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1 Gabbro layering induced by simple shear in the Oman ophiolite Moho transition
2 zone

3
4 David Jousselin¹, Luiz F. G. Morales², Marie Nicolle¹, and Aurore Stephant¹

5 1: Université de Lorraine, CRPG, 54501 Vandoeuvre les Nancy, France

6 2: Deutsches GeoForschungsZentrum (GFZ), Section 3.2 Telegrafenberg, 14473, Potsdam,
7 Germany

8
9 **Abstract**

10
11 We investigate the origin of modal layering in gabbro lenses of the Moho transition zone in
12 the Oman ophiolite with a microstructural study. Gabbro lenses exhibit a shape preferred
13 orientation of plagioclase crystals, that are euhedral and devoid of any intracrystalline
14 deformation. This texture and field kinematic indicators show a strong simple shear
15 deformation in magmatic conditions. The parallelism of the lineation in gabbros and the
16 plastic lineation of the host dunite indicate that their development is contemporaneous, and
17 that the magmatic features are passively coupled to the solid-plastic flow of the host mantle.
18 We also found undeformed-isotropic and weakly deformed-roughly layered gabbro. The host
19 rock is plagioclase and clinopyroxene impregnated dunite; it contains euhedral plagioclase
20 suggesting that some grains crystallized in suspension. There is no clear boundary between
21 the gabbro and the host rock; on the contrary, the limit is diffuse, with increasing plagioclase
22 and clinopyroxene content from the dunite to the gabbro over tens of meters. This suggests
23 that the gabbro corresponds to melt impregnated dunite. We defined 4 gabbro types, from
24 unlayered (type 1) to well layered (type 4) with progressively more continuous and distinct
25 layers. We characterized deformation with crystal shape and crystallographic preferred

26 orientation (CPO) measurements. Unlayered samples have a random fabric; type 2 have a
27 very weak shape fabric and planar CPO, defined by olivine and plagioclase (010) planes; type
28 3 have a weak fabric, with a lineation defined by the [001] olivine axis and the [100]
29 plagioclase axis, which reflects the shape fabric; type 4 have a strong shape fabric and CPO,
30 with a lineation defined by the [100] olivine and plagioclase axis. We interpret the
31 progression from isotropic to clear S-L fabrics as a result of increasing deformation imposed
32 by the flowing host mantle. The type 2 gabbros must result from compaction; with increasing
33 simple shear, the lineation is developed in type 3 samples; finally, with lower melt content,
34 suspension flow switches to plastic deformation in the olivine-rich layers, leading to plastic
35 olivine fabrics in type 4 samples. We deduce that layering originates from simple shear,
36 which other studies show induces strong segregations in suspended particles, and plastically
37 deformed rocks. To build the isotropic stage, melt must accumulate faster than the
38 deformation, suggesting that melt is extracted by dikes.

39

40 **1. Introduction**

41

42 Layering in igneous rocks is a focal issue because it is related to magma emplacement and
43 evolution. Modally layered gabbros in ophiolites are regarded as relics of the low velocity
44 zone beneath the axial melt lens reported at fast oceanic spreading ridges (e.g. Detrick et al,
45 1987; Caress et al, 1992), and represent a key section in the ridge melt plumbing system.
46 Several models have been proposed to explain the formation of layered gabbro in ophiolites.
47 The earliest models advocated the accumulation of crystals in a magma chamber (e.g.
48 Smewing, 1981); others proposed that layering results from the tectonic transposition of melt
49 either sinking from above as it crystallizes from the melt lens (Quick and Denlinger, 1993
50 known as the "glacier model") or flowing from beneath as it is extracted from the mantle

51 (Nicolas et al, 1988). The model of Henstock et al (1993) is a variation of the gabbro glacier
52 model where layering originates from cyclic melt sills rather than sedimentation at the
53 bottom of a permanent melt lens followed by deformation. Alternatively, layers may represent
54 stacked sill intrusions (Boudier et al, 1996a; Kelemen et al, 1997a; Lissenberg et al, 2004;
55 known as "sheeted sill model"). No consensus emerges from these models, each implies
56 different melt paths, times of residence and extents of interaction with the host rock. One
57 problem that hinders our knowledge of the origin of modal layering is that we see only the
58 final products, i.e. the layered gabbros, and have no trace of evolutionary stages since the melt
59 was first emplaced. This may be because transitional stages are brief relative to geological
60 time scales, and thus are rarely fossilized. The Oman ophiolite may enable to capture such
61 short lived processes which could have occurred at the ridge axis itself. Mapping of mantle
62 diapirs and dike distribution show that a spreading axis which produced a 50 Km wide portion
63 of oceanic crust -similar to that of fast spreading-ridges- is preserved in the southern massifs
64 (Ceuleneer et al, 1988; Boudier et al, 1997). The Moho transition zone (MTZ) in the Oman
65 ophiolite is a few meters to a few hundreds meters thick, and is characterized by gabbro
66 lenses imbedded in dunite, plagioclase and clinopyroxene impregnated dunite, and depleted
67 harzburgite (Boudier and Nicolas, 1995). Identification of this unit as the uppermost mantle is
68 based on the recognition of mantle fabrics and the occurrence of residual orthopyroxene in the
69 MTZ, showing that dunite results from dissolution of harzburgite pyroxene by a circulating
70 melt (Sinton, 1977; Nicolas, and Prinzhofer, 1983). The gabbro lenses in the MTZ are
71 indistinguishable from layered gabbros in the lower crust; they have the same type of modal
72 layering and chemical composition (Kelemen et al, 1997a), which suggests that they formed
73 in the same way. The presence of melt at the MTZ is now recognized by a growing number of
74 marine geophysical studies at fast and intermediate spreading ridges (Garmany, 1989;
75 Crawford and Webb, 2002; Nedimovic et al, 2005), underscoring the importance of

76 understanding the structure of the MTZ. This paper presents new field observations and a
77 microstructural study of gabbroic rocks in the MTZ associated with the well-known Maqsad
78 mantle diapir (Ceuleneer et al, 1988; Jousselin et al, 1998). We distinguish four types of
79 samples which represent different evolutionary stages of the gabbro layering. Because
80 universal-stage measurements are time consuming and tedious to acquire, especially for
81 plagioclase, published crystallographic preferred orientation (CPO) data in Oman layered
82 gabbro are limited to seven examples dispersed in four studies: one in Benn and Allard, 1989;
83 three in Boudier and Nicolas, 1995; one in Boudier et al, 1996a with olivine only; two in
84 Yaouancq and MacLeod, 2000, with plagioclase only; the latter also contain fabric data for
85 six foliated gabbros of the unlayered upper part of the gabbro section. Of the five olivine
86 CPOs, two are in MTZ gabbro lenses (Boudier and Nicolas, 1995), the others are in the crust.
87 Fifteen more plagioclase fabrics were measured in studies devoted to anorthosite layers in the
88 foliated upper crust (Morales et al, 2011). The use of a scanning electron microscope (SEM)
89 equipped with an electron back-scattered diffraction (EBSD) system allowed us to gather a
90 dataset of 27 olivine CPOs and 35 plagioclase CPOs. The acquisition of this unprecedented
91 dataset was essential to reveal possible deformation stages within the different types of
92 gabbro observed. We also characterized deformation by crystal shape preferred orientation
93 measurements in 7 thin sections. Deformation analysis coupled to sample distribution, and
94 description of the layering, permit us to discuss the origin of gabbro layering and magma
95 extraction processes.

96

97 **2. Geological setting and field observations**

98

99 The MTZ in ophiolites represents a level where part of the melt extracted from the mantle is
100 collected, circulates and partially crystallizes, before feeding the overlying oceanic crust

101 (Karson and Collins, 1984; Boudier and Nicolas, 1995; Sano and Kimura, 2007). It offers the
102 opportunity to observe the distribution of melt ponding and percolating in a deforming matrix.
103 In the Oman ophiolite, the development of a thick (>100 meters) MTZ is related to the
104 presence of mantle diapirs that carry the melt from below (Nicolas, et al, 1996; Godard et al,
105 2000). The Maqsad mantle diapir region has been extensively studied, providing a well-
106 known general framework for detailed studies of the MTZ and layered gabbro lenses
107 (Rabinowicz et al, 1987; Ceuleneer et al, 1988; Boudier and Nicolas, 1995; Kelemen et al,
108 1997a; Jousselin et al, 1998; Koga et al, 2001). The crust-mantle interface (Moho) in this area
109 is nearly horizontal, and dikes in the sheeted dike system are vertical. The region can thus be
110 viewed as a paleospreading center dissected by erosion, without any subsequent deformation.
111

112 Gabbro lenses in the MTZ are always magmatically deformed (i.e. with a grain shape
113 preferred orientation of anisometric and euhedral crystals ascribed to flow in the dense
114 suspension; e.g. Benn and Allard, 1989; Nicolas, 1992; Yaouancq and MacLeod, 2000),
115 without sample-scale evidence of plastic deformation (such as augen pyroxene grains), and
116 are usually subhorizontal. Lens thickness varies from a few centimeters to tens of meters, with
117 a horizontal extent of a few meters to a hundred meters; many lenses are < 1m thick, and
118 some tend to cluster in the upper part of the MTZ. Layer thicknesses vary from a few
119 millimeters to a few tens of centimeters. Graded layers are common features (about 20-25%
120 of 200 layers in outcrops of our field study), but the strong majority of individual layers tend
121 to be homogeneous from the base to the summit, with sharp limits at each boundary. Bulk and
122 layer composition are variable. Leucotroctolite bulk compositions seem dominant and
123 clinopyroxene-rich layers seem more rare than those rich in olivine or plagioclase. Table 1
124 shows representative variations of the layer composition. Although we are not aware of any
125 rigorous systematic measurements of lens and layer dimensions and modal compositions, our

126 observations agree with field impressions and the few sample descriptions provided by other
127 workers (Boudier and Nicolas, 1995; Boudier et al, 1996a; Kelemen et al, 1997a; Korenaga et
128 al, 1997). Nevertheless, the presence of several tens of meters thick lenses, and the relative
129 importance of graded layers (qualified as an important feature in Kelemen et al, 1997a), seem
130 overestimated. All structural features are generally concordant: the contact of gabbro lenses
131 with the host dunite, modal layering (Fig. 1), and the gabbro magmatic foliation and lineation
132 are all usually parallel to the asthenospheric plastic foliation and lineation of the host dunite.
133 However several outcrops with less deformed gabbros show semi-discordant lenses with
134 irregular shapes and rough layering, or discordant layers, and a few outcrops show isotropic
135 gabbros, troctolites, and olivine-rich troctolite patches (Fig. 2). In particular, one outcrop
136 (N22°59'32", E57°59'46", called hereafter the Khilah outcrop) presents a spectacular case of
137 mostly isotropic gabbros, extending over five hundred meters (Fig. 3). The outcrop contains a
138 few 1 to 20 meters wide zones with poorly layered gabbros. When it is present, layering is
139 parallel to the plastic foliation of the host peridotite observed 20 to 100 meters away. Except
140 for the roughly layered zones, and a few randomly oriented heterogeneities (mainly
141 centimeter sized dunite bodies) (Fig. 2B), the gabbro seems a relatively homogeneous mix of
142 plagioclase (60-80%), olivine (10-30%) and clinopyroxene (0-20%) (Fig. 2A). The transition
143 from the host peridotite (mainly plagioclase and clinopyroxene impregnated dunite) to the
144 isotropic gabbro is diffuse, with increasing plagioclase and clinopyroxene impregnations
145 towards the center of the outcrop over few meters. In parts of the impregnated dunite,
146 plagioclase crystals are automorphic, suggesting that there was enough melt for the crystals to
147 grow in suspension (Fig. 4A). When plagioclase and clinopyroxene reach 25%, they contour
148 and isolate olivine grains in dunite and the rock becomes isotropic (Fig. 4B). This near
149 poikilitic texture (with olivine crystals larger than oikocrysts) gives way to phaneritic textures

150 with a hypidiomorphic granular fabric when the plagioclase and clinopyroxene fraction
151 increases and the rock becomes a gabbro.

152

153 The general characteristics of gabbro lenses bear similarities with those of plagioclase and
154 clinopyroxene impregnations in the MTZ dunite (Fig 5). In the impregnated dunite,
155 clinopyroxene and plagioclase grains are devoid of any intracrystalline deformation, but they
156 have an elongated shape, parallel to the plastic stretching lineation of the host dunite, with
157 more elongated grains, and stronger shape preferred orientation associated with the stronger
158 olivine CPOs in the dunite, suggesting crystals filled melt pockets which shape was governed
159 by strain (Jousselin and Mainprice, 1998). As for the layered gabbro lenses versus the
160 isotropic gabbro, field observations of well transposed melt impregnations parallel to the
161 foliated dunite are much more common than isotropic impregnations within poorly foliated
162 dunite; however isotropic impregnations are not rare. All strongly elongated impregnations
163 occur in dunite whereas some of the untransposed ones occur in residual harzburgite, where a
164 few corroded orthopyroxene grains can be observed. Some of the impregnations are
165 continuous with the tip of gabbro lenses or form diffuse contacts with gabbro lenses (Fig. 5;
166 figure 1a in Boudier et al, 1996a) suggesting that they are cogenetic.

167

168 **3. New structural observations, and kinematic analysis**

169

170 Kelemen et al. (1997a) assume that deformation by simple shear would have obliterated
171 graded layers, and conclude that most deformation must have been pure shear (flattening
172 during compaction). This would suggest that the gabbro lenses were not affected by the
173 surrounding mantle flow and therefore would be late or off-axis features, whereas their study
174 rightfully points to chemical compositions that argue that the lenses were emplaced on-axis.

175 However, we find numerous and robust indicators that gabbro lenses and the host rock
176 recorded a strong simple shear deformation (Fig. 6), except for the local isotropic zones
177 aforementioned: (i) well developed lineation in the foliation plane, (ii) folds in the gabbro
178 lenses with an axis consistently parallel to the lineation (Fig. 6A-B), (iii) synmagmatic normal
179 faults with an azimuth at high angle with the magmatic lineation and S/C shear bands (Fig
180 6C-D; Nicolas, 1992), (iv) the frequent CPO measurements in the host dunite, that show [100]
181 crystallographic axis of olivine at a small angle to the lineation (Fig. 7A; Ben Ismail and
182 Mainprice, 1998; Dijkstra et al, 2002). In some cases, an obliquity of the olivine and
183 plagioclase shape preferred orientation with the layering is discernible (Fig. 6E). This
184 evidence indicates moderate simple shear deformation, but in most cases, all structures are
185 parallel, pointing to a very large strain, including in the graded layers (Nicolas, 1992). It
186 should also be noted that a 50% compaction, as calculated by Browning (1984) and used by
187 Kelemen et al (1997a), seems insufficient to produce a strong foliation (Higgins, 1991). The
188 parallelism of the shape fabric in melt impregnated dunite, the magmatic lineation in gabbros,
189 and the plastic lineation of the host dunite, indicate that their development is
190 contemporaneous, and that the magmatic features are passively coupled to the plastic flow of
191 the surrounding peridotitic matrix.

192

193 **4. Microstructural analysis**

194

195 *4.1. Gabbro layering and shape preferred orientation*

196

197 We present a microstructural study of samples of the MTZ, with an emphasis on the preserved
198 cases of isotropic gabbros, and weakly layered samples that may represent the earliest
199 subsequent stages of evolution, and which have not been studied before. We have studied 10

200 samples in the Khilah outcrop, and 52 others in its vicinity (Fig 3). Four types of samples
201 were distinguished: type 1 is characterized by the absence of layering (Fig. 2A-B); type 2
202 shows weakly defined layers which can be followed over few centimeters (Fig. 2C-D); type 3
203 shows more strongly defined layers, still with diffuse or wavy limits (Fig.2E-F); the more
204 common type 4 corresponds to the presence of very well defined layers with sharp and
205 straight limits (Fig.1). Type 3 layers can rarely be followed over two meters, and type 4 layers
206 may be followed over several meters. All samples display a magmatic texture; plagioclase
207 show euhedral magmatic laths, and a few are twinned, which implies sufficient freedom for
208 crystals to rotate without undergoing plastic deformation. Clinopyroxene is tabular or round-
209 shaped with no evidence of deformation. In type 1-3 samples, some of the olivine grains show
210 clear crystallographic faces suggesting a cumulative origin, or overgrowth around the edges
211 of mantle xenocrysts (Boudier, 1991). In all samples, olivine does not show any dynamic
212 recrystallization, but some grains have undulose extinction suggesting light plastic
213 deformation. Field observations of crystal alignment and aggregate elongation indicate that
214 deformation increases from type 1 to type 4 samples. To evaluate the importance of the shape
215 fabric, we performed shape preferred orientation analyses based on hand drawings of seven
216 thin sections, sectioned parallel to the lineation and perpendicular to the magmatic foliation
217 (XZ plane). Two type 1 samples were analyzed; as no foliation and lineation is visible in
218 these, the thin sections were cut parallel to the orientation of the nearest observable XZ plane
219 from nearby outcrops. For each crystal, we measured the longest chord connecting any two
220 points on the perimeter, and the orientation of this axis with respect to the X axis. As
221 anticipated, the two type 1 samples do not show any crystal shape preferred orientation; this
222 was also checked on a thin section cut perpendicularly; preferred orientation in type 2 to 4
223 gradually changes from weak to strong (Fig 7B).

224

225 4.2. Crystallographic preferred orientation

226

227 Of sixty-two gabbro samples we collected, forty were chosen on the basis of their type variety
228 and freshness for CPO analysis. Phases and orientation were mapped using the SEM-EBSD
229 facility at Geosciences Montpellier (e.g. Fig. 1C) with a 45-100 μm grid spacing. Due to
230 alteration or lack of a mineral phase, we obtained 27 olivine CPO and 35 plagioclase CPO
231 usable measurements (100 measured grains per phase, except 5 cases with >75 measured
232 grains which were considered valid because the olivine fabric seemed unambiguous. Pole
233 figures are plotted with one point per grain. Grain counting was done manually, because
234 automatic counting from the map counts a single grain as several when it is cut by veins).
235 Alteration is particularly important in our weakly deformed samples, which choice is more
236 limited than for the type 4 samples; thus to reflect the variety of the microstructures while
237 insuring that enough grains are measured to obtain a valid CPO, eight parallel thin sections
238 were cut for two type 2 samples, and representative CPOs were obtained once the
239 measurements were compiled. Our study also includes 2 olivine CPOs in the MTZ host
240 dunites, measured with a universal stage. A selection of representative CPOs of olivine and
241 plagioclase is shown in Fig. 7; the full CPO dataset is available in online Supplementary
242 Information, including samples with specific patterns described below.

243

244 The two type 1 samples show random CPOs. The five type 2 samples show essentially planar
245 fabrics, where the (010) crystal faces of olivine and plagioclase define the magmatic foliation.
246 The type 2 olivine fabric is not regular, one seems random (07OD21B), in the other cases the
247 [001] axis draws a girdle in the foliation plane, and the [100] axis orientation is erratic, except
248 for one case (07OD44E) where it draws a girdle in the foliation plane. The plagioclase fabric
249 is better defined, with the [100] axis drawing a girdle in the foliation plane, even defining a

250 weak lineation in two cases (07OD21B and 10-OM43I); the [001] axis orientation is
251 imprecise, with a light tendency to lie in the foliation plane (clear for one sample: 07OD32).
252 The type 3 samples have a more consistent CPO; both olivine (4 samples) and plagioclase (5
253 samples) show a lineation superimposed on the (010) foliation. In olivine, the [001] axis
254 corresponds to the lineation, while [100] is perpendicular to it; in plagioclase, [100]
255 corresponds to the lineation, and [001] has a somewhat erratic orientation. The type 4 samples
256 have the same plagioclase CPO as type 3 samples; however, olivine fabrics are drastically
257 different with very well defined [100] (010) CPOs, and a weak tendency of the [001] axes to
258 concentrate near the Y axis, with one exception showing a [100] (001) fabric (10-OM42G3).
259 Olivine CPOs in the host dunite show the classic [100] (010) mantle fabric (Ben Ismail and
260 Mainprice, 1998).

261

262 **5. Interpretation and discussion**

263

264 *5.1. Comparison with sill models*

265

266 The model where modally layered gabbro of the lower crustal section formed in sills (Boudier
267 et al, 1996; Kelemen et al, 1997a) is inferred on the analogy with gabbro lenses of the MTZ
268 that are interpreted as sill intrusions. This interpretation relies on the common elongated sill-
269 like shape of the MTZ gabbro lenses (Fig. 1A) and the presence of graded layers that were
270 thought to indicate a lack of deformation. We have shown that the gabbro lenses are strongly
271 deformed (Fig. 6) and that lenses may have shapes that differ from those of simple sills (Fig.
272 2H). Also there is no microstructural study showing that the layered gabbro lenses have
273 intrusive contacts, or observations of layered gabbro lenses branching with dikes or any root-
274 like bodies tectonically transposed after emplacement, which would support that the lenses

275 are the remains of sills. Unlike what can be observed in Oman, Bedard (1990; 1993) describes
276 sharp intrusive contacts, with reaction rims and host rock xenoliths in gabbro sills of the Bay
277 of Island ophiolite. In the Annieopsquotch ophiolite, Lissenberg et al (2004) describe
278 dendritic crystals and comb structures in modally layered gabbro sills, and note that the
279 gabbros do not show any fabric. It is surprising that no such clear symptomatic criteria for a
280 sill origin is present in Oman. This might be because of a lack of compositional or thermal
281 disequilibrium between the lenses and the host rock, but even rare layered sills corresponding
282 to the dying stage of the Oman magmatism are not found. On the contrary, many gabbro
283 lenses have diffuse contacts (Fig. 5) rather than sharp ones, the tip of the lenses often show a
284 progressive transition from the gabbro to the host impregnated dunite over a few centimeters,
285 and all of the layered gabbro have a clear fabric. This suggests that the sill model is not
286 applicable to many of the gabbro lenses of the Oman ophiolite MTZ. Also, the presence of
287 euhedral plagioclase within the impregnated dunite (Fig. 4A) shows that suspension flow is
288 not confined within the lenses, and that the lenses may result from a segregation rather than
289 represent the remains of the melt conduits.

290

291 *5.2. Melt emplacement.*

292

293 With its diffuse limits (Fig. 3C), the gabbro of the Khilah outcrop clearly does not represent a
294 sill intrusion. The transition from the impregnated dunite to the gabbro, and the presence of
295 dunite patches within the gabbro strongly suggest that the gabbros represent zones where
296 impregnating melt crystallized great volumes of plagioclase and to a lesser extent
297 clinopyroxene, to the point where the petrologic designation of the rock switches from
298 plagioclase-dunite to troctolite or gabbro although it is in essence a massively impregnated
299 dunite. A consequence of this interpretation is that a part of the olivine grains in the gabbro

300 must be mantle xenocrysts. The textures, the large grain size (1 to 5 mm), and the coupling of
301 gabbro layers orientation with asthenospheric mantle flow show that melt emplacement at the
302 Khilah outcrop is contemporaneous with mantle flow and thus must be ascribed to ridge
303 processes. This outcrop is structurally above isotropic melt impregnations in depleted
304 harzburgite at the Mahram village, above the Maqsad mantle diapir (Fig. 3). It is beneath a >2
305 Km wide zone, where gabbros at the base of the crustal section are roughly layered, and
306 resemble those observed at the Khilah outcrop. Isotropic and poorly layered gabbro blocks are
307 particularly abundant in riverbeds near the Khilah outcrop but are also found elsewhere,
308 suggesting that this type of outcrop is not unique. The position at the apex of the mantle
309 diapir, probably centered on the inferred paleoridge axis, may explain why the whole area
310 shows several outcrops that are not strongly affected by the diverging ridge flow. This
311 situation raises the question of how isotropic gabbro bodies evolve when they are not
312 fossilized in this state and endure the deformation imposed by the host rock; the layered
313 gabbro lenses are the only obvious candidates for the possible result.

314

315 *5.3. Fabric evolution*

316

317 The poikilitic textures in impregnated dunite show olivine grains that are free to rotate (Fig.
318 4b), implying that melt reached the critical melt fraction (near 30%, Van der Molen and
319 Paterson, 1979) where the solid matrix is disaggregated by the melt and the fabric is lost, thus
320 forming the type 1 gabbro. Four isotropic CPOs in melt impregnated harzburgite and dunite
321 samples have been reported before (Boudier et al, 1996; Joussetin et al, 1998; Joussetin and
322 Mainprice, 1998), and interpreted in this manner; however in these cases only a small fraction
323 of plagioclase and clinopyroxene was precipitated from the melt in the residual dunite, thus
324 the modal composition was not shifted towards that of a gabbro. The situation observed in the

325 Khilah outcrop is rare because it shows a stage that can only be ephemeral. As melt
326 progresses through the solid dunitic matrix, it fills more space, thus the fluid pressure will
327 drop, and the melt mush will start to compact. This will lead to fading of the type 1 stage and
328 emergence of a planar fabric which is exactly what is observed in type 2 samples.

329

330 As melt fraction decreases and more transient solid chains form and interact, coupling with
331 the simple shear imposed by the surrounding mantle flow is more efficient, and leads to the
332 development of a stronger magmatic lineation in the olivine and plagioclase CPO as seen in
333 type 3 samples. [001] (010) olivine CPO is generated by magmatic flow (Benn and Allard,
334 1988), or may be favored by plastic deformation in the presence of melt (Holtzmann et al,
335 2003) or by mantle hydration (Jung and Karato, 2001). The euhedral shape, the preferred
336 shape orientation and its correlation with the CPO, and the context of the magmatic rock with
337 magmatic texture for plagioclase, where most olivine grains are embedded in plagioclase and
338 clinopyroxene grains that are themselves not deformed, suggest that at this stage plastic
339 intracrystalline deformation is not a major factor to produce the CPO. We interpret the
340 [001](010) olivine CPOs in type 3 as similar to the magmatic fabric in a sample of Oman
341 layered gabbro of the crustal section (Benn and Allard, 1988). Note that the term "magmatic"
342 refers to the physical conditions required to orient crystals without any intracrystalline
343 deformation; it does not refer to the olivine origin which can be cumulative or mantellic. As
344 the [001] axis is the longest axis in euhedral olivine, it aligns with the flow, and the CPO
345 reflects the shape fabric. The [100] (010) plagioclase CPO in type 3 and type 4 samples
346 compare well with previously reported magmatic fabrics (see review in Benn and Allard,
347 1988), and the lack of evidence for plastic deformation leaves no doubt that the plagioclase
348 fabrics are of magmatic origin.

349

350 Type 4 samples show a [100](010) olivine CPO which corresponds to the classic high-
351 temperature gliding system. The unique case of [100] (001) CPO also corresponds to a less
352 common high-temperature gliding system; it has been reported in two harzburgite samples of
353 the Maqсад diapir (unpublished personal data), a harzburgite at the Garret transform (Cannat,
354 et al, 1990), Hess Deep (Boudier et al, 1996b), and dunite associated with chromite pods in
355 the New Caledonia ophiolite (Cassard et al, 1980); i.e. cases where the peridotite is associated
356 with melt circulation. We now try to understand how such a plastic fabric can be generated in
357 gabbros with a prominent magmatic texture. Boudier and Nicolas (1995) have reported [100]
358 (010) olivine CPOs for two strongly deformed gabbro samples; they classify the origin of
359 strain in olivine as questionable. Vernon (2000) notes that solid-state strain in the interstices
360 between undeformed and aligned crystals may assist rotation and alignment without plastic
361 deformation of the rotated crystals. While he considers observations where the solid-state
362 strain is thought to be minor, he also points out that it is unknown to what degree this process
363 can produce strong alignment of undeformed crystals. Indeed, in solid-state deformation,
364 large viscosity contrasts may also be present and mechanisms of particle orientation in
365 magmatic flow can also apply to the situation of rigid crystals embedded in a weak solid
366 matrix deforming plastically, such as amphiboles in a phyllite (Fergusson, 1979).

367 Experimental constraints for plagioclase deformation at high temperature suggest that olivine
368 is weaker than plagioclase at oceanic Moho conditions (Seront, 1993; Dimanov et al, 1998).

369 The possibility of deforming olivine plastically while plagioclase crystals remain undeformed
370 is enhanced by the strong segregation observed at this stage. We argue that as a critical
371 threshold of olivine connectivity is reached, olivine deformation rapidly switches from
372 magmatic to plastic. This last stage of deformation probably contributes to the layering
373 sharpening, as deformation must concentrate in the weakest layer: either melt (and possibly

374 plagioclase) rich layers if enough melt is present within this layer, or more probably at this
375 last stage, olivine rich layers when the melt fraction is greatly reduced.

376

377 Once gabbro is fully crystallized, it must be under lithospheric conditions (i.e. mantle flow is
378 frozen). As no low temperature deformation is recorded, gabbro in lithospheric conditions
379 must simply drift away from the ridge axis and not be further deformed. Thus the strong
380 olivine plastic fabric must develop in a tight window at the asthenosphere/lithosphere
381 boundary, with little or no melt, where most of the deformation is accommodated by the
382 olivine rich layers. This implies that under high temperature conditions, and with the presence
383 of melt to enhance diffusion, simple shear is capable of erasing the pre-existing type 3 fabric
384 and of producing a new and strong plastic olivine CPO, within a few hundred meters of flow.

385

386 It is interestingly fitting that the samples with the largest fractions of clinopyroxene are type 3
387 and type 4 gabbros. For a parental MORB melt, clinopyroxene must be the last phase to
388 crystallize, at near 1160°C (Feig et al, 2006), when the mush is crystal-rich and the final
389 stages of deformation are reached. Still, more data are needed to establish a correlation
390 between modal composition and gabbro types, and we will see in the next section that modal
391 composition should be used with caution.

392

393 IODP hole 1309D, at the Mid-Atlantic ridge, traverses melatroctolites, troctolites and olivine
394 gabbros that might be viewed as similar to our samples. In the IODP hole, the olivine CPO is
395 thought to result from a mantle fabric modified by incoming melt, which corroded olivine
396 grain boundaries and penetrated along olivine tilt walls (Drouin et al, 2010). We do not think
397 that the fabrics of our samples are inherited from a previous mantle fabric. The IODP samples
398 show small olivine grains embedded in large plagioclase poikiloblasts; whereas in our

399 samples, olivine crystals remain large, they do not show evidence for corroded boundaries,
400 and the plagioclase blades are not parallel to olivine tilt walls. Our outcrops top the
401 harzburgite section, whereas those of the IODP hole lie above evolved gabbro, which indeed
402 could provide an evolved melt able to dissolve olivine grains (Suhr et al, 2008). Finally, the
403 CPO analysis of the IODP samples relies on the relative concentration of maxima for each
404 crystallographic axis rather than their orientation as no X,Y,Z structural frame nor layering is
405 visible. It shows strong maxima for the [001] axis, which is not something we observe in our
406 samples.

407

408 Given the field relationships, and the coincidence of the different CPOs with aspects of the
409 shape fabric and layering in our samples, we argue that there is a continuum from type 1
410 samples where all mantle fabric heritage is lost, to type 4 samples where a new fabric is
411 produced (Fig. 8). In this last stage, where olivine is so segregated that it constitutes thin
412 dunite-like layers, the fabric is similar to the host dunite fabric to which it is coupled. We
413 suppose that many of the olivine crystals in the gabbro are of mantellic origin, but this is
414 deduced from the texture of type 1 samples, not from the fabric developed in type 3 and type
415 4 samples, which could equally affect olivine of magmatic origin.

416

417 *5.4. Layering formation*

418

419 Most of the observed microstructures imply a strong simple shear deformation. We show that
420 layering does not predate shearing but is linked to the development of deformation. The CPOs
421 induced by the simple shear allow us to follow a continuous evolution of the deformation
422 which is correlated with the development of layering defined by type 1 to type 4 samples.
423 Field relations from type 1 to type 2 and 3 at the Khilah outcrop, and from the type 3 to type 4

424 in other places are coherent with this evolution, and we think it is unlikely that the different
425 types represent unrelated gabbro bodies. This idea is reinforced by the consideration that
426 types 1 to 3 do not represent steady-state situations, and should be more deformed when they
427 are not frozen at this stage.

428

429 Some of the reasons why simple shear in magmatic rocks can cause crystal and melt
430 segregation are summarized by McBirney and Nicolas (1997). At least two processes are
431 relevant to the generation of layering in our case: segregation of suspended solids (crystals) of
432 differing sizes, and transposition of inhomogeneities. Similarly, the creation of layering by
433 shearing is accepted in plastically deformed rocks, where a "massive" (unlayered) plutonic
434 rock can turn into a layered gneiss, with better defined and thinner layers for more strongly
435 deformed rocks (e.g. Myers, 1978). Also, shearing lead to transpose heterogeneities into
436 lenticular beds (e.g. Ramsay and Graham, 1970) producing other layers. In addition there is a
437 wide range of physical experiments and models that produce segregation in suspended
438 particles, slurries, or granular material during simple shear deformation (e.g. Sokolowski and
439 Herrmann, 1992; Santra et al, 1996; Barentin et al, 2004; May et al, 2009), including
440 asymmetric layers (e.g. Komnik et al, 2004). These investigations indicate that any type of
441 difference in the particle species may lead to shear-induced segregation (Plantard et al, 2006).
442 This suggests that the complexity of crystal size, geometry, surface properties, and density
443 variations provide multiple factors favoring the generation of layers. On the basis of these
444 studies and our observations, we argue that a large fraction of gabbro layering can originate
445 from mechanical sorting during strong shearing and tectonic transposition of heterogeneities.
446 This model solves a paradox pointed by Koga et al (2001): the highly variable lithologies are
447 thought to arise via different degrees of crystal fractionation from a common parental melt;
448 however, the limited range of variability in olivine, plagioclase and clinopyroxene

449 compositions suggests that the differences in extent of crystallization must be small. If layers
450 are created through mechanical sorting, their modal compositions do not reflect crystal
451 fractionation variations from a sequence to another, and it becomes possible to create various
452 lithologies from a single cumulate sequence.

453

454 *5.5. Timing and consequences on melt extraction process*

455

456 The small frequency of isotropic or weakly deformed gabbros suggests that they are transient
457 features, which are not often preserved because they must be frozen in the short time lapse
458 between emplacement and the shearing and tectonic transposition inexorably imposed by the
459 surrounding mantle flow. This is coherent with the observation of residual harzburgite in
460 isotropic impregnations, where the orthopyroxene dissolution reaction with incoming melt is
461 started but not completed, whereas transposed melt impregnations imply sufficient time for
462 deformation to accumulate and thus longer melt residence within the rock, leading to
463 resorption of all the orthopyroxene grains.

464

465 The isotropic stage implies that melt accumulated rapidly with respect to the mantle strain
466 rate. How fast melt accumulates (t) can be estimated by dividing the volume of melt that was
467 present, by the melt flux from the melt feeding conduit. Considering that isotropic gabbro is
468 distributed in a sphere with a diameter L equal to the length of the outcrop, and that the
469 minimum melt fraction corresponds to that required to disaggregate the solid framework
470 (30%), it gives:

$$471 \quad t = [4/3 \times (L/2)^3 \times 0.3] / [V_m \times (D/2)^2 \times f]$$

472 where V_m is the ascending melt velocity, D is the diameter of the melt conduit which we take
473 as circular, and f is the melt fraction in this conduit. For a porous flow melt conduit, values on

474 the order of one meter per year for V_m , one hundred meters for D , and one percent for f seem
475 reasonable (Kelemen et al, 1997b). This gives a time of 250 000 years. On the other hand,
476 gabbro layering seems to develop over distances less than a hundred meters as type 2 and 3
477 samples are present within the Khilah outcrop and at its outskirts. Given that the host dunite
478 flows at a velocity near the ridge spreading velocity or faster (Jousselin et al, 1998), for a
479 velocity around 10 cm/year we conclude that layering must develop over a time of about a
480 thousand years.

481

482 These numbers are not very precise, and are only intended to provide orders of magnitude.

483 There was probably more than 30% melt present at the time of the formation of the Khilah

484 outcrop, mantle foliation geometry and shear sense inversion beneath the Moho suggest that

485 mantle flow is faster than ridge spreading rate (Ildefonse et al, 1995, Michibayashi et al,

486 2000), and dunite bands that are interpreted as relics of porous flow conduits, are often

487 thinner than a hundred meters. So the discrepancy between the two results could be more

488 important. This suggests that porous flow conduits cannot deliver melt fast enough to destroy

489 the solid framework of the host dunite and accumulate within a time window small enough to

490 not be affected by the host rock shearing. Another possibility is that melt was extracted from

491 dikes, as proposed by Nicolas (1986) for depth of 0 to 60 Km, and by Kelemen et al (1997b)

492 for very shallow mantle. It would take less than a year and a half for a 10 cm wide and 100 m

493 long dike, with a melt velocity of 1.5 cm/s (Lago et al, 1982) to fill the necessary melt

494 volume.

495

496 *5.6. Origin of gabbro layering in the lower crust?*

497

498 We investigate whether our model for the origin of layering in gabbro lenses of the MTZ is
499 adaptable to gabbro layers in the lower crust. Several lines of evidence suggest that this is
500 possible: recent marine geophysical investigation shows that the lower gabbros contain
501 similar local melt accumulations (Canales et al, 2009); Nicolas (1992) indicates that the
502 strong simple shear kinematic criteria are also ubiquitous in the layered gabbros of the crustal
503 section; we found type 2 and type 3 crustal gabbro at the inferred Maqsad paleoridge axis, and
504 out of the 3 published olivine CPOs measured in crustal layered gabbro, one presents a
505 [001](010) fabric, typical of the type 3 gabbro (Benn and Allard, 1988). As the host rock is
506 not dunite, it is possible that the gabbro is devoid of olivine xenocrysts, and that melt recycles
507 plagioclase and clinopyroxene crystals of the host rock instead. On the other hand, wehrlite
508 crustal intrusions, which are rooted in the MTZ magmatic mush, may provide an olivine
509 xenocryst source, and may produce olivine rich layers when they are tectonically transposed
510 into concordance by the surrounding magmatic flow (Jousselin and Nicolas, 2000; Koga et al,
511 2001).

512

513 **6. Conclusion**

514

515 We show that modal layering in gabbro lenses of the MTZ does not predate shearing but is
516 linked to the development of simple shear deformation, imposed by the surrounding mantle
517 flow. We collected the first extensive CPO dataset for these rocks, which allows us to follow
518 the coevolution of deformation and layering. We found three distinct deformation stages that
519 follow the emplacement of isotropic gabbro. First the melt mush is compacted, leading to
520 planar fabric (type 2 gabbros) and the emergence of a rough layering. Then simple shear leads
521 to a magmatic (driven by the shape of crystals in suspension) fabric (type 3 gabbros); at this
522 stage layer boundaries are very irregular and layer extension is limited to a couple meters at

523 the most. In the last stage (type 4 gabbros), segregated olivine bands switch to high-
524 temperature plastic fabrics, layer boundaries are very sharp and often can be followed over
525 more than three meters. Most gabbro layers are fossilized at this last stage. To fossilize the
526 initial isotropic stage, the melt input must be fast relative to the host dunite strain rate. This
527 suggests that melt reached the MTZ through hydrofracturing dikes. When melt ceases to rise
528 and ponds at the Moho level, textural analysis shows that it disperses through the host dunite
529 and isolates olivine grains; as a result, a large fraction of the olivine grains in the layered
530 gabbro lenses of the MTZ must be mantle xenocrysts.

531

532 The sheeted sill model for the Oman ophiolite gabbros mainly relies on the observation of
533 isolated layered gabbro lenses embedded in mantle dunite, which could not possibly derive
534 from the subsidence of a perched magma lens in the upper crust, and chemical constraints that
535 imply that few layers represent isolated systems (sills or small convection cells within a
536 magma chamber) (Browning, 1984, Kelemen et al, 1997a). On the other hand, gabbro glacier
537 models mainly focus on the identification of strong deformation in layered gabbros of the
538 lower crust. In this model, the deformation is related to the flow out of the magma lens
539 perched at the top of the crustal section, which was the only known magma lens at the time
540 these models were developed. A strong merit of our model is to be coherent with constraints
541 from the sheeted sill and the gabbro glacier models. Our model is not intended to describe the
542 dynamics of the whole magma chamber, but offers an explanation based on new data for the
543 formation of the gabbro layering at the base of the ridge magmatic system.

544

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546

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554

555

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557

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735

736

737 **Tab and figure caption**

738

739 Table 1: Modal composition at the thin section scale for a selection of our samples. See the
740 microstructural analysis paragraph for the definition of gabbro type. Modal composition
741 within different layers is provided when layer boundaries are observed within the thin section.

742

743 Figure 1: 3 views on layered gabbro lenses at outcrop/sample/thin section scales. A) A series
744 of 10-40 cm thick layered gabbro lenses embedded in dunite. Hammer handle is 40 cm. B)
745 Close up views on layers within a lens, with sharp and linear boundaries (referred as type 4 in
746 the text). Pictures height is 30 cm. C) Thin section phase maps of samples 07OD48 (top) and
747 07OD47B3 (bottom) constructed from MEB-EBSD measurements (N.I.: not indexed).

748

749 Figure 2: views on isotropic, poorly layered, and irregular-shaped gabbro layers and patches.

750 A) Isotropic gabbro at the center of the Khilah outcrop. B) Dunitic small bodies with random
751 orientations and diffuse contacts within isotropic gabbro at the Khilah outcrop. C-D) Two
752 examples of 1 m-long rough layers emerging from isotropic gabbro (referred as type 2 in the
753 text). E-F) slightly better developed layering, with wavy boundaries and frequent layer
754 terminations (referred as type 3 in the text) G) Several discordant layers H) small altered
755 gabbroic lens with an irregular shape, with its longest axis approximately parallel to the
756 stretching lineation in host dunite.

757

758 Figure 3: A) Lineation map of the Maqsad diapir (adapted from Jouselin et al, 1998) with
759 samples distribution. B) close up on the situation of the Khilah outcrop; location shown by a
760 rectangle in A. The Khilah outcrop is the southernmost and largest circled isotropic gabbro
761 outcrop. C) Boulders collected at the Khilah outcrop, with progressive increase in plagioclase
762 and clinopyroxene content, mimicking the diffuse transition from impregnated dunite to
763 gabbro. D) Field sketch of the eastern part of the Khilah outcrop; location shown by a grey
764 rectangle in B); the western part is more monotonous with essentially isotropic gabbro.

765

766 Figure 4: close up on melt impregnated dunite at the periphery of the Khilah outcrop. A)
767 plagioclase and clinopyroxene impregnated dunite in the MTZ near the Mahram pass (see Fig.
768 3B), with a few automorphic plagioclase grains (pointed by arrows). B) plagioclase oikocrysts
769 isolating olivine grains in the impregnated dunite at the western limit of the Khilah outcrop.
770

771 Figure 5: from bottom to top, (1) foliated plagioclase impregnations in dunite, (2) three 1 cm
772 bands, rich in plagioclase aggregates of impregnating crystals, and (3) thin lenses of layered
773 gabbro (type 4) in the background.
774

775 Figure 6: kinematic indicators of simple shear in layered gabbro lenses. A-B) Asymmetrical
776 folds; as is the case for strong deformation, fold axis are rotated parallel to the lineation
777 direction. C-D) Normal shear zones in cross-section and planar view. The planar view shows
778 the consistent orientation of the shear plane, and the cross-section view explains the color
779 variations in map view induced by the movement at the shear zone. E) Close-up view on a
780 layer with olivine crystals at a consistent angle to the layering.
781

782 Figure 7: a selection of fabrics and shape fabrics from our microstructural study. A) Olivine
783 CPO for a dunite (host rock of the gabbro lenses) showing a classic [100] (010) mantle fabric.
784 The obliquity between the [100] axis and the lineation [X] indicates a dextral shear sense. B)
785 Histograms of the orientation of the long axis in XZ thin sections of plagioclase grains for
786 four samples. The lineation corresponds to the 90° orientation. As deformation progress from
787 type 1 to type 4 gabbros, measurements show a better shape preferred orientation parallel to
788 the lineation. C) CPO of olivine and plagioclase for 6 samples, showing deformation
789 evolution in the 4 sample types. Type 1 samples show no CPO; type 2 samples show a planar
790 fabric defined by the (010) planes of olivine and plagioclase; type 3 samples show a [001]

791 (010) olivine and [100] (010) plagioclase magmatic fabric, with a lineation superimposed on
792 the planar fabric. Type 4 gabbros are characterized by a switch to olivine plastic deformation
793 with a strong [100] lineation. Contours are at 0.5% intervals of uniform distribution.

794

795 Figure 8: model for the formation of layered gabbro lenses. The model relies on the
796 correlations of gabbro lenses shape changes, the absence of layering in type 1 gabbro and the
797 development of layering from type 2 to type 4 gabbros, and the evolution of the fabric due to
798 the host mantle (gray) shearing; it implies melt (white) delivery from dikes, and integration of
799 mantle olivine within layered gabbros

Melt impregnation forms isotropic gabbro in the Oman ophiolite Moho transition zone

We measured crystallographic fabric for transition from isotropic to layered gabbro

Olivine fabric evolves from planar to [001](010)-magmatic to [100](010)-HTplastic

We deduce that gabbro layering originates from shear caused by host mantle flow

Isotropic stage means melt collected faster than shear rate, thus extracted by dikes

Type 1 No Fabric



Type 2 S-Fabric



Type 4 S-L Fabric with [100] (010) olivine fabric



Type 1 No Fabric



Type 3 S-L Fabric with [001] (010) olivine fabric



Type 1 - Type 2 - Type 3 - Type 4

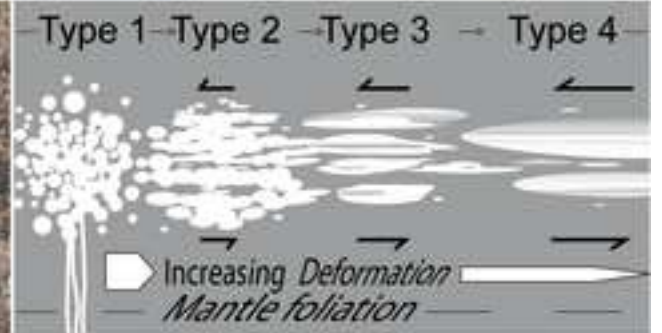


Figure 1

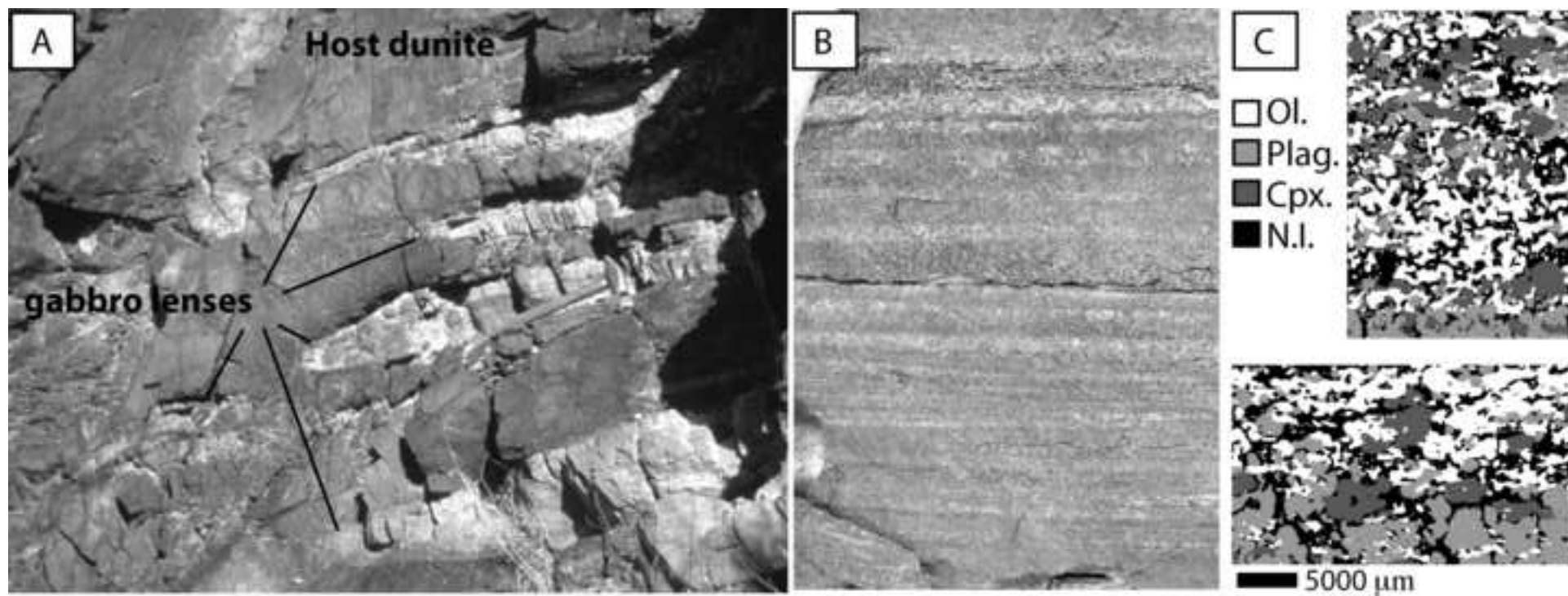


Figure 1 colour version (online only, not readable printed B&W)

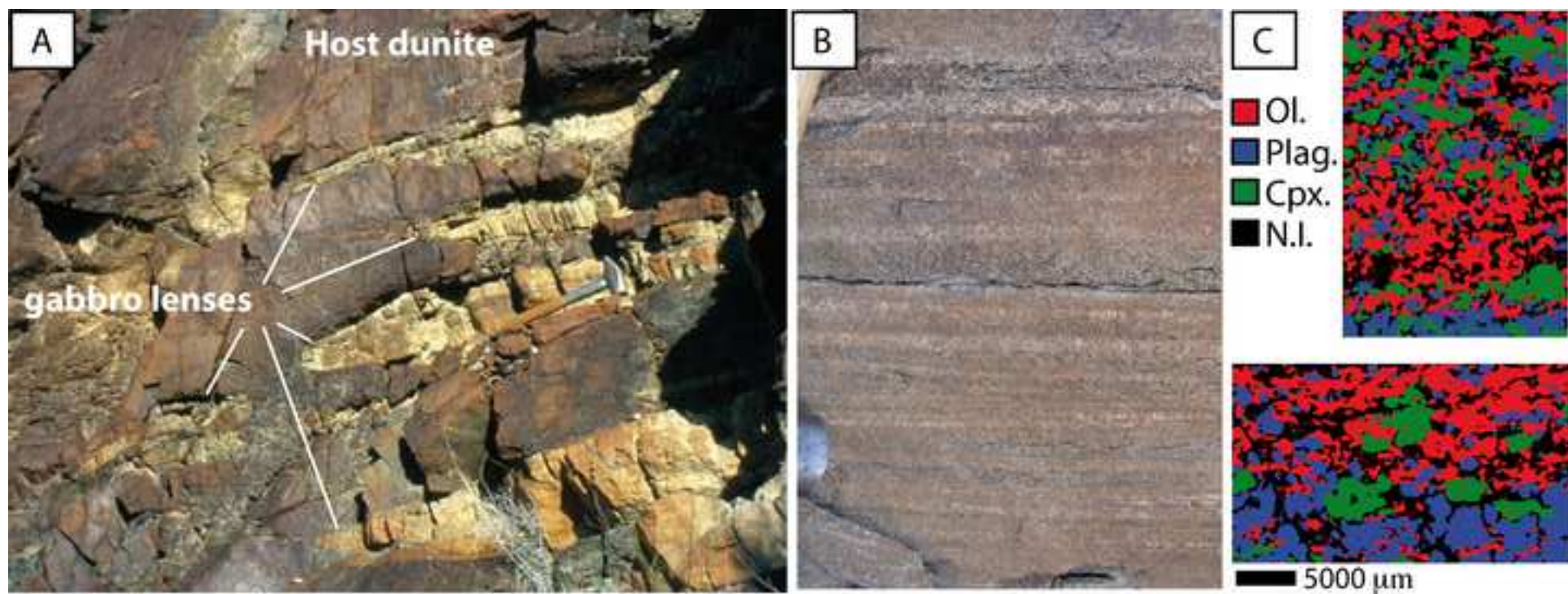


Figure 2 (can be printed in B&W)



Figure 3 (can be printed in B&W)

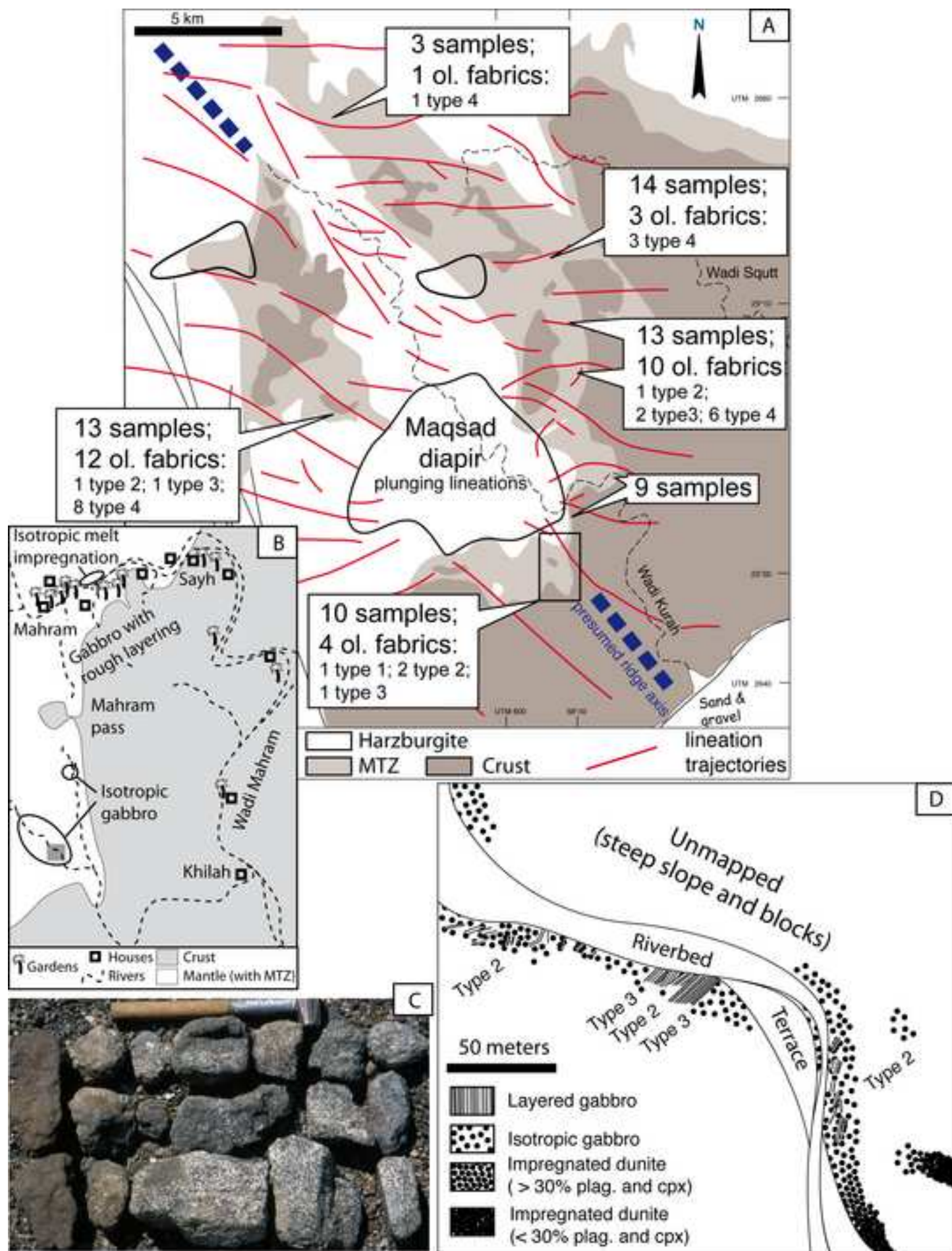


Figure 4 (can be printed in B&W)

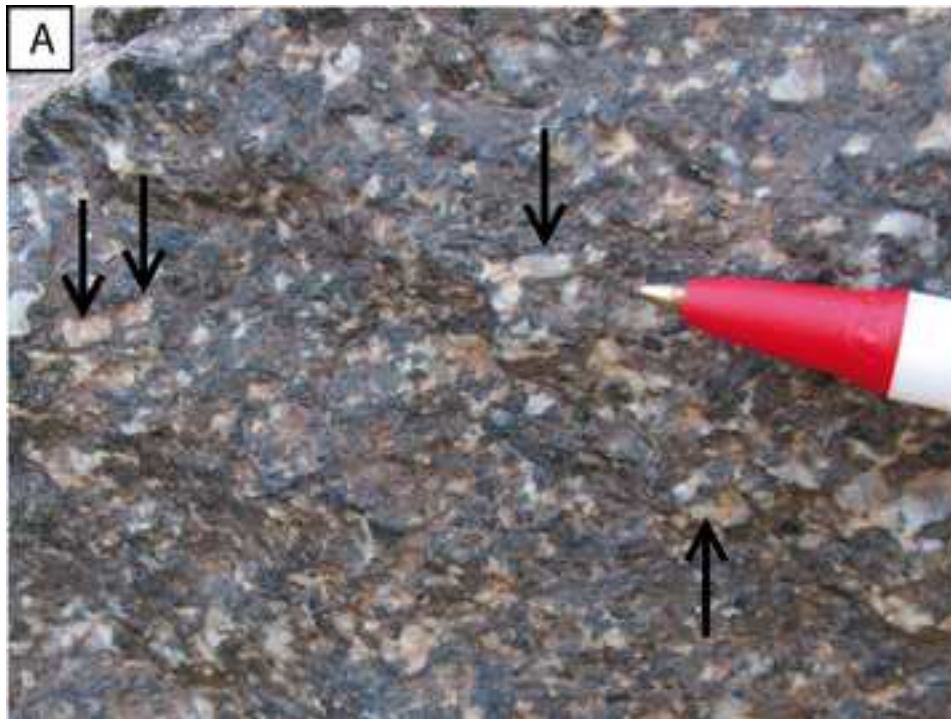


Figure 5 (can be printed in B&W)



Figure 6 (can be printed in B&W)

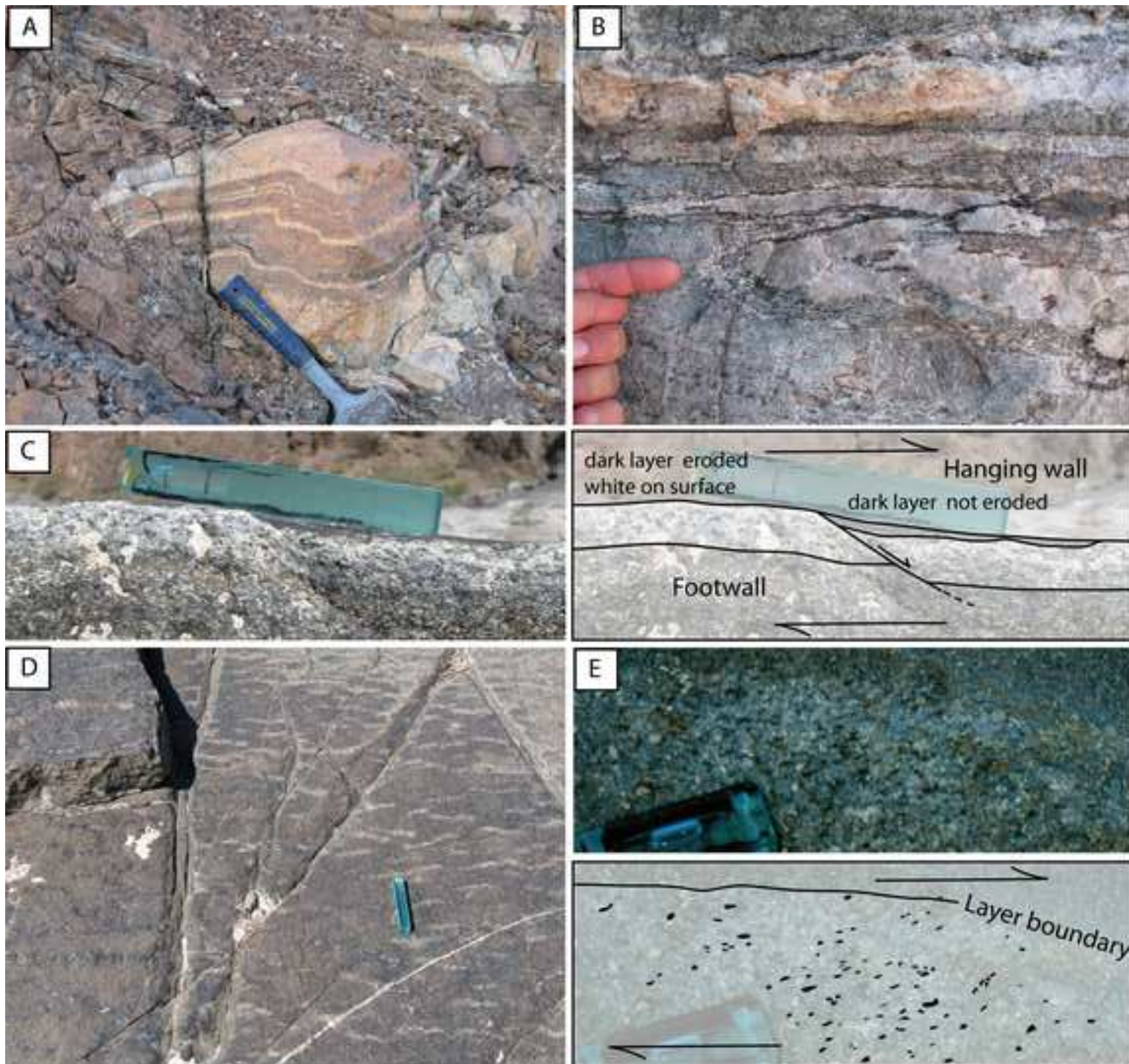


Figure 7 (can be printed in B&W)

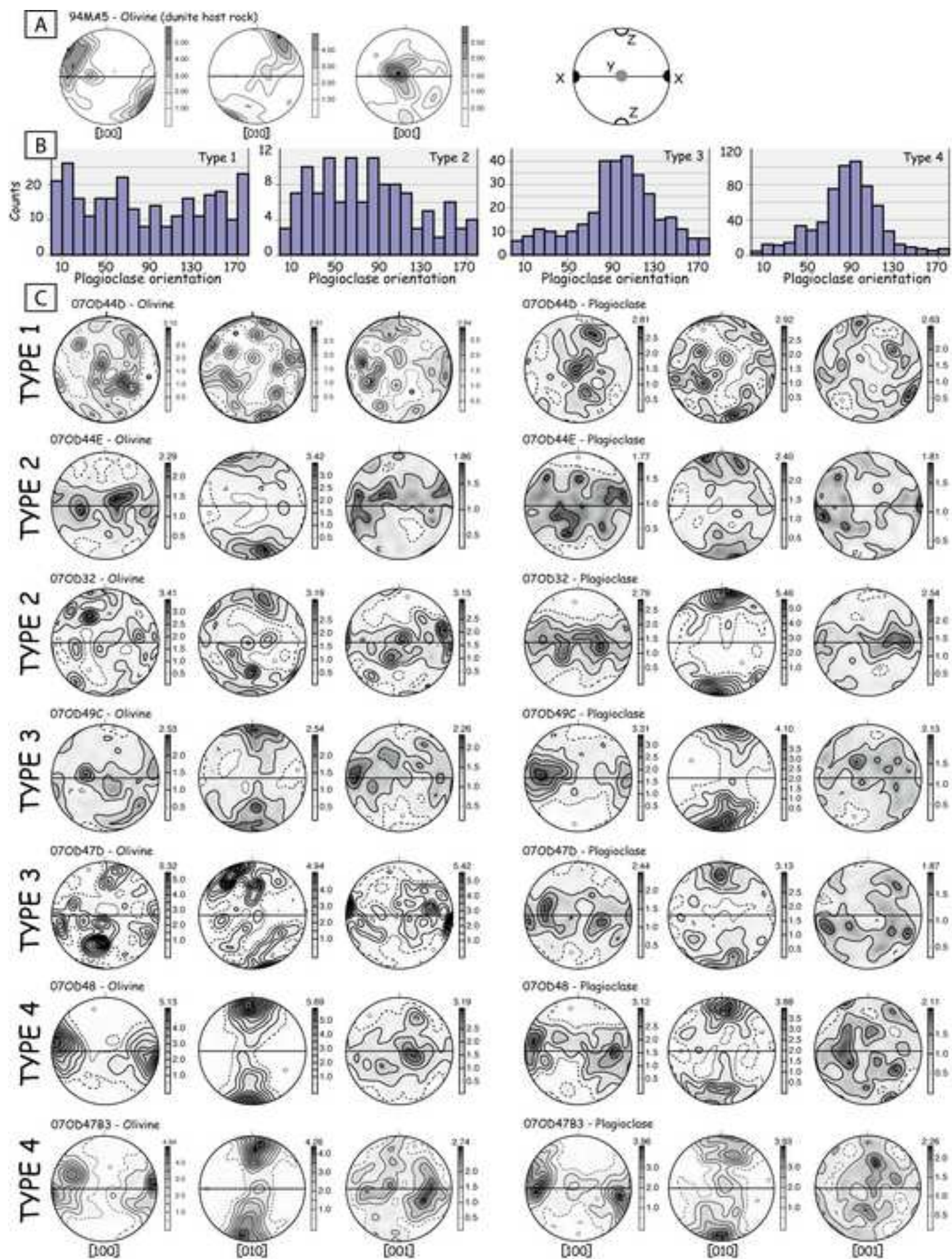
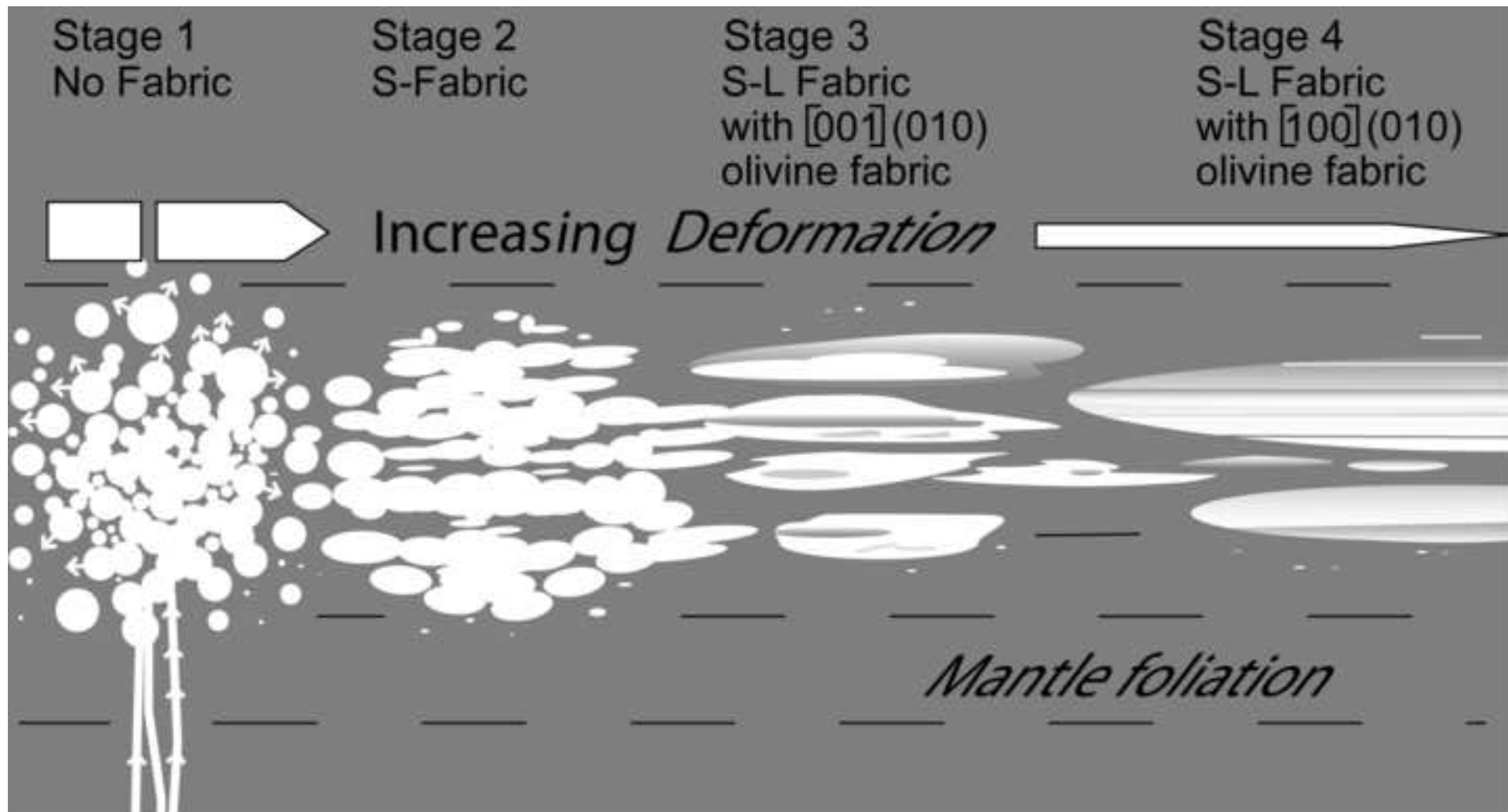


Figure 8 (can be printed in B&W)



Table

Sample/ layers	Type	Modal composition Global/layer ol-plag-cpx	
07OD44D unlayered	1	15-75-10	
07OD49E unlayered	1	22-78-0	
07OD44B 1 layer	2	15-76-9	
07OD44E 1 layer	2	14-89-1	
07OD21B 1 layer	2	19-77-4	
07OD32 2 layers	2	40-60-0	34-66-0 56-43-0
07OD47D2 1 layer	3	26-74-0	
07OD49C 3 layers	3	36-49-15	44-56-0 22-17-61 13-86-1
10OM26-2 3 layers	3	7-91-2	7-91-1 2-96-2 14-82-4
10OM43A 1 layer	3	11-88-1	
07OD48 3 layers	4	46-28-26	3-76-21 68-11-21 37-26-37
07OD47B1 2 layers	4	9-61-30	8-53-39 11-89-0
07OD47B3 2 layers	4	43-40-15	69-19-12 15-65-20
07OD47A 2 layers	4	40-58-2	12-87-1 95-3-2
10OM43L 3 layers	4	23-77-0	27-71-1 7-93-0 37-63-0
10OM26-4 3 layers	4	10-83-7	14-76-10 1-96-3 12-82-6

