preserved as pseudomorphs during retrogression (e.g. Maruyama & Liou, 1988; Martin & Tartarotti, 1989; Massone 1995; Clarke *et al.*, 1997). Despite the many occurrences of lawsonite blueschists all over the world (e.g. Tsujimori & Ernst, 2014), chemically unaltered lawsonite is rarely found in exhumed subduction complexes. This indicates that its preservation requires a rather uncommon P-T evolution and exhumation history (Zack *et al.*, 2004; Whitney & Davis, 2006). The potential processes responsible for the preservation of fresh lawsonite have been discussed, mainly in studies concerning lawsonite eclogites (e.g. Tsujimori & Ernst, 2014; Tsujimori *et al.*, 2006; Whitney & Davis, 2006). Several lawsonite-bearing blueschist occurrences also have been assigned to a counterclockwise P-T path involving retrograde, nearly isobaric cooling (e.g. Wakabayashi, 1990; Krogh *et al.*, 1994; Perchuk *et al.*, 1999; Smith *et al.*, 1999).

This study reports new geological, petrological and geochemical data of the North Makran Blueschists (NMB), which contain fresh lawsonite in a blueschist assemblage without retrograde

overprint. Jadeite is also part of the metamorphic mineral assemblage, making the NMB a rare and motivating object to study the formation and preservation of such minerals. Isochemical phase diagram sections (P-T sections) were calculated using free-energy minimization (Connolly, 2005) to specify pressure and temperature conditions of equilibration. Results point to the importance of young and warm subduction/accretion coupled with fast exhumation as tectonic circumstance under which counterclockwise P-T paths evolve and minerals of the lawsonite-blueschist facies are preserved.

GEOLOGICAL SETTING

Blueschists and ophiolites outline the former convergent plate boundaries (e.g. Okay, 1989; Maruyama *et al.*, 1996). In southeast Iran, the Makran accretionary wedge developed above the still active northward subduction of the Arabian oceanic plate beneath the Eurasian continent (Fig. 1). This wedge extends ~1000 km from the Strait of Hormuz in the west to near Karachi, Pakistan, in the east. The present-day north-northeast-trending convergence has a slower rate of 35.5-36.5 mm/a in the west than in the east (40-42mm/a in the east; DeMets *et al.*, 2010). The Cenozoic turbiditic sediments of the Makran accretionary wedge were likely deposited on the Arabian oceanic crust (McCall, 2002). Ophiolites and a low-grade metamorphic complex with blueschist lenses, the Deyader Complex, are thrust southwards onto the wedge (Burg *et al.*, 2013). Imprecisely located blueschist samples to the north-east of the study area are dated 87.9 ± 5 Ma (K-Ar ages on sodic amphiboles; Delaloye & Desmons, 1980). This age is consistent with clastic glaucophane in Campanian/Maastrichtian (ca 83.5 -65.5 Ma) sandstones of the wedge (Dolati, 2010). The lack of datable metamorphic zircons and the scarcity of very fine grained, often altered phengitic mica prevented obtaining geochronological constraints from the studied rocks.

Deyader Complex

The metamorphic Deyader Complex (DC) extends about 65 km from east to west, <25 km in north-south direction and has faulted contacts with the adjacent formations (Fig. 2). It is part of the “Coloured Mélange” ascribed to the Tethys sutures in Iran (Stöcklin, 1968; McCall, 1997). Most of the DC consists of dismembered and tectonically mixed, multiply folded very low-grade (pumpellyite-actinolite facies) metasediments, mostly shales, sandstones, pebbly mudstones and marbles. Meter- to kilometer-scale blocks of mostly metabasic rocks in a low grade shale matrix show greenschist- and blueschist-facies overprint. The gross structure places the Deyader Complex in an antiformal stack, so that to the north, north-dipping normal faults delineate the contact to Jaz Murian Quaternary deposits covering ophiolitic harzburgites. North and west of Yagri Jaan and to the west of Guank settlements (Fig. 2), thrust faults place the ophiolites onto the DC.

Blueschist occurrences

The largest (~30 km²) blueschist outcrop extends around the mountain Kuh-e Taftah in the northeastern corner of the Deyader Complex (Figs. 2 and 3a) and exposes a ~3 km thick continuous section (Fig. 3b). The Kuh-e Taftah klippe was likely linked to smaller outcrops to the northwest, now isolated after erosion of incised valleys near the village of Zeyarat (Figs. 2 and 3a). These outcrops are klippen on low-grade metasediments (Fig. 4a). The western basal thrust contact of blueschists show dominantly top to SW-wards movement (Fig. 4b) but the eastern and southern boundary of the main blueschist klippe is a southeast dipping thrust that brings ophiolite-derived serpentinite and sediments on top of blueschists (Fig. 4c). On the

106 southwestern side of the antiformal stack (Fig. 2) blueschists occur as <200 m long tectonic
107 lenses in the low-grade slaty matrix of the DC.

108 Blueschists were classified in the field according to their macroscopic texture into (1) meta-
109 pillow lavas (2) massive blueschists and (3) layered blueschists. Meta-pillow basalts (Fig. 5a)
110 occur at the northwestern tip of the ~5 km² blueschist outcrops to the east of Zeyarat (Figs. 2 and
111 3a). They were also found in the southwestern part of the Kuh-e Taftah klippe and as blocks and
112 lenses scattered within the slaty matrix of the DC. Meta-pillows are not or weakly deformed, so
113 that their bottom-tailed shape demonstrates their normal position in larger scale outcrops.

114 Massive blueschists were classified into two textural types: fine grained (<0.5mm) and coarse
115 grained (up to several mm) rocks. Both types show freshly cut blue surfaces and black weathered
116 exposure. A weak foliation is common. Fine grained, massive blueschists occur in the western
117 part of Kuh-e Taftah. They commonly form thick (>1m) layers within layered blueschists. They
118 also are abundant as blocks in the DC matrix. In view of their homogeneous texture and outcrop
119 features, they are interpreted as metabasalts. Coarse grained massive blueschists (Fig. 5b) are
120 mainly found in the eastern part of Kuh-e Taftah (Fig. 3b). Blueish domains and slightly finer
121 white minerals often define a coarse compositional layering interpreted as originally magmatic.
122 Accordingly, these rocks are interpreted as metagabbros. Metabasalts and metagabbros are
123 weakly deformed but are cut by subvertical conjugate fractures filled with breccias of blueschist
124 fragments cemented by calcite (Fig. 5c). Layered blueschists occur on the eastern side of Kuh-e
125 Taftah and as blocks within the slaty Deyader matrix. Most of the layered blueschists are
126 characterized by few millimeter thick green and usually few centimeter thick blue layers. The
127 well-defined layering and graded beddings in some layers suggest sedimentary protoliths. One
128 very distinct, continuous sandy layer (Mak-08-54, Fig. 5d) occurs within the eastern section of

the Kuh-e Taftah (Fig. 3b). Graded bedding shows an upward younging direction. Other layered blueschists, the only type found in the southern part of the DC, are alternating blue and green metasediments (Fig. 5e). The blue amphibole-rich layers may represent metamarl or very fine volcanoclastic sediments whereas the green layers are similar to the slaty matrix of the DC. Layered blueschists are often strongly folded (Fig. 5f) and are interpreted as metavolcanoclastic sequences. The layered blueschists locally show sedimentary structures and lack evidence of hornfels overprint. This suggests that they were deposited on gabbro, which was eroded and exposed before metamorphism.

PETROGRAPHY

Seventy five thin sections were investigated under the optical microscope to choose 15 representative rocks of different blueschist types and mineral assemblages (Table 1). In very fine-grained samples, X-ray diffraction (XRD), electron microprobe and Raman spectroscopy were employed to determine the mineralogical composition.

Metagabbros

Metagabbros are comprised of (~10-20%) sodic (Na) and (~40-50%) sodic-calcic (Na-Ca)-amphiboles, lawsonite (~30%), titanite $\pm$ Na-pyroxene $\pm$ rutile $\pm$ pumpellyite $\pm$ quartz $\pm$ aragonite $\pm$ actinolite (10-15%). A weak alignment of small sodic amphibole, sodic pyroxene and lawsonite grains defines the main foliation. This foliation is subparallel to compositional layering and wraps around large amphibole grains. Blue Na-amphibole rims green 2-4 mm big Na-Ca amphiboles (Fig. 6a). Finer grained lawsonite (<0.3 mm) is the main non-mafic mineral commonly forming elongated columnar crystals in textural equilibrium with sodic amphibole. Titanite grains <0.4 mm are the main accessory minerals (Fig. 6a). Round grains of aragonite (ca

~0.2 mm in diameter) are present between amphiboles and lawsonite in a few samples. Quartz and albite constitute small fillings between lawsonite grains (Fig. 6b), probably a product of the transformation from plagioclase, which is preserved in rare relicts, to lawsonite. Blueschist-facies metamorphism is incipient since glaucophane replaced only the outermost rim of relict green amphiboles and occurs in pressure shadows and along fractures and cracks between mineral fragments of Na-Ca-amphibole. Glaucophane shows no later overprint. Na-pyroxene is intergrown with blue amphibole and often has blurred grain boundaries. Veins, cracks and micro shear zones filled with pumpellyite, albite and actinolite cut fractures filled with sodic amphibole and thus represent a later brittle event.

Metapillow-basalts

Metapillow-basalts rocks comprise augite phenocrysts (~15%), sodic pyroxene, Na-amphibole, lawsonite, minor Na-Ca-amphibole, titanite, albite and rare rutile. Augite phenocrysts (0.5mm diameter; Fig. 6c) are common remnants of the igneous mineral assemblage while plagioclase skeletons are recognized but replaced by tabular lawsonite. Augite crystals are zoned with higher Ca content in the core and an iron enriched rim, spanning from diopside to augite compositions. Parts of the augite grains are replaced by sodic pyroxene aligned with sodic amphibole along the weak foliation (Fig. 6d). Similar features of sodic pyroxene pseudomorphs after augite have been described from blueschists of the Tavşanlı Zone in northwest Turkey (Okay, 1980, 1982). Sodic amphibole is found at the rim of augite phenocrysts and in the fine-grained matrix (Fig. 6d). Lawsonite is the other main matrix mineral (Fig. 6c) and occasionally includes micrometer-sized albite. Titanite (up to 0.4 mm in size) is the main accessory mineral, which rarely contains rutile cores. The weak foliation is ubiquitous but the igneous texture of the metapillows is preserved. Metamorphic minerals such as sodic pyroxene and amphibole in pressure shadows next to augite

phenocrysts and the alignment of blue amphibole and deformed lawsonite suggest deformation during blueschist facies metamorphism. Neither lawsonite nor sodic amphibole or pyroxene show retrograde overprint.

Metabasalts

Metabasalts contain Na-amphiboles, Na-Ca-amphiboles, lawsonite, titanite and rutile $\pm$ pumpellyite $\pm$ albite, $\pm$ sodic clinopyroxene, $\pm$ quartz $\pm$ aragonite, $\pm$ calcite. The main rock-forming minerals are amphiboles and lawsonite. Sodium-calcium-amphiboles are usually the largest grains ($\sim 200\ \mu\text{m}$) except for some coarse ($< 2\ \text{mm}$) rutile grains in few samples (Fig. 6e). Sodic amphibole is lavender-blue in the fine-grained matrix and rims the larger Na-Ca-amphiboles. Fine-grained columnar lawsonite within cleavage planes builds up the rest of the matrix. In few samples from small blueschist lenses within the low-grade DC matrix, pumpellyite is in textural equilibrium with lawsonite (Fig. 6e), whereas in most other basalts, pumpellyite is restricted to veins or shear bands. Clinopyroxene is rare but represents either cores of original basaltic phenocrysts or Na-pyroxene associated with sodic amphibole. Albite was found within lawsonite as few μm -sized remnants of the basaltic matrix. Rutile grains ($< 2\ \text{mm}$) are often replaced by titanite, the most abundant accessory mineral (Fig. 6e). Calcite, actinolite and pumpellyite occurs in late veins and micro shear zones.

Metasediments

Blueschist-facies metasediments have mainly volcanoclastic origin and display various textures and grain sizes. They contain sodic amphiboles, lawsonite, Na-Ca-amphiboles, titanite, $\pm$ sodic pyroxene $\pm$ mica, $\pm$ pumpellyite $\pm$ quartz $\pm$ albite $\pm$ calcite $\pm$ calcic amphibole. These rocks contain a higher amount of white mica (Fig. 6f) than rocks with a magmatic protolith. Quartz

within lawsonite is a by-product of plagioclase to lawsonite transformation. In few samples, mostly small blocks within the DC, pumpellyite is in equilibrium with lawsonite. Some strongly folded samples have interlayers of only Na-amphibole and lawsonite mimicking primary sedimentary laminae (Fig. 6g). Sodic amphibole in fold hinges and pressure shadows of mineral boudins further demonstrates deformation at blueschist-facies conditions. Metamarl interlayers are fine-grained and consist of Na-amphibole, lawsonite, titanite, quartz and minor pumpellyite, white mica, calcic amphibole, albite and calcite. They have higher mica content than volcanoclastic sediments. One 30cm thick metasandstone/greywacke layer contains mainly quartz (~70%) with white mica (~10%), Na-amphibole (~10%) and lawsonite (~10%; Fig. 6h). Unfortunately, white mica is strongly altered and could not be used for geochronology. Pumpellyite, Ca-amphibole, calcite and albite occur in veins and shear bands that cut foliation.

GEOCHEMISTRY

Mineral Chemistry

Mineral compositions were measured with a JEOL JXA 8200 Electron Microprobe at ETH Zürich using 15kV acceleration voltage and 20nA beam current with a beam diameter of 1µm. Counting time on the peak was set to 40s for Si, Al, Na, Mg, Ca, Cr, K, Ti, Fe and Mn and 20s for each background. Natural and synthetic silicate and oxides were used as standards and measurements corrected with the Φ - ρ -Z method. Mineral compositions were recalculated on the base of charge-balance to estimate $\text{Fe}^{2+}/\text{Fe}^{3+}$ ratios and H_2O . Representative analysis are given in Table 2 and 3.

Amphiboles

217 The Makran blueschists contain three amphibole types (Ca, Na-Ca, Na) representing successive
 218 metamorphic stages and possibly relics of primary magmatic minerals. Blue sodic amphiboles
 219 are mostly unzoned. Glaucophane and crossite are dominant in all blueschists, whereas
 220 magnesio-riebeckite occurs in metasediments (Fig. 7a). Ferric (Fe^{3+})-normalized amphibole
 221 formulae were calculated on the basis of 23 oxygens and 13 cations + K + Na. Representative
 222 sodic amphibole analyses are listed in Table 2a. The amphibole X_{Mg} ($\text{Mg}/(\text{Mg}+\text{Fe}_{\text{tot}})$) is mostly
 223 <0.45 in metasediments (Fig. 7a) and between 0.55 and 0.65 in metagabbros and metabasalt (Fig.
 224 7b and c). These small chemical variations within sodic amphiboles are related to protoliths,
 225 indicating that the Fe^{2+} , Fe^{3+} and Al^{vi} content reflects bulk composition rather than changing P-T
 226 conditions or different ambient oxygen fugacity ($f\text{O}_2$) (Okay, 1980b). The sodic-calcic
 227 amphiboles are mostly unzoned barroisite and winchite (Fig. 7b, Table 2b). Barroisite is typical
 228 in metagabbro, whereas winchite is more abundant in metabasalts and metasediments. The X_{Mg}
 229 of amphibole is higher in metagabbros and metabasalts (0.58-0.72) than in metasediments (0.5-
 230 0.6, Fig. 7b). Calcic amphiboles are actinolite in veins crosscutting foliation and magnesio-
 231 hornblende with actinolite cores in larger grains (Fig. 7c, Table 2c). Actinolite in metagabbro has
 232 X_{Mg} between 0.69 and 0.77, magnesio-hornblende has lower values (0.63-0.66). Metasediments
 233 have lower X_{Mg} in actinolite (0.61-0.68) and magnesio-hornblende (0.45-0.55).

234 Overall, amphiboles in metagabbros show a distinct compositional trend with core to rim
 235 increase of Fe^{3+} , Na and Al from magnesio-hornblende/actinolite to barroisite to glaucophane.
 236 One example of amphibole zonation is shown in the Appendix A2. Optically, the boundaries
 237 between glaucophane and barroisite are sharp, whereas they are diffuse between barroisite and
 238 hornblende or actinolite. Such variations in geochemistry probably represent changes in $f\text{O}_2$,

which could be related either to interactions with fluids during metamorphism or to a pressure increase. Phase-diagram section calculations will address this question.

Clinopyroxenes

Pyroxenes are mostly metamorphic matrix grains but relicts of magmatic augite are found as phenocrysts in meta-pillows and as rare cores of magnesio-hornblende in metagabbros. Sodic pyroxene is predominantly jadeite, whereas fewer grains classify as omphacite or aegirine-augite (Fig. 8, Table 2d). Jadeite is typically unzoned and is found around magmatic augite of meta-pillows and associated with glaucophane in metagabbros. The jadeite component varies from Jd₃₃₋₈₆, depending on the protolith and the adjacent mineral. The content is generally ~Jd₇₀, whereas aegirine content is low (Ae₀₋₂₄). Fine grained pyroxene in the matrix of metasediments is omphacite.

Lawsonite

Euhedral lawsonite occurs in all samples, is unzoned and nearly pure. Metagabbros show the lowest ferric iron content with most values <0.8 and few grains up to 1.2 Fe₂O₃wt% (Fig. 9a, Table 3a). Metabasalts and volcanic metasediments show intermediate values between 0.7 and 2.2 Fe₂O₃wt% (Fig. 9, Table 3a). Layered blueschists have the highest ferric iron contents (2.2-6.2 Fe₂O₃ wt%), mostly around 2.5wt% (Fig. 9). High ferric iron contents in lawsonite either reflect bulk chemistry or could result from the transformation of barroisite into glaucophane, which releases Fe³⁺ (e.g. Black, 1973, Spear et al., 1982, Gibbons *et al.*, 1986). Ferric iron (Fe³⁺) freed from barroisite occupies the site of Al^{iv} in lawsonite (Fig. 9b), while Al^{iv} is incorporated in glaucophane (Appendix A2). This is consistent with higher Fe₂O₃ in some lawsonite of fine-

260 grained blueschists, where more barroisite transformed into glaucophane, compared to coarse
261 metagabbros at similar bulk iron ratios.

262 *Pumpellyite*

263 Pumpellyite rarely replaces lawsonite in fine grained metasediments but mostly occurs in late
264 veins and fracture zones crosscutting the foliation. In these veins, pumpellyite-(Al) crystals grew
265 antitaxially and are euhedral without signs of deformation. Few samples contain pumpellyite in
266 textural equilibrium with lawsonite. Representative analyses of unzoned minerals are given in
267 Table 3b.

268 *Titanite*

269 Titanite is the most abundant accessory mineral. It is often euhedral and unzoned (Fig. 10a)
270 within the lawsonite matrix or along grain boundary with amphiboles aligned within foliation.
271 Titanite often contain inclusions of rutile (Fig 10a) in euhedral, newly grown grains or rims
272 larger grains of rutile (Fig. 10b). Alumina (Al₂O₃) values are between 0.3wt% in metasediments
273 and 1.3wt% in metagabbros (Table 3c). Metagabbros have overall lower Ti content but higher
274 Fe³⁺ and Al concentrations than metabasalts and metasediments (Fig. 10c), which is related to
275 protolith bulk chemistry.

276 *Mica*

277 Rare white mica has Si contents of 3.6 to 3.9 atoms per formula unit (apfu) and K contents of
278 0.62-0.87, which define phengite (Table 3d). They lie within the cleavage in most rocks or in
279 pressure shadows of larger minerals. In some samples with larger grains, phengites have yellow

280 to brown alteration rims, but usually micas are so small that they are identified by microprobe
281 analyses or XRD and could not be used for geochronology.

282 *Plagioclase*

283 Nearly pure albite (Ab₉₉) is rare, usually restricted to µm-sized side products of lawsonite
284 formation in blueschist facies and in late veins with pumpellyite.

285 *Accessory minerals*

286 Rutile is the dominant accessory in metagabbro and metabasalt, while pyrite was rarely identified
287 in some metasediments. Aragonite, identified by XRD and Raman spectroscopy, occurs
288 occasionally within the matrix of mostly metagabbros.

289 **Bulk Chemistry**

290 The compositions of three different protoliths (Mak-06-08, Mak-08-47 and Mak-06-18) used for
291 phase diagram calculations are presented in Table 3. Their bulk chemical composition was
292 measured with XRF and the ferric/ferrous iron ratio determined using colorimetric analyses
293 (photometer Cary 50 in concentration mode at 522 nm) at the University of Bern (Table 4).
294 Representative rock cubes (~400g) were crushed and split several times to have a representative
295 homogenous mixture. From this powder about 1.7g was used for XRF and 20-50µg for
296 colorimetric analysis. Additional 37 samples were analyzed and used to run calculations during
297 the course of this study. This data, however, is not further used in this study but could be
298 obtained from the author upon request. The presented samples have moderate SiO₂ (~49wt%),
299 high Fe₂O₃ (10-15wt%) and low K₂O content typical for their basic composition. The molar bulk
300 Fe³⁺/Fe_{tot} ratios range from 0.41 to 0.48 and show lowest ferric content in metapillow basalt

Mak-08-47, and highest in metasediment Mak-06-18. High modal amounts of lawsonite and glaucophane correspond to higher Fe^{3+} contents. Strong deformation and small grain sizes are also typical for samples with high ferric iron values.

THERMODYNAMIC MODELLING: PHASE DIAGRAM SECTIONS

Estimating P-T conditions by conventional methods is not possible for the NMB, since no suitable geothermobarometers can be applied. Stability fields and mineral compositions were calculated by minimization of Gibbs free energy (Connolly, 2005) combined with the thermodynamic database of Holland & Powell (1998, with updates). Calculations were performed in the Na_2O - CaO - FeO - Fe_2O_3 - MgO - Al_2O_3 - SiO_2 - H_2O - TiO_2 model system with the solution models listed in Table 5. Due to the low amount of K_2O (<0.23 wt%) and MnO (<0.2 wt%) in the three samples used for thermobarometric calculations, these components are neglected for simplicity. The upper limits for T and P were chosen based on the absence of epidote (temperature) and garnet (pressure), consistent with the stability of glaucophane (e.g. Evans, 1990). The presence of lawsonite and absence of albite as a main mineral in equilibrium with pumpellyite places the minimal pressure and temperature limits (Heinrich & Althaus, 1988; Frey *et al.*, 1991; Okamoto & Maruyama, 1999). Accordingly, the calculated temperatures range between 200 and 500°C for pressures between 5 and 15 kbar. We avoided samples with aragonite, which would imply water activity <1. We assumed water saturation since amphibole and lawsonite are the main rock-forming minerals. Phase diagram sections for different fluid $X(\text{CO}_2)$ were calculated for sample Mak-08-47. The results have shown that increasing the amount of CO_2 in the fluid suppresses the titanite stability field in favor of rutile. However, the abundance of titanite in the studied samples suggests that water activity is 1 and therefore CO_2 in the fluid was not considered (Castelli *et al.*, 2007; Vitale Brovarone *et al.*, 2011). The three

investigated rock types (metagabbro Mak-06-08, metapillow basalt Mak-08-47 and metasediment Mak-06-18) allow testing whether all blueschists recrystallized under similar conditions. The investigated P-T range in phase diagram sections (Figs. 11-13) comprise four metamorphic facies: lawsonite-blueschist facies (LB), epidote-blueschist facies (EB), pumpellyite-actinolite (PA) and greenschist facies (GS).

Comparison of data and modeled values

We used a quantitative fitting method to compare modeled data with the measured ones. For this purpose, we defined a cost function Ω :

$$\Omega = \sum \frac{(Y_i^{meas} - Y^{mod})^2}{N} \quad (1)$$

Where Y_{meas} is the measured value (e.g. Na(apfu) in amphibole) and Y_{mod} is the modeled one. N is the number of measurements. This function has its minimum where measured and modeled values fit best. This approach is used in Figures 11, 12 and 14.

Metagabbro Mak-06-08

The isochemical phase diagram section (P-T section) in the mentioned 5-15kbar and 200-500°C window was calculated for metagabbro Mak-06-08 resulting in dominantly tri- and quadri-variant fields (Fig. 11a). The P-T section predicts coexistence of lawsonite and glaucophane for temperatures <440°C (Fig. 11a). The upper temperature limit (<400°C) is set by lawsonite and amphibole coexistence and the absence of rutile (Fig. 11b). Lowest pressure is defined by the absence of albite and the occurrence of sodic amphibole (>6kbar) at temperatures <350°C. Blueschist-facies minerals have a large common stability field at low temperatures and high pressures. Mineral and modal compositions of blueschist phases were used to further constrain

pressure and temperature. Because glaucophane and jadeite are the only Na-bearing phases at blueschist facies conditions, the sodium (Na) content in these two minerals is reliable to constrain P-T estimations. Measured and modeled Na (apfu) in sodic pyroxene overlap around 12kbar at 380°C and 14kbar at ~450°C (Fig. 11b, dark blue), which is consistent with the stability of the peak assemblages sodic amphibole and lawsonite. Modeled X_{Mg} of the same pyroxenes is consistent with mineral analyses, showing a best fit (Fig. 11c, blue lines) crossing the same field. Na content in barroisite (grey shaded area, Fig. 11d) lies within the albite and rutile stability fields, which is consistent with petrographic observations. Corresponding conditions are 8-9kbar and >470°C (Fig 11d). Sodium in sodic amphibole (Fig. 11d, dark blue line) lies outside the stability field of lawsonite at ~440°C. Nevertheless, the overlap of Na and X_{Mg} in jadeite and blueschist assemblage constrain the peak conditions to 11-12kbar at 360-400°C (Fig. 11d). Rutile, albite and barroisite suggest P-T conditions of ~450-500°C and 8-9kbar, typical for greenschist or lower amphibolite facies prior to glaucophane crystallization around barroisite. Relict plagioclase within lawsonite is also consistent with greenschist to lower amphibolite-facies metamorphism before blueschist-facies overprint.

Metapillow basalt Mak-08-47

Point counting indicates that metapillow basalt Mak-08-47 contains 15% magmatic augite, whose chemical contribution was subtracted from the bulk chemical composition, so that phase-diagrams could be calculated considering metamorphic minerals only. The corrected bulk chemical is considered to be a better approximation of the effective bulk composition and was used to calculate a P-T section, in which water is considered to be in excess (Fig. 12). Rare tri-variant fields occur at low pressures, where quadri-variant fields are generally dominant (Fig. 12a). Quadri-variant fields also occur along the epidote-lawsonite reaction, whereas penta-

variant fields are restricted to higher pressures (Fig. 12a). Lawsonite is the main Ca-bearing phase at temperatures <260°C for ~5kbar and <450°C for ~15kbar. Glaucophane and jadeite are the main Na-bearing phases at high pressure/low temperature conditions. The Na-amphibole-in reaction marks the upper temperature limit at ~360°C and the lower pressure boundary at ~6kbar (Fig. 12b). The titanite-in reaction marks the upper pressure limit (13-15kbar) at temperatures < 350°C. Mineral and modal compositions were modeled to narrow down the P-T conditions of the blueschist assemblage. The best-fit between modeled and measured Na-content in jadeite (blue color; Fig. 12b) crosses the lawsonite and parts of the amphibole stability fields. The actual lawsonite modal composition (~40%) is consistent with the modeled one and the according isopleth crosses the amphibole stability field (Fig. 12c). This information allows constraining narrow blueschist metamorphic conditions of ~280-320°C and 13-14kbar (Fig. 12d). Relict albite and rutile and the composition of amphibole older than glaucophane suggest earlier P-T conditions of ~350-500°C and 6-9kbar.

Metasediment Mak-06-18

The calculated P-T section of Mak-06-18 shows tri-variant fields at low pressures and high temperatures (Fig. 13a). Quadri-variant fields dominate low pressure conditions and along the lawsonite-epidote reaction, whereas penta-variant fields are common at higher pressures and temperatures (Fig. 13a). Lawsonite is the main Ca-bearing phase at <300°C and ~7kbar and <450°C and ~15kbar. Sodic pyroxene is stable over a large P-T range but coexists with lawsonite and mica in the very narrow field 1 only (Fig. 13a). The best fit between modeled and measured Na in clinopyroxene (Fig. 13b; red lines) defines a narrow temperature range of 310-330°C. Sodic amphibole is restricted to <280°C, where modeled Na values fit best with the measured ones (Fig. 13c). The estimated modal composition of lawsonite goes through the Na-amphibole

stability field. However, in the calculated section, glaucophane does not coexist with the other blueschist assemblage minerals. The modeled sodic pyroxene content is overestimated (20 modal % instead of measured ~5-10 modal %) as well as chlorite (20 modal % instead of <5 modal %), whereas lawsonite is underestimated (20 instead of 30 modal %). Amphibole is shifted towards lower temperatures because modeled chlorite and pyroxene incorporate the necessary elements (Mg, Fe, Si, Al and Na). This artifact will be addressed in the discussion and induces to ignore sodic amphibole in estimating peak conditions for this sample. The stability field of mica and the absence of rutile suggest pressures < 10 kbar (Fig. 13d). Combined with the mica, lawsonite assemblage and the Na content in pyroxene, blueschist conditions are defined at 8 ± 1 kbar and $320\pm 10^\circ\text{C}$ (Fig. 13d).

DISCUSSION

The North Makran blueschists have been reported in several geological and tectonic studies (e.g. Maruyama *et al.*, 1996; McCall, 1997) and the Deyader occurrences were positioned on the Fannuj quadrangle map of the Geological Survey of Iran (Eftekhari-Nezhad *et al.*, 1979). We present the first detailed petrographic and mineralogical investigation of these rocks.

Parageneses of mafic low-temperature blueschist

The NMB have dominantly mafic protoliths, such as gabbros, basalts and volcanoclastic sediments, which represent pieces of oceanic crust and its sedimentary cover. The main blueschist assemblage, independent on the protolith, is sodic amphibole, sodic pyroxene, lawsonite and titanite, whereas mica is only prominent in metasediments. Lawsonite presence in all blueschist types points to low temperature/high pressure metamorphism. The results from phase equilibrium modeling and petrography of samples from the Kuh-e Taftah and basaltic

blocks in the DC show relatively similar P-T conditions, whereas metasedimentary blocks to the west of Halak Abad (Fig. 2) yield lower pressures. Few samples with lawsonite and pumpellyite in equilibrium (e.g. Fig. 6e) indicate local PT-conditions close to the PA-LB facies transition. Outcrops with interlayered omphacite-actinolite bearing greenschists and glaucophane-lawsonite blueschists suggest that metamorphic conditions were close to the GS-BS facies transition, where the formation of glaucophane depends on the chemical composition of the protolith. At the same P-T conditions, glaucophane may form in volcanoclastic or marl layers, while minerals typical for lower greenschist facies crystallize in silt and shale (Okay, 1989). This difference is attributed to the higher amount of iron in volcanoclastic metasediments, which expands the glaucophane stability field (Maruyama et al., 1986). Greenschist-facies metapillow basalt blocks in the DC with similar bulk chemistry as the blueschist pillows show assemblages of omphacite + actinolite + albite + chlorite + quartz. The formation of glaucophane and lawsonite may thus be a consequence of overprinting greenschist-facies assemblages through the reaction:

This suggests that blocks in the DC experienced different pressures, ranging from GS to BS conditions and aforementioned reaction could also explain the overall low chlorite content of the NMB.

Calculating P-T conditions of mafic blueschists

The pressure-temperature calculations for mafic blueschists are challenging, especially when there are few peak phases and no mica or garnet required for conventional thermobarometers. More specifically, in the NMB lawsonite and glaucophane are both stable over a large pressure range at low (<400°C) temperatures in these rocks. Measured mineral chemistry and modal

amounts were compared to calculated ones produced by phase diagram sections to further narrow down the P-T range. Estimating ferric/ferrous iron ratios correctly for the NMB is challenging since Fe^{3+} can be seated in amphibole and lawsonite. As a first approach, we recalculated P-T sections for Mak-08-47 as a purely ferrous system and compared it to calculations with measured iron ratios. The purely ferrous P-T section is dominated by tri-variant fields at low temperature/high pressure conditions and quadri-variant fields over the rest of the calculated P-T range (Fig. 14a). Blueschist-facies assemblage is restricted to temperatures below 300°C but the best fit for modeled and measured Na in jadeite is obtained out of the assemblage stability field (Fig. 14b). Incorporating ferric iron results in a better fit between measured and modeled amounts of lawsonite (Fig. 14c). Lawsonite stability is extended towards ~30°C higher temperatures and epidote stability is suppressed in the ferrous system (Figs. 14d). Our example also shows that ferric iron shifts stability fields significantly, in case of rutile, for example, the shift can be up to 6kbar and 100°C (Fig. 14d). Overall, in the ferrous system, the modeled assemblages and mineral compositions do not overlap with measured values, showing that implementing accurate bulk ferric/ferrous iron ratios improve the result of P-T section calculations. Once phase diagram sections were calculated considering measured bulk iron ratios, lawsonite modal compositions were well reproduced and sodium in clinopyroxene and amphibole yielded good fits in reasonable P-T conditions. The estimated blueschist-facies conditions of 300-350°C and 9-14 kbar are close to greenschist and pumpellyite-actinolite facies, which is consistent with mineralogy and field observations. Consequences of incorporating ferric iron in thermodynamic models are that the amount of some phases are under- or overestimated since not all solid solution or mineral models include Fe^{3+} realistically. Lawsonite, for example, is modeled as the pure endmember ($\text{CaAl}_2\text{Si}_2\text{O}_7(\text{OH})_2 \cdot (\text{H}_2\text{O})$) since there exists no solid solution

model. In the NMB though, it incorporates up to 3wt% of Fe_2O_3 in analyzed metabasalts and metasediments (Fig. 9). High modal contents of lawsonite (>30%) imply a significant amount of ferric iron, which is predicted by the model to be in chlorite or epidote. Consequently, chlorite modal composition may be overestimated and the epidote-in reaction can shift to lower temperatures. Overall, incorporating ferric iron improves calculations and results in good fits between model and reality.

P-T path of the North Makran Blueschists

Like for blueschists in the Franciscan Complex (Coleman & Lee, 1963), in western Turkey (Okay, 1982) and in Ladakh (Honegger *et al.*, 1989; Groppo *et al.*, 2016) the replacement reaction in large grains of coarse grained metagabbro, - basalts or metasediments (glaucophane rims barroisite) and metapillow basalt (sodic amphibole and jadeite rims augite phenocrysts) is incomplete. For this reason, changes in amphibole chemistry are used to infer pressure and temperature changes in the NMB. Crystallization conditions relate to the site occupancy of Na, which is increasingly incorporated into the M4 site at rising pressures (Brown, 1977b; Laird & Albee, 1981). The mineral assemblages and the amphibole compositional variations were used together to infer the P-T path. *Stage 1 – Amphibolite facies*

Relict green actinolite, magnesio-hornblende and omphacite in cores of amphiboles, plagioclase and occasionally rutile, were preserved in coarse grained metagabbros and fewer metabasalts or volcanoclastic metasediments. Magnesio-hornblende chemistry suggests >480°C, whereas actinolite identifies slightly lower temperatures ~450°C. This positions those amphiboles along the greenschist/amphibolite-facies transition. According to our models rutile and omphacite are stable in both metamorphic facies. Considering our phase diagram calculations, which place

crystallization of these relict minerals at 440-540°C and 2-4kbar (Fig. 15), and geochemical correlations and P-T conditions for similar mineralogy elsewhere in the world (c.f. Chapter 11 in Spear, 1993), metamorphic stage 1 records amphibolite facies metamorphism., .

Stage 2 – Transition amphibolite-blueschist facies

A pressure increase is responsible for barroisite overprinting actinolite and hornblende, while temperature remains either stable or decreases slightly. The pressure increase is recognized from the higher amount of Na within the M4 site (Brown, 1977b) in barroisite with respect to calcic amphiboles. Using Brown's tentative isobars yields a pressure increase to 6-8kbars at the greenschist-blueschist transition. The dominance of barroisite in metagabbro could either mean that metagabbro experienced slightly higher temperature (e.g. 430-520°C at >6kbar; Ernst 1979) than winchite-bearing metabasalts and metasediments or could be a consequence of different protolith compositions. Mineral chemistry of Na-Ca amphiboles in equilibrium with titanite and few samples with coexisting rutile suggest 360-500°C at 6-9 kbar. This metamorphic stage lasted long enough to allow almost complete transformation of large magnesium-hornblende and actinolite grains into Na-Ca-amphibole. This stage was not preserved in very fine grained and highly deformed samples.

Stage 3 – Glaucophane-lawsonite blueschist facies

Glaucophane, lawsonite and jadeite mark the peak blueschist conditions at 300 -350°C and 9-14 kbar (Fig. 15). Higher Fe³⁺ values in sodic than in calcic-sodic amphiboles and increasing Na in M4 indicate slight cooling and pressure increase. At lower pressures, barroisite would have been replaced by actinolite. Titanite replacing rutile is consistent with cooling from stage 2 to stage 3. The lack of plagioclase and hornblende supports temperatures below 450 - 550°C (Winkler,

1976; Maruyama *et al.*, 1983; Spear, 1993). Crystallization of lawsonite, glaucophane and occasionally jadeite on the foliation suggests that fine-grained rocks were still deforming at that stage. Cooling could be related to hydration, due to the flow of fluids, which are needed to crystallize high volume percentages of lawsonite as observed in the NMB.

Stage 4 –Pumpellyite-actinolite facies

Pumpellyite and actinolite in post-foliation veins show that the metamorphic path crossed the pumpellyite-actinolite facies without overprinting the previous blueschist-facies assemblages. Metasediments with coexisting lawsonite and pumpellyite yield P-T conditions below ~6kbar at < ~350 °C. Albite, and to a lesser extent chlorite and calcite, also crystallized in veins suggesting a temperature <150°C and pressure <4 kbar. Aragonite did not react to calcite, supporting that the aragonite/calcite stability boundary was crossed at low temperatures <150°C (Carlson & Rosenfeld, 1981).

P-T path

These four metamorphic stages define a counterclockwise P-T path (Fig. 15) that meets two possible explanations: (a) The oceanic crust was altered to stage 1 amphibolite conditions well before subduction occurred and barely cooled before it experienced pressures of 9-14kbar. The more likely scenario, however, is that (b) early amphibolite conditions represent the earliest stage of subduction/accretion along a high metamorphic geothermal gradient (~15°C/km). Pressure and temperature estimates for blueschist facies rocks point to pressure increase, temperature decrease and hydration during later stages of the burial. Exhumation was accompanied by significant cooling, resulting in a cold geothermal gradient ~8°C/km.

Lawsonite preservation in a young subduction setting

523 It is usually argued that preserving lawsonite and other metastable minerals, such as glaucophane
524 and jadeite, requires fast exhumation under relatively cold conditions (Ernst, 2006 and references
525 therein; Song *et al.*, 2007). In typical subduction zones, material is transported along a cold
526 geothermal gradient to depth where increasing pressure leads to blueschist formation and is then
527 overprinted by higher temperature conditions. The protolith of the NMB, however, was
528 metamorphosed under amphibolite and greenschist facies conditions before experiencing
529 blueschist-facies conditions and then crossed the lawsonite-out reaction at ca. 150°C along the
530 retrograde path. Conspicuously, pristine lawsonite is often preserved in blueschists that followed
531 a counterclockwise P-T path, so that retrogression mainly occurred in the lawsonite stability field
532 (e.g. Smith *et al.*, 1999; Ukar & Cloos, 2014). Retrograde paths through low temperatures in a
533 hydrated system appear to play a major role in lawsonite preservation. The lack of persistent
534 chemical or structural retrograde overprint in the NMB and no evidence for post-blueschist
535 deformation, except the cracks corroborates fast exhumation. Our constructed P-T path is
536 consistent with those calculated in numerical models of warm subductions (e.g. van Keken *et al.*,
537 2011), where the prograde path develops along a higher geothermal gradient (~15°C/km) than in
538 a cold subduction. The thermal regime in subduction zones is controlled by several factors
539 including the age of the subducted lithosphere and the amount of previously subducted material
540 or the maturity of a subduction zone, respectively (e.g. Peacock, 1991). If the ~100 Ma initiation
541 age of subduction in Makran is correct (Alabaster *et al.*, 1982; Şengör, 1990; Moghadam &
542 Stern, 2011), the 87.9 ± 5 Ma Makran blueschists (Delaloye & Desmons, 1980) have been
543 metamorphosed relatively shortly after subduction started. Besides, the chemical similarity of
544 blueschist metapillow basalts and Late Cretaceous lavas of the North Makran Ophiolites suggests
545 that the blueschist protolith formed not too long before it was subducted. While the pressure

increase from stage 2 to 3 is indisputable, the origin of amphibolite and greenschist facies described in stage 1 has two possible explanations. (1) Oceanic crust was altered under greenschist to lower amphibolite facies temperatures after exposure at the seafloor shortly after formation and buried while still warm under constant to slightly declining temperatures. (2) Stage 1 greenschist conditions are the result of early burial stages in a warm subduction zone along a higher metamorphic geothermal gradient in the prograde ($\sim 15^{\circ}\text{C}/\text{km}$) than in the retrograde path (Fig. 15). In both cases consecutive hydration and slight cooling with increasing pressure, would explain the transition from stage 2 to 3, resulting in blueschist overprint at $>25\text{km}$ depth, if metamorphic pressures equal lithostatic pressures. Reactions from stage 3 to 4 in the NMB indicates that the exhumation happened along a low geothermal gradient $\sim 8^{\circ}\text{C}/\text{km}$ (Fig. 15). Taking an equivalent depth $\sim 30\text{km}$ of the NMB metamorphic peak conditions, fast exhumation ($>1\text{ km}/\text{Ma}$, Draper & Bone, 1981) would have resulted in blueschist exposure less than 30 Ma after subduction. That is consistent with detrital sodic amphibole in Campanian-Maastrichtian turbidites of the Inner Makran (Dolati, 2010), suggesting that blueschists were exhumed and eroded less than 20 Ma after metamorphism. Thus, the exhumation of the NMB occurred during ongoing subduction. Changing of physical conditions in subduction zones, such as slab-detachment or the underplating of spreading –ridge, often involving serpentinite exhumation and mélangé formation, could trigger blueschist exhumation (Tsujimori et al., 2006). In the North Makran, blueschist exhumation might be related to the obduction of the North Makran Ophiolites, which was completed before the Upper Cretaceous, as recorded by Campanian-Maastrichtian shallow water limestones (Dolati, 2010) unconformably covering the ophiolites. This overall conclusion is consistent with counterclockwise P-T paths identified in other young subduction zones with relatively young subducted oceanic lithosphere (e.g.

569 Wakabayashi, 1990; Gerya *et al.*, 2002; Willner *et al.*, 2004; Glodny *et al.*, 2005; Agard *et al.*,
570 2009).

571 **CONCLUSIONS**

572 The North Makran Blueschists consist of metagabbro, metabasalt and volcanoclastic
573 metasediments representing a segment of oceanic crust. The blueschist paragenesis glaucophane,
574 lawsonite, titanite $\pm$ sodic pyroxene $\pm$ mica indicates a low temperature/high pressure
575 metamorphism during ductile deformation, witnessed by metamorphic minerals in fold hinges
576 and aligned within foliation. Pressure-temperature estimates of different blueschist protoliths in
577 North Makran yield metamorphic peak conditions of 300-380°C at 9-14 kbar. Slight P-T
578 differences in calculations of the main outcrops reflect variations in chemical compositions of
579 the protoliths, whereas in smaller blocks they might also identify locally varying pressure
580 conditions. Petrography and mineralogy record four successive stages of amphibolite –
581 amphibolite-blueschist transition – blueschist –pumpellyite-actinolite facies, defining a
582 counterclockwise P-T path with retrogression through the lawsonite stability field. Assuming that
583 metamorphic pressure equals lithostatic pressure, the corresponding counterclockwise P-T path
584 accounts for the preservation of fresh lawsonite and jadeite in a warm young subduction system,
585 whilst these minerals would be overprinted at greenschist facies conditions under a conventional
586 clockwise evolution.

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1 FIGURE CAPTIONS

2 Figure 1: Study area (framed) in the Makran accretionary wedge and its tectonic setting.

3 Convergence rate of the Arabian plate towards stable Eurasia after DeMets *et al.*, 2010.

4 Figure 2: Simplified geological map of the Deyader Complex and surrounding ophiolites with
5 overview of blueschist distribution. Ages of ophiolitic rocks range between Jurassic and Eocene.

6 Figure 3: Map (a) and profile (b) of the main blueschist outcrop around the Kuh-e Taftah, small
7 arrows indicate younging direction in the graded metasandstones of Fig. 5d. Samples Mak-08-
8 18, Mak-08-20 south of Esfand and samples Mak-08-61, Mak-08-64, Mak-08-65 are out of this
9 map.

10 Figure 4: Faulted contacts of blueschists with the underlying low grade rocks and the overlying
11 North Makran ophiolites: (a) blueschist thrust southwards on low grade metasediments of the
12 Deyader Complex at the western boundary of the Kuh-e Taftah klippe (N 026°53'37.4''/E
13 059°30'8.9''), (b) thrust contact of the Kuh-e Taftah blueschist klippe on low grade
14 metasediments (N026°53'17.1''/E059°31'16.2''), (c) serpentized harzburgite of the North
15 Makran ophiolites and metasediments of the Deyader Complex thrust on the Kuh-e Taftah
16 blueschists, with northward sense of shear in close-view inset (N026°51'24.3''/E059°32'26.5'').

17 Figure 5: Field photographs of blueschist outcrops. (a) normally oriented meta-pillow lava to the
18 east of Zeyarat (N026°54'46.1''/E059°29'37.4''), (b) coarse-grained meta-gabbro at the eastern
19 flank of the Kuh-e Taftah (N026°53'5.3''/E059°33'28.4''), (c) tectonic breccia within brittle
20 fractures filled with calcite (N026°53'54.9''/E059°31'39.2''), (d) continuous layer of meta-
21 sedimentary blueschist showing graded bedding (white arrow shows upward direction)
22 (N026°53'23.2''/E059°31'30.5''), (e) metasediments with alternating green and blue layers

(N026°45'48.2''/E059°15'46.6''), (f) folded volcanoclastic metasediments in the western part of Kuh-e Taftah (N026°53'24.1''/E059°31'16.4'').

Figure 6: Mineralogy and textures of North Makran blueschists. Mineral abbreviations after Whitney & Evans (2010). (a) Photomicrograph with transmitted light of metagabbros sample Mak-06-08, (b) back-scattered electron image of Mak-09-222, (c) photomicrograph with transmitted light of meta-pillow lava sample Mak-08-47, (d) sodium distribution map of metapillow lava Mak-08-47, dashed white lines indicate foliation, (e) photomicrograph with transmitted light of metabasalt sample Mak-08-37, (f) aluminum distribution map of layered blueschist Mak-05-08, (g) photomicrograph with transmitted light of strongly folded Mak-06-18, white lines emphasize compositional layering, (h) photomicrograph with transmitted light of metasandstone Mak-08-54.

Figure 7: Amphibole classification after Leake, 1978; Leake *et al.*, 1997. (a) Sodic amphiboles plotted in the $\text{Fe}^{3+}/(\text{Fe}^{3+}+\text{Al}^{\text{vi}})$ vs. $\text{Mg}/(\text{Mg}+\text{Fe}^{2+})$ diagram, (b) sodic-calcic amphiboles plotted in the Si (apfu) vs. $\text{Mg}/(\text{Mg}+\text{Fe}^{2+})$ diagram, (c) calcic amphiboles plotted in the Si (apfu) vs. $\text{Mg}/(\text{Mg}+\text{Fe}^{2+})$ diagram.

Figure 8: Compositional diagrams for clinopyroxene. (a) Sodic pyroxenes plotted in the Jd-Quad-Aeg diagram and (b) magmatic pyroxenes plotted in the En-Wo-Fs diagram. Symbols as in Figure 9.

43 Figure 9: Fe_2O_3 in lawsonite versus (a) CaO and (b) Al_2O_3 in different blueschist types. Symbols
44 as in Figure 7.

45 Figure 10: Titanite in blueschists: (a) Ti elemental distribution map of euhedral titanite of
46 metagabbro Mak-09-222 with rutile inclusion, (b) back-scattered electron image of titanite
47 replacing rutile in Mak-08-37, (c) Ti vs. $\text{Fe}^{3+}+\text{Al}$ diagram of titanite from four different
48 blueschist protoliths.

49 Figure 11: Isochemical phase-diagram section (P-T section) of metagabbro sample Mak-06-08.
50 (a) P-T section compiled with measured bulk ferric/ferrous iron ratio. Color code for variance
51 field = darker color for higher variance. (b) Modeled Na (apfu) in jadeite presented as the $\log_{10}$
52 of the cost function Ω ($\log(\Omega)$ details in main text), scale of color code = dark colour (low
53 values) are best fits. (c) Compositional isopleths for modeled X_{Mg} in jadeite, scale of color code
54 = dark blue colour (low values) are best fits. (d) Peak blueschist P-T estimation combining
55 stability field of peak assemblages (light shaded area), Na in jadeite (blue shaded area) and X_{Mg}
56 in jadeite (green line). Na content in barroisite is marked with grey shaded pattern, suggesting an
57 earlier higher temperature lower pressure metamorphic event.

58 Figure 12: P-T section of meta-pillow lava sample Mak-08-47. (a) Phase-diagram section with
59 darker gray shades representing higher variance fields. Calculations were done using measured
60 bulk ferric-ferrous iron ratio, 15% modal augite was subtracted from the bulk chemical
61 composition. (b) Modeled Na (apfu) in jadeite presented as $\log(\Omega)$, scale of color code = dark
62 colour (low values) are best fits. (c) Modeled modal amount of lawsonite presented as $\log(\Omega)$. (d)
63 Blueschist facies P-T determination combining stability field of peak assemblages (light shaded
64 area), Na in glaucophane (blue shaded area), Na in jadeite and modal lawsonite. Na content in

omphacitic pyroxene between augite and glaucophane lies within the albite and rutile stability field (dark shaded area) identifying an earlier metamorphic overprint.

Figure 13: P-T section of metamarl sample Mak-06-18. (a) P-T section compiled with measured bulk ferric/ferrous iron ratio (color code as in Fig. 11).. (b) Modeled Na (apfu) in jadeite and mineral in- and out reactions. Red lines define the narrow range of measured sodium in jadeite. Color bar represents Na in pyroxene as atoms per formula unit. (c) Modeled Na in sodic amphibole, scale of color code in apfu. (d) Estimation of blueschist-facies conditions combining stability field of peak assemblages (light shaded area) and Na in jadeite (red lines).

Figure 14: P-T section of metapillow sample Mak-08-47 calculated with purely ferrous iron. (a) P-T section compiled with all iron as ferrous iron (color code as in Fig. 11a). (b) Na in pyroxene presented as $\log(\Omega)$, scale of color code = dark colour (low values) are best fits. (c) Modeled modal amount of lawsonite. (d) Shifting mineral in/out reactions using purely ferrous versus measured ferric/ferrous iron ratios. Grey lines = in/out reactions with calculated with measured ferric/ferrous iron ratio. Shaded areas with different colours represent the shifts.

Figure 15: Preferred P-T paths obtained from combined P-T section study. Albite breakdown reaction is taken from Holland (1980). Mineral abbreviations as in Figure 6. The metamorphic facies and their abbreviations are after Liou *et al.*, (2004). Patterned areas represent different stages and blueschist facies conditions of the three protoliths.

Figure 1

Figure 2

Figure 3

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Figure 11

Figure 13

Figure 14

Figure 15

Table 1. Representative mineral assemblages in the Northern Makran Blueschists (NMB)

Sample	Rock type	NP	Au	NA	NCA	CA	Law	Pump	Ab	Chl	Wm	Cal	Arag	Qtz	Ttn	Ru	Fe-ox
Mak-06-07	metagabbro	x		x	-	-	x	+	-					-, x	x	x	x
Mak-06-08	metagabbro	x		x	-		x	+	-			+			x	-	
Mak-06-11	metagabbro			x	-		x					+	x		x, +	-	
Mak-06-13	metagabbro			x	-	+	x	+	-			+	x		-, x		x
Mak-06-15	metagabbro	x		x	-	-, +	x	x							x	-	
Mak-08-42	metagabbro			x	-		x	x, +					x	x	x	x	
Mak-06-09	metabasalt		o	x	-		x	+	-, +			+	x		-, x		
Mak-06-10	metabasalt	x		x			x	+	-			+			x	-	
Mak-06-16	metabasalt			x	-		x	+	+			+	x		+	-	x
Mak-08-03	metabasalt			x	x	+	x	+							x		
Mak-08-47	metapillow	x	o	x			x		o						x	-	
Mak-08-04	metavolcanoclastic			x	-		x	+	+			+		x	x		x
Mak-08-08	metavolcanoclastic			x		+	x	+							x		
Mak-06-17	metamarl			x			x		+	+	x	+	x	x	+	-, x	
Mak-06-18	metamarl	x		x	-	+	x	+			x		x	x	x		
----->																	
major modal composition									----->								
									minor modal composition								

NP sodic pyroxene, Au augite, NA sodic amphibole, NCA sodic-calcic amphibole, CA calcic amphibole, Law lawsonite, Pump pumpellyite, Ep epidote, Ab albite, Chl chlorite, Wm white mica, Cal calcite, Arag Aragonite, Qtz quartz, Ttn titanite, Ru rutile, Fe-ox iron oxide. O initial magmatic phase, x: peak metamorphism, +: retrograde

Table 2. Normalized major and minor element composition of amphiboles and pyroxenes of the NMB

	a) Na amphibole				b) Na-Ca amphibole				c) Ca amphibole		d) Na pyroxene			
	Mak-06-08	Mak-06-08	Mak-09-222	Mak-09-47	Mak-06-08	Mak-06-08	Mak-09-222	Mak-09-188	Mak-06-08	Mak-06-08	Mak-06-08	Mak-06-09	Mak-06-12	Mak-06-17
	crossite	glaucophane	glaucophane	glaucophane	barroisite	winchite	barroisite	winchite	mg-hornblende	actinolite	jadeite	jadeite	omphacite	jadeite
latitude	26°53'18.1"	26°53'18.1"	26°53'15.7"	26°54'59.2"	26°53'18.1"	26°53'18.1"	26°53'15.7"	26°53'45.6"	26°53'18.1"	26°53'18.1"	26°53'18.1"	26°53'22.8"	26°53'24.1"	26°50'44.3"
longitude	59°33'9.4"	59°33'9.4"	59°32'25.0"	59°29'26.4"	59°33'9.4"	59°33'9.4"	59°32'25.0"	59°30'03.2"	59°33'9.4"	59°33'9.4"	59°33'9.4"	59°33'18.2"	59°33'19.6"	59°03'45.3"
SiO ₂	56.23	57.71	58.23	55.28	49.87	54.11	50.08	57.21	48.08	55.54	57.51	56.03	60.86	56.67
TiO ₂	0.20	0.38	0.29	0.12	0.55	0.29	0.20	0.07	0.52	0.10	0.00	0.04	0.24	0.36
Al ₂ O ₃	6.77	7.05	8.00	7.72	9.99	6.14	5.85	5.60	9.98	1.61	17.94	11.53	8.56	10.59
Cr ₂ O ₃	0.07	0.08	0.10	0.00	0.08	0.07	0.07	0.00	0.04	0.14	0.00	0.00	0.01	0.00
Fe ₂ O ₃ *	5.80	4.94	4.78	8.55	10.57	3.98	5.71	2.51	11.79	2.71	0.89	0.62	0.78	2.29
FeO	8.38	8.08	7.48	7.17	2.93	8.62	6.22	8.97	1.39	9.37	4.65	10.84	12.24	12.84
MnO	0.16	0.14	0.12	0.04	0.24	0.36	0.16	0.28	0.25	0.31	0.13	0.08	0.18	0.11
MgO	10.93	10.89	11.40	10.47	11.62	12.32	14.19	13.27	12.99	15.81	2.24	3.76	9.92	1.42
CaO	2.36	1.15	1.81	1.46	7.11	6.35	6.57	6.17	9.71	10.39	3.75	6.46	1.80	2.67
Na ₂ O	5.99	6.61	6.24	7.09	4.07	3.93	3.38	3.69	2.69	1.52	11.91	10.62	5.41	12.46
K ₂ O	0.03	0.02	0.03	0.04	0.10	0.14	0.05	0.08	0.10	0.08	0.00	0.00	0.04	0.00
H ₂ O*	2.13	2.15	2.19	2.13	2.11	2.09	2.15	2.15	2.11	2.11	0.00	0.00	0.00	0.00
Total	99.04	99.20	100.70	99.80	99.23	98.30	100.24	100.01	99.65	99.69	99.02	99.99	100.04	99.41
X _{Mg}	0.38	0.36	0.63	0.56	0.63	0.64	0.66	0.68	0.66	0.71	0.44	0.38	0.58	0.15

*Ferric (Fe³⁺)- and water normalized amphibole formulae were calculated on the basis of 23 oxygens and 13 cations + K + Na.

Table 3. Normalized major and minor element composition NMB minerals

	a) lawsonite			b) pumpellyite		c) titanite		d) phengite			
	Mak-09-47	Mak-06-08	Mak-08-18	Mak-06-09	Mak-08-16	Mak-09-222	Mak-08-47	Mak-09-222	Mak-09-188	Mak-08-18	Mak-09-54
latitude	26°54'59.2"	26°53'18.1"	26°50'43.1"	26°53'22.8"	26°50'43.2"	26°53'15.7"	26°54'59.2"	26°53'15.7"	26°53'45.6"	26°50'43.1"	26°53'27.1"
longitude	59°29'26.4"	59°33'9.4"	59°03'47.2"	59°33'18.2"	59°03'47.3"	59°32'25.0"	59°29'26.4"	59°32'25.0"	59°30'03.2"	59°03'47.2"	59°31'31.7"
SiO ₂	38.98	38.01	38.89	43.93	47.46	30.43	30.35	58.60	59.02	59.99	59.02
TiO ₂	0.05	0.06	0.09	0.07	0.05	38.50	38.45	0.02	0.00	0.02	0.00
Al ₂ O ₃	30.60	31.13	28.88	25.75	24.43	1.20	0.85	17.09	19.65	17.57	19.65
Cr ₂ O ₃	0.00	0.01	0.01	0.04	0.02	0.00	0.00	0.01	0.00	0.00	0.00
Fe ₂ O ₃	0.48	0.00	0.00	0.00	0.00	0.47	0.76	3.20	3.42	4.79	3.42
FeO	0.00	0.56	2.87	3.82	5.01	0.00	0.00	0.00	0.00	0.00	0.00
MnO	0.00	0.00	0.05	0.03	0.02	0.07	0.00	0.05	0.10	0.08	0.10
MgO	0.01	0.00	0.04	2.37	2.12	0.00	0.05	8.44	6.36	6.60	6.36
CaO	17.50	17.83	16.54	13.73	10.45	29.04	28.40	0.10	0.04	0.12	0.04
Na ₂ O	0.00	0.00	0.01	1.34	3.30	0.01	0.06	0.00	0.00	0.00	0.00
K ₂ O	0.00	0.02	0.04	0.00	0.05	0.01	0.04	9.49	7.91	7.42	7.91
H ₂ O	11.89	12.30	11.79	5.97	5.95	0.27	0.26	4.69	4.71	4.71	4.71
Total	99.51	99.92	99.21	97.05	98.86	100.00	99.22	101.70	101.21	101.40	101.21
X _{Mg}	0.05	0.00	0.02	0.53	0.43	0.05	0.05	0.84	0.79	0.73	0.79

*Fe₂O₃ and H₂O from recalculated mineral formula based on charge balance.

Table 4. Bulk chemistry obtained with XRF and colorimetric analysis

rock type	sample	latitude	longitude	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Cr ₂ O ₃	NiO	Total	X _{Mg}	Fe ³⁺ /Fe _{tot}
metagabbro	Mak-06-08	N26°53'18.1"	E59°33'9.4"	49.79	1.16	16.10	4.21	5.03	0.16	8.00	10.25	3.80	0.06	0.13	0.06	0.01	99.83	0.61	0.430
metabasalt	Mak-08-47	N26°54'59.2"	E59°29'26.4"	48.43	1.25	16.52	5.04	6.36	0.17	5.87	10.50	3.41	0.19	0.20	0.00	0.01	99.26	0.48	0.416
metamarl	Mak-06-18	N26°50'44.3"	E59°03'45.4"	49.99	2.24	13.31	7.09	7.05	0.21	4.82	8.68	4.16	0.23	0.51	0.01	0.00	99.73	0.38	0.475

Table 5. Solid solution models used for the phase diagram sections, other minerals were incorporated as endmembers.

Mineral/phase	solution model	abbreviation	source	comments
Amphibole	Act(M)	Amph	Massone & Willner (2008)	low temperature clinoamphibole
Carbonate	Cc(Ae)	Cc	Anovitz & Essene (1987)	solution model for calcite
Carbonate	Do(AE)	Do	Anovitz & Essene (1987)	solution model for Dolomite
Carpholite	Carp(M)	Carp	Massone & Willner (2008)	Mn-Fe-Mg Carpholite
Chlorite	Chl(HP)	chl	Holland <i>et al.</i> (1998)	extended model
Chloritoid	Ctd(HP)	Ctd	-	Mn-Fe-Mg Ctd
Clinoamphibole	GiTrTsMr	Amph	Massone & Willner (2008)	high pressure clinoamphibole
Clinopyroxene	Omph(GHP2)	Cpx	Diener & Powell (2012)	modification of the Green, Holland and Powell (2007) omphacite
Epidote	Ep(HP)	ep	Holland & Powell, 1998	non-ideal cz-fep solution
Feldspar	feldspar	Fsp	Fuhrman & Lindsley (1988)	ternary feldspar model
Garnet	Gt(HP)	Gt	-	HP 98 quaternary garnet model
Ilmenite	IlGkPy	Ilm	-	ideal ilmenite-geikielite-pyrophanite solution
Mica	Mica(M)	Mica	Massone & Willner (2008)	Margarite-Muscovite-Paragonite
Pumpellyite	Pu(M)	Pu	Massone & Willner (2008)	Fe ²⁺ -Fe ³⁺ -Mg-pumpellyite
Sudoite	Sud(M)	Sud	Massone & Willner (2008)	Fe-Mg Sudoite

The solution model files can be obtained from at http://www.perplex.ethz.ch/Perple_X_6.7.0_data_files.zip/solution_models.dat.

1 TABLE CAPTIONS

2 Table 1: Representative mineral assemblages of four different blueschist protoliths.

3 Table 2: Representative major and minor element compositions of amphiboles and pyroxenes of
4 the NMB.

5 Table 3: Representative major and minor element compositions of lawsonite, pumpellyite,
6 titanite and phengite of the NMB.

7 Table 4: Bulk chemical composition obtained by XRF and colorimetric analysis.

8 Table 5: Solid solution models used in isochemical phase-diagram section calculations with
9 Perple_X.

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