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1 **EARLY SUBDUCTION DYNAMICS RECORDED BY THE**  
2**METAMORPHIC SOLE OF THE MT ALBERT OPHIOLITIC**  
3 **COMPLEX (GASPÉ, QUEBEC)**

4

5 *Benoît Dubacq<sup>1,\*</sup>, Mathieu Soret<sup>1,2</sup>, Ella Jewison<sup>1</sup>, Philippe Agard<sup>1</sup>*

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71 Sorbonne Université, CNRS-INSU, Institut des Sciences de la Terre de Paris, IStEP UMR 7193, F-  
875005 Paris, France

9

102 University of British Columbia, Okanagan, Earth, Environmental and Geographic Sciences  
11Kelowna, BC, Canada

12

13\* corresponding author: [Benoit.Dubacq@sorbonne-universite.fr](mailto:Benoit.Dubacq@sorbonne-universite.fr)

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16petrology

17

## 181. INTRODUCTION

19Understanding the mechanisms of emplacement of ophiolites has been the subject of decades of  
20studies focused on the sole of these ophiolites (Williams and Smith, 1973; Searle and Malpas, 1982;  
21Spray et al., 1984; Jamieson, 1986; Hacker, 1991; Mahmood et al., 1995; Gnos, 1998; Dimo-Lahitte et  
22al., 2001; Ishikawa et al., 2005; Cowan et al., 2014; Rioux et al., 2016; amongst many others).  
23Ophiolite soles are generally thin (<500 m) portions of heavily deformed peridotite and  
24metamorphosed oceanic crust, found at the base of most large-scale ophiolites. Their present-day  
25structure results from the stacking of three main units: one of mantle origin and two of crustal origin.  
26Figure 1 presents a conceptualised frame for the formation of ophiolite soles during subduction  
27in infancy. The top of the sole, found beneath porphyroclastic peridotite, is typified by tectonized  
28harzburgite with a mylonitic to ultramylonitic overprint, common occurrence of secondary  
29clinopyroxene, amphibole and late serpentine. The median and lower units of the sole are  
30metamorphic rocks of mainly mafic nature, with metamorphic grade decreasing downwards. These  
31two units are commonly referred to as ‘metamorphic sole’, and originate from oceanic crust. They are  
32interpreted as sea-floor mafics and sediments re-crystallising at depth, immediately below the nascent  
33mantle wedge, within the first few million years of the life of the subduction/obduction system (e.g.,  
34Dewey, 1976; Wakabayashi and Dilek, 2000, 2003): the top of the subducted oceanic plate is  
35metamorphosed up to granulite facies against the still hot overlying peridotite, and accreted to the base  
36of the future ophiolite when the rheological contrast between the two is minimum (Agard et al., 2016  
37and Fig. 1 a-b). This allows exhumation of the sole together with the ophiolitic body, as subduction  
38proceeds until obduction (Fig. 1c). The consistency of ductile strain in the high-grade metamorphic  
39rocks of the sole and in the deformed peridotite (top of the sole) has led numerous authors to suggest  
40these units share common history (e.g. Searle & Malpas, 1980; Boudier et al., 1982; Spray, 1984;  
41Jamieson, 1986; Prigent et al., 2018), including exhumation. In this model, burial of the oceanic crust  
42and exhumation of the sole are fast, which is supported by dating (e.g., Hacker and Mosenfelder,  
431996; Hacker et al., 1996). Later blueschist facies metamorphism is observed in margin units  
44originating further away from the trench (as for the Saih Hatat region in Oman, e.g. Agard et al., 2010)

45and less frequently in the metamorphic sole itself (Wakabayashi, 1990; Plunder et al., 2016), an  
46evidence of cooling of the geothermal gradient over time. In this general scheme, the metamorphic  
47rocks originating from subducted oceanic crust contain essential information about ophiolite  
48emplacement and geological processes occurring at the plate interface in nascent subduction zones. In  
49the overlying peridotite, information is lacking or much less precise in terms of evaluating strain  
50mechanisms, estimating geothermal gradients (through thermobarometry) and dating (with e.g. U-Pb  
51radiochronology on granitoid rocks from slab melting,  $^{40}\text{Ar}/^{39}\text{Ar}$  on amphibole). Chemical exchange  
52from crust-derived metamorphic rocks to peridotites at the base of ophiolitic massifs has also been  
53documented as a proxy to mantle wedge metasomatism and linked to dehydration reactions in  
54metamorphic soles together with deformation and refertilisation of the peridotite (e.g. Ishikawa et al.,  
552005; Linckens et al., 2011; Soret et al., 2016; Prigent et al., 2018).

56Continued petrological and structural work, largely based on the Cenomanian Semail ophiolite (in  
57Oman and United Arab Emirates) but also carried out on much older ophiolites such as found in the  
58Ordovician Bay of Islands complex (see compilation in Agard et al., 2016), has revealed impressive  
59consistency in the peak metamorphic conditions of metamorphic soles, with an apparent inverted  
60metamorphic gradient. The high-temperature unit at the top of the metamorphic sole is  
61metamorphosed and accreted first, around 1 GPa and 850°C, then the lower unit is accreted around 0.5  
62GPa and 550°C. Soret et al. (2017) have shown that this process has been acting repetitively for step-  
63wise accretion of subunits within the high-temperature unit of the Semail ophiolite. Interestingly, and  
64in line with the consistency of pressure-temperature estimates between and within metamorphic soles,  
65no evidence has been found for a link with the paleo-location of the ridge crest of the structurally  
66overlying ophiolitic units: in Oman, metamorphic sole is found on both sides of the paleo-ridge, with  
67identical conditions of crystallisation.

68Despite progress on thermodynamic models for amphibole and mafic systems (see Green et al., 2016;  
69Palin et al., 2016), large uncertainties remain on the depth of accretion and on pressure-temperature-  
70time paths of metamorphic soles due to their chiefly mafic nature (making thermobarometry imprecise  
71compared to metapelites). In the present context of subduction initiation, a counter-clockwise  
72pressure-temperature path is expected following general cooling of the geothermal gradient through

73time, as presented by Hacker and Gnos (1997) or Searle and Cox (1999) for the Semail ophiolite.  
74However thermo-mechanical modelling of obduction of this ophiolite (Duretz et al., 2016) yielded  
75clockwise pressure-temperature paths for units equivalent to metamorphic soles, with a clockwise  
76component increasing away from the plate interface. Yet no clockwise or counter-clockwise  
77component was evidenced by Soret et al. (2017) due to limited preservation of the prograde history.  
78In this publication, a petrological study of selected sections through the sole of the Mont Albert  
79ophiolitic complex (Quebec, Canada) is reported. Although exposure quality is poor due to forest  
80cover, the crustal section of the sole appears generally fresh with limited greenschist-facies  
81retrogression. The petrology of the sole is similar to that of the Semail ophiolite, with the advantage  
82that thin layers of aluminosilicate-bearing metapelites are found scattered within subunits of the Mont  
83Albert sole, partly preserving prograde mineral assemblages. The diversity of mineral assemblages in  
84metapelites allows deriving robust estimates of the peak metamorphic conditions, consistently with  
85thermodynamic modelling of the metamorphism of the mafic rocks. As for the Semail ophiolite, units  
86and subunits in the metamorphic sole of the Mont Albert ophiolitic complex appear accreted in a step-  
87wise manner. Estimated pressure-temperature paths are clockwise, with exhumation above the plate  
88interface along a warmer thermal gradient than burial. This has implications for the evolution of the  
89thermal gradient around the plate interface. Clockwise pressure-temperature paths are reconciled with  
90the progressive cooling of the plate interface by rapid accretion and exhumation of metamorphic soles,  
91within the first few million years of subduction initiation.

## 92. **GEOLOGICAL SETTING**

### 93 **2.1. Structural organization and radiometric constraints**

94The Mont Albert ophiolitic complex (Fig. 2) is located 35 km south-east of the shore of the Saint  
95Lawrence river and the city of Sainte-Anne-des-Monts, in the Gaspé Peninsula of the Quebec province  
96of Canada. The Mont Albert ophiolitic complex is an incomplete Ordovician ophiolitic sequence  
97(Beaudin, 1983; Gueddari et al., 1999) with peridotite overlying a metamorphic sole mainly composed  
98of amphibolite (*'amphibolite du diable'*) showing an apparent inverted metamorphic gradient. A few  
99kilometres to the south-west, Mont Paul and Mont du Sud are part of the same ophiolitic system and  
100are included in the Mont Albert ophiolitic complex. There is no remnant of crustal rocks above the

101peridotite, therefore the age of the ophiolitic complex has been constrained in earlier studies with  
102radiometric dating carried out on the metamorphic sole and with structural and stratigraphic  
103correlation.

104The Mont Albert peridotite and its basal amphibolite are classified in the Dunnage zone and correlated  
105to a series of Quebec ophiolites (including from south to north: the Mount Orford, Lac Brompton,  
106Asbestos, Thetford Mines ophiolites) via a Taconian suture zone between Laurentia and Lower  
107Palaeozoic peri-Laurentian terranes (see Pinet and Tremblay, 1995; Malo et al., 2001, 2008; De Souza  
108et al., 2012; Tremblay and Pinet, 2016). This suture zone extends along the Appalachians to western  
109Newfoundland, where the Bay of Islands Complex, a klippe of the Dunnage zone, is the most  
110complete ophiolite of the orogeny (Cawood and Suhr, 1992). The Dunnage zone represents the  
111Ordovician oceanic basin related to the Iapetus ocean and located outboard of the continental passive  
112margin of Laurentia defining the Humber zone (Williams, 1979; De Souza et al., 2014). The Mont  
113Albert ophiolite and its sole overlay unconformably the Schick-Schock volcanic flows and  
114pyroclastics metamorphosed to lower greenschist facies that appear in the internal Humber zone in  
115recent publications (reviewed in Tremblay and Pinet, 2016), although Lux (1986) suggested they are  
116part of the Dunnage zone. These volcanics are subalkaline tholeiitic basalts of N-MORB-type, with  
117geochemical evidence in favour of their eruption in the Humber Zone during the rifting event which  
118led to the opening of the Iapetus ocean (Camiré et al., 1995). The Mont Albert ophiolitic complex is  
119separated from the upper Ordovician to Devonian sediments and volcanics of the Gaspé Belt to the  
120south by a fault zone (Schick-Schock South Fault, Fig. 2) part of the Baie Verte-Brompton Line.

121Radiometric dating using  $^{40}\text{Ar}/^{39}\text{Ar}$  by Malo et al. (2008) on amphibole yielded cooling ages in the  
122range 457-461 Ma for the highest-grade metamorphic rocks of the sole, crystallisation ages in the  
123ranges 454-458 Ma for the lower grade metamorphics of the sole and 455-456 Ma for the greenschist  
124facies overprint of the Schick-Schock Group, in agreement with earlier ages (Lux, 1986; Pincivy et al.,  
1252003). These ages are in the same range as the 456 (+/-5) Ma U/Pb age obtained among older ages by  
126Trzcieski et al. (1995, unreviewed) on zircon from an “unusual magnetite-rich orthopyroxenite layer”  
127in the peridotite, as reported by Pincivy et al. (2003) and Tremblay and Pinet (2016).

## 128 2.2. Nature of the ophiolitic complex

129The Mont Albert ophiolitic complex has first been mapped in detail by Alcock (1927) who interpreted  
130it as a lenticular magmatic injection, where the surrounding amphibolite was thought representative of  
131early magmatic phases, followed by the principal ultramafic body. MacGregor and Basu (1979)  
132present a detailed petrographic review of the Mont Albert massif based on extensive sampling and  
133electron microprobe analyses carried out in the mid to late 1960s. These authors regard the massif as  
134an ultramafic intrusion into the Schick-Schock group, the amphibolite being interpreted as a contact  
135metamorphism aureole into which they identified kyanite-bearing gneisses and possible partial melting  
136(see also MacGregor, 1964).

137The ophiolitic nature *sensu stricto* of the Mont Albert massif has been popularised by the study of  
138Beaudin (1983). Trzcinski (1988) later suggested that its metamorphic sole was a retrogressed  
139eclogite, using the co-existence of garnet and clinopyroxene in the high-temperature unit for the  
140terminology but suggesting peak metamorphism around 840°C and at least 1.2 GPa to account for the  
141presence of kyanite in metasediments – which corresponds to the upper garnet granulite field as  
142defined by Spear (1993). In this view, the whole metamorphic sole and peridotite massif were  
143subducted and later exhumed along the surrounding faults in the stability field of kyanite (buried along  
144a thermal gradient around 16°C/km). Rejecting the eclogitic nature of the sole in line with other  
145authors (e.g. O'Beirne-Ryan et al., 1990), Whitehead et al. (1995) interpreted the *amphibolite du*  
146*diable* as a dynamothermal sole formed ‘in a shear zone within an oceanic domain by the progressive  
147underplating of overridden crustal rocks to the base of an overriding oceanic fragment’, where shear  
148heating implicitly plays a prominent role as heat source. This definition is not necessarily inconsistent  
149with current models (e.g. Agard et al., 2016; Rioux et al., 2016) but overlooks the apparent pressure  
150gradient and the depth of the process as implied by kyanite, which eases explaining dating  
151inconsistencies between initiation of basin closure based on fossil evidence and  $^{40}\text{Ar}/^{39}\text{Ar}$  cooling ages  
152on the amphibolite appearing 20 Ma older (Whitehead et al., 1995).

153There is now little doubt on the ophiolitic nature of the Mont Albert (and associated Mont Paul and  
154Mont Du Sud), mostly thanks to large-scale studies of ophiolites obducted during the Taconian

155orogeny showing clear consistency both in terms of petrography and ages along the north-eastern  
156Appalachians (e.g. Whitehead et al., 1995; Pincivy et al., 2003; Malo et al., 2008; De Souza et al.,  
1572012; Tremblay and Pinet, 2016). Tremblay and Pinet (2016, and references therein) advocate genesis  
158of these ophiolites within a supra-subduction zone environment – with already-established plate  
159convergence – based on extensive evidence of subduction of the Laurentian margin prior and during  
160ophiolite formation. Similarly, the metamorphic sole is now interpreted as formed in a process  
161equivalent to that of the Semail ophiolite and other soles worldwide, as discussed at length by Agard et  
162al. (2016).

### 1633. NATURE, STRUCTURE AND DEFORMATION OF THE SOLE

164The Mont Albert, Mont Paul and Mont du Sud are characterised by alpine tundra and rare krummholz  
165on the peridotite (studied by e.g. Sirois and Grandtner, 1992; Martin and Germain, 2016) contrasting  
166with the generally dense forest cover found over most of the *amphibolite du diable*. Exposure of the  
167metamorphic sole is further restrained by the presence of numerous boulders of both local and remote  
168origin related to the last glacial maximum (see Olejczyk and Gray, 2007). Consequently, exposed  
169sections through the metamorphic sole are not continuous over scales of hundreds of metres as in  
170Oman, complicating the study of mineralogical changes with distance to the contact of the peridotite,  
171as folding and possible late faulting cannot be rigorously evaluated. The Mont Albert ophiolitic  
172complex has nevertheless been mapped in detail and shows a simple structure, with the peridotite  
173monotonously overlying the metamorphic sole, and mappable metamorphic grades within the sole  
174(Fig. 2b-c).

175The overall structure of the Mont Albert is a large syncline with fold axis around 240° (e.g.  
176MacGregor and Basu, 1979; Gagnon and Jamieson, 1986). Exposure of the sole is best on the northern  
177part of the massif, where foliation is parallel to the contact and dips steeply to the south in the range  
17850-70°. In order to show a representative section through the metamorphic sole of the Mont Albert  
179ophiolitic complex, a schematic log based on several small-scale sections is provided in figure 3a with  
180field photographs (Fig. 3b-l). Late small-scale normal faulting on the north-east ridge of the massif,  
181related to the ‘*Marches du Géant*’ fault system (Malo et al., 2008), only allows for approximate  
182evaluation of the structural distance of metamorphic sole outcrops to the contact with the peridotite.



183The following general description starts from the structural summit of the ophiolitic complex, going  
184downwards, with distances expressed as the apparent structural distance to the contact.

### 185 **3.1. Structure and mineralogy of the peridotite**

186The peridotite is typified by harzburgite with earth yellow to brass colour due to weathering (Fig. 3b-  
187c-d-e). 49 samples have been collected and studied for their mineralogy, which will be detailed  
188elsewhere.

189Serpentinisation is pervasive, altering the rock density on various degrees. The base of the peridotite is  
190mapped as a ~20 m-thick serpentinite layer (Fig. 3 d) where serpentinisation is generally intense and  
191accompanied by minor chalcedony. This serpentinite layer is not regarded as representative of the  
192entire part of the sole with peridotite origin (part of red rectangle in the mantle wedge in Fig. 1c) first  
193because contacts between this layer and the less serpentinised peridotite are only clear on the north-  
194eastern part of the massif, then due to the fact that porphyroclastic peridotite is dominant hundreds of  
195metres away from the contact, as observed by MacGregor (1979, using whole texture and chromian  
196spinel as a strain indicator insensitive to serpentinisation). Therefore the extent of the deformed  
197peridotite section of the sole into the mantle sequence is unclear. Away from this serpentinite layer,  
198serpentinisation remains important irrespective of the distance from the contact with the amphibolite  
199metamorphic sole. Grain size varies wildly from cm-scale orthopyroxene forming positive relief  
200alteration to micrometric crystals in peridotite with ultramylonitic texture (see also Laurent and  
201Hebert, 1979; MacGregor, 1979). Dunite and minor amphibole-bearing lherzolite and websterite are  
202found inter-layered with the harzburgite. In thin section, amphibole (consisting of pargasite, Mg-  
203hornblende and tremolite) appears of metamorphic origin linked to deformation stages in mylonites,  
204together with secondary olivine, aluminous spinel and clinopyroxene. Metre-thick chromitite lenses  
205with aspect ratio around 10 are sporadically found along the axial plane of the syncline with associated  
206kammererite (mauvish pink Cr-Mg-chlorite, as reported by MacGregor and Basu, 1979). Penninite  
207(Mg-chlorite with Si content greater than that of clinochlore) is frequently found all over the massif in  
208haloes around chromian spinel. The main foliation in the peridotite is highlighted by serpentine-rich  
209planes and clearly parallel to the contact with the metamorphic sole when observed on the northern

210part of the massif (Fig. 3e, also Gagnon and Jamieson, 1986). Outcrops on the south-west part of the  
211massif (near lake Isabelle) are obscured by intense serpentinisation and provide only poor exposure of  
212the base of the peridotite.

### 213 3.2. Metamorphic rocks from the sole

214The high-grade unit of the *amphibolite du diable* is found underlying the peridotite (Fig. 3b-e-f-g). It is  
215a heterogeneous but generally massive, dark, mafic metamorphic rock with well-defined foliation but  
216without clear evidence for simple shear deformation. Lineation was only found for late amphibole.  
217The maximum thickness of this unit is estimated in the range 80-100 m. Metamorphic grade decreases  
218away from the contact. The term amphibolite to describe rocks immediately below the contact is  
219somewhat abusive as amphibole content may be as low as 30%, with more abundant garnet-  
220clinopyroxene assemblage in varying relative amounts and minor plagioclase (1-5%). Orthopyroxene  
221was not observed. Grains are generally millimetre-sized (1-5 mm) with garnet occasionally reaching 1  
222cm. Away from the contact, the amphibole and plagioclase content increases (apparently gradually) at  
223the expense of garnet and clinopyroxene, which disappear from mafic rocks about 15 m (for garnet)  
224and 25 m (for clinopyroxene) away from the contact. Garnet amphibolite is also found ~250 m from  
225the contact on the north-eastern flank of Mont Olivine, in rocks that are apparently large (>10 m)  
226boulders with no connection to the bedrock. Grain size decreases away from the contact to  
227approximate 0.5 mm in the garnet-absent amphibolite. Epidote is ubiquitous as a retrogression phase,  
228rimming clinopyroxene and amphibole, and as individual crystals, in varying amounts (<1 to 10%).  
229Garnet-rich layers (Fig. 3g) and iron oxide-rich layers are found alternating with the garnet-  
230clinopyroxene mafic rocks close to the contact. The iron oxide-rich layers contain abundant chlorite,  
231mica and epidote. Corundum is observed in some of these layers <10 m away from the contact.

232About 35 m away from the contact, an intriguing pinkish 1.5 m-thick quartz-plagioclase-amphibole-  
233biotite-sphene-garnet layer with retrogressed pegmatitic texture is found cutting the foliation at a low  
234angle (Fig. 3h). Of seemingly magmatic origin, it probably corresponds to the outcrop described and  
235interpreted by Gagnon and Jamieson (1986) as a dyke injected after the metamorphic sole developed  
236its foliation. Due to its orientation with respect to the foliation, we prefer referring to this as a sill. It is

237heavily retrogressed with epidote on its margins co-existing with white and dark mica, and fibro-radial  
238gedrite.

239Rare biotite-rich layers are found within 20 m from the contact. The first clear occurrences of  
240aluminous metapelites appear about 25 m away from the contact as alternating dark red and pale grey  
241layers ranging between 2 and 20 cm in thickness within the mafic rocks (metapelites are more easily  
242identified in fallen boulders on the flanks of the north-east arête of the Mont Albert and on the north  
243path to the summit just before the final ascent). These metapelites contain biotite (in greater  
244proportions in the dark red layers), quartz, plagioclase, garnet, sillimanite, staurolite and muscovite as  
245described below in greater detail, with scapolite, Fe-Ti oxides, epidote and chlorite in varying but  
246generally minor proportions. Further away from the contact (45-55 m, Fig. 3i), pelitic schists contain  
247kyanite with abundant mm-sized garnet, biotite, quartz, plagioclase, epidote and late muscovite.

248The low-grade unit of the metamorphic sole (Fig. 3j-l) is typified by metabasalt with “inverted”  
249metamorphic grade within the upper greenschist to amphibolite facies. A section with good exposure  
250is found on the shore of the Cascapedia river towards Mont du Sud; other interesting outcrops include  
251the shore of the lake on top of ‘*ruisseau du Plaque Malade*’, the base of the north-east arête of Mont  
252Albert (corresponding to the fourth zone described by Gagnon and Jamieson, 1986) and the path south  
253of *Lac du Diable* (where O'Beirne-Ryan et al., 1990, reported sporadic migmatites, which were not  
254confidently identified in this study). The difference between the base of the high-grade unit and the top  
255of the low-grade unit is not clear-cut in terms of metamorphic grade. However these units differ in  
256terms of strain and retrogression. The lower unit is variably spilitized (see e.g. Skelton et al., 2010 for  
257comparison) and shows shearing and boudinage of former pillow-lavas (Fig 3j-k) together with  
258ubiquitous recumbent folding highlighted by feldspar-rich layers (felsic amphibolite of Gagnon and  
259Jamieson, 1986). In addition to green amphibole, albite, epidote and chlorite are present. The top of  
260the unit is rich in iron oxide, the base contains pyrite up to ~2 mm-large.

261Metasediments in the low-grade unit appear mainly as quartzite, in proportion of 5-10 % of the sole  
262thickness. White mica, chlorite and rare garnet have been found disseminated in the quartzite and in  
263cm-thick beds.

264

265

| Rock type                    | Main unit  | Main minerals (>5%)    | Minor minerals (≤5%) | Accidental minerals (<1%) |
|------------------------------|------------|------------------------|----------------------|---------------------------|
| amphibolite                  | high grade | Amp, Pl, Cpx           | Grt, Opq, Ep, Rt     | Ser, alt. φ               |
| metasomatic rocks            | high grade | Ep, Chl, Opq           | Crn, Mrg, Pg, Rt     | Qz, Ms, Spn               |
| amphibolite                  | low grade  | Amp, Qz, Ep, Chl       | Cal, Fsp             | Opq, Ccp                  |
| quartzite                    | low grade  | Qz, Pl, Bt, Ep         | Chl                  |                           |
| amphibolite                  | low grade  | Amp, Qz, Ep, Pl        | Opq                  |                           |
| amphibolite                  | low grade  | Amp, Ep, Pl, Opq       | Qz                   | Cc, Spn                   |
| amphibolite                  | low grade  | Amp, Pl, Ep, Chl       | Qz, Opq              | Cc                        |
| amphibolite                  | low grade  | Amp, Ep, Opq           | Qz                   | Cc, Spn                   |
| schistose layer in quartzite | low grade  | Amp, Qz, Pl, Ep, Chl   | Opq                  | Spn                       |
| schistose layer in quartzite | low grade  | Phg, Qz, Opq, Chl, Amp | Grt, Ep              | Cc                        |
| amphibolite                  | low grade  | Amp, Ep, Pl, Qz        | Opq                  |                           |
| amphibolite                  | low grade  | Amp, Ep, Qz            | Pl, Cc, Opq          |                           |
| amphibolite                  | high grade | Amp, Cpx, Ep, Opq      | Pl                   | Fsp                       |
| amphibolite                  | high grade | Grt, Amp, Cpx, Ep      | Pl, alt. φ           | Ccp, Cv                   |
| amphibolite                  | high grade | Amp, Cpx, Ep, Opq      | alt. φ               |                           |
| amphibolite                  | high grade | Cpx, Grt, Amp, Ep      | Pl, alt. φ           | Qz                        |

|                               |              |                           |                  |              |
|-------------------------------|--------------|---------------------------|------------------|--------------|
| amphibolite with garnet layer | high grade   | Grt, Amp, Cpx, Ep         |                  |              |
| amphibolite                   | high grade   | Amp, Cpx, Pl, Ep          | alt. $\phi$      | Mrg          |
| amphibolite                   | intermediate | Amp, Cpx, Pl, Ep, Mrg     | Ser, alt. $\phi$ | Ccp, Cv      |
| Sill / metasediment contact   | high grade   | Fsp, Qz, Chl, Amp         | Ms, Bt, Grt, Opq | Ep, Aln, Spn |
| metapelite                    | high grade   | Ab, Qz, Chl, Ep, Grt, Opq | Ms, Ap, Bt       | Mnz          |
| metapelite                    | high grade   | Qz, Grt, Phg, Bt          | St, Opq, Ky, Pl  | Rt, Chl      |
| metapelite                    | high grade   | Qz, Ms, Bt, Grt, Pl, Ky   | Opq, Ep          | Chl          |
| sill                          | high grade   | Ab, Amp, Spn, Opq         | Ep, Ms           | Mnz          |
| metapelite                    | high grade   | Bt, Qz, Ep, Grt           | Pl, Opq          | Chl, Zrn     |
| metapelite                    | high grade   | Qz, Pl, Grt, Phg          | Bt, Spn, Ep      | Rt, Chl      |
| metapelite                    | high grade   | Phg, Grt, Qz, Pl          | Bt, Spn, Ky      | Amp, Chl, Ap |
| metapelite                    | high grade   | Grt, Bt, Pl, Sil, Opq     | St, Phg, Scp     |              |

266Table 1. Mineralogy of samples used in this article. Main minerals are sorted from more to less abundant. Alt.  $\phi$ : minute alteration phases replacing plagioclase (Ms, Mrg, Ntr, Ep etc., see Fig. 4).

## 2694. **PETROGRAPHY AND MINERALOGY**

270In this section, the textural relationships between minerals are presented with microphotographs and  
271SEM images, separating metabasalts from rocks with sedimentary protoliths. The ‘sill’ (Fig. 3h) and  
272oxide-rich layers are presented with the non-mafic metamorphic rocks. The mineralogy is summarized  
273in table 1. All abbreviations in figures, tables and appendix are after Whitney and Evans (2010).

### 274 **4.1. Sampling and analytical techniques**

275104 samples have been collected on the Mont Albert and Mont du Sud massifs. Only samples from the  
276metamorphic sole are presented here (using 29 samples selected out of the 55 metamorphic rocks  
277collected). Scanning electron microscopy (SEM) was used after optical microscopy at ITeP  
278(Sorbonne Université, Paris, France) using a Zeiss Supra 55VP apparatus associated to a SSD detector  
279PTG Sahara for imaging and elemental mapping in energy-dispersive spectroscopy mode.

280Electron probe micro-analyses were carried out at CAMPARIS (Sorbonne Université, Paris, France)  
281with both Cameca SX-5 and SX-100 instruments. Point measurements were made in classical  
282analytical conditions (15 kV acceleration voltage and 10 nA beam current allowing  $\sim 2\mu\text{m}$  beam size in  
283wavelength-dispersive spectroscopy mode) using diopside (Ca, Mg, Si),  $\text{MnTiO}_3$  (Mn, Ti), orthoclase  
284(K, Al),  $\text{Fe}_2\text{O}_3$  (Fe), albite (Na) and  $\text{Cr}_2\text{O}_3$  (Cr) as standards for calibration of elements indicated in  
285parentheses. Elemental mapping has been carried out with identical voltage and either 10 nA current  
286and counting time of 300 ms per point or with increased current (100 nA) and counting time of 100 ms  
287per point. Analyses were calibrated with the manufacturer’s software using standards as for point  
288analyses, and it was ensured that results of mapping were consistent with point measurements.

### 289 **4.2. Mafic rocks**

#### 290 *4.2.1. High grade unit*

291At the thin-section scale, rocks sampled at the contact with the peridotite show porphyroblastic texture  
292(Fig. 4a) with garnet, pale green clinopyroxene, deep green amphibole crystals aligned within the  
293foliation, plagioclase and epidote. Garnet is typically millimetre-sized and disseminated throughout  
294samples (Fig. 4b) or in garnet-rich layers (Fig. 3g). Quartz inclusions are rarely ( $\sim 5\%$ ) found in garnet  
295porphyroblasts. Clinopyroxene appears as large ( $>5\text{ mm}$ ) crystals with undulose extinction, and in

296small (100-500  $\mu\text{m}$ ) optically homogeneous crystals. Clinopyroxene is found disseminated in the rock  
297and in cm-thick bands (Fig. 4b) parallel to the amphibole foliation and showing both types of crystals.  
298Several types of symplectite are found throughout the samples, involving garnet, clinopyroxene,  
299amphibole, plagioclase, oxides and epidote, with all six phases or a combination of some of them.  
300Clinopyroxene-amphibole symplectite with and without plagioclase (Fig. 4f) is observed wherever  
301clinopyroxene is stable. Epidote-amphibole symplectite is seen in some rocks less than 10 m away  
302from the contact. Garnet-clinopyroxene symplectite with plagioclase or with epidote and oxides (Fig.  
3034f and g), both usually with retrogressive mica, are found in garnet-bearing samples regardless of the  
304distance to the contact. Plagioclase in the symplectite is rarely preserved. It is usually replaced by fine  
305intergrowths of epidote and muscovite (Fig. 4 h-i). Under the optical microscope, these intergrowths  
306appear as a dark, turbid phase (Fig. 4d-e-g) with second order birefringence tentatively identified as  
307diaspore by O'Beirne-Ryan et al. (1990). In this study diaspore has not been found in these  
308intergrowths, instead margarite, albite, adularia and natrolite appear as frequent alteration products of  
309the (previously-retrogressed?) plagioclase (Fig. 4 h-i). Chalcopyrite is found sporadically throughout  
310retrogression assemblages, accidentally with covellite. Translucent epidote crystals are frequently  
311associated with retrogressed plagioclase, and late yellow epidote cross-cuts most samples, chiefly  
312along the foliation and less frequently at a sharp angle with it. This leads to compositional banding on  
313the scale of centimetres in some samples, as noted by O'Beirne-Ryan et al. (1990). In the  
314clinopyroxene-free zone, pale yellow epidote is aligned with the amphibole (Fig. 4h) and makes up to  
31540% of the sample. Large amphibole crystals are often zoned, with pale green cores and darker rims  
316(Fig. 4a).

#### 317       4.2.2. *Low grade unit*

318Strain is marked by folding in the low-grade part of the metamorphic sole. The top of this unit is  
319characterized by elongated,  $\sim 100 \mu\text{m}$ -long amphibole showing a well-marked foliation, sometimes  
320with crenulation (Fig. 5b). However crystal size may be larger with amphibole reaching 3 mm in some  
321samples. Albite is ubiquitous and makes up to 50% of some samples. Sphene, chlorite, hematite and  
322ilmenite are observed in almost all samples. Orthoclase has been found in samples on the south end of  
323the section along the Cascapedia river. Calcite-filled spherulites with epidote rims (Fig. 5c) are

324interpreted as former vesicles (see e.g. Schiffman and Staudigel, 1995). These are increasingly found  
325downwards in the metamorphic sole and show evidence of shearing. Amphibole is more  
326heterogeneous downwards, with pale green cores and darker blue-green rims (Fig. 5a). Symplectites  
327are not observed.

### 328 **4.3. Metasediments and non-mafic rocks**

329Sillimanite-bearing metapelites (closest to the contact, Fig. 6f-g-h) have well-developed schistosity  
330marked by biotite. Euhedral to sub-euhedral mm-sized garnet is found co-existing with prismatic  
331sillimanite and well-preserved plagioclase including sillimanite needles (Fig. 6f). Garnet hosts  
332numerous inclusions: biotite (~300 µm), oxides, staurolite, plagioclase, apatite, sillimanite (Fig. 6h)  
333and abundant negative crystal shape inclusions resembling peritectic silicate melt inclusions found in  
334migmatites and granulites (nanogranites, see Fig. 6h-i and Cesare et al., 2015). Titano-ilmenite is  
335found in infrequent but large (cm-sized) crystals around garnet and plagioclase, it shows generalized  
336exsolution. Scapolite appears in large (~1cm) poikilitic crystals. Staurolite is found both in the  
337foliation and cutting the foliation, including titano-ilmenite and plagioclase (Fig. 6f-g). Staurolite in  
338contact with plagioclase and sillimanite is often euhedral with some faces resorbed. The staurolite at  
339an angle with the foliation is locally observed growing on garnet. Muscovite is present as a late phase  
340at sharp angle with the foliation.

341Red oxide-rich layers apparently associated with metasediments in the field contain corundum, epidote  
342and abundant Fe-Ti oxides (Fig. 6d-e). Corundum appears dark blue in thin section due to numerous  
343minute rutile inclusions. It is haloed by margarite, paragonite and diaspore, associated with chlorite, all  
344cross-cutting the foliation marked by epidote and corundum. These assemblages and their  
345retrogression have already been mentioned in gneissic metabasalts in contact with peridotite (Bucher  
346et al., 2005 ; Operta et al., 2003; Pratt, 1906) and interpreted as the product of fluid-rock interactions  
347and metasomatism of metasediments in contact with ultramafic rocks.

348Minerals in the 'sill' 35 m away from the contact (§ 3.3; Fig. 3h) are strongly retrogressed (Fig. 6d),  
349with little textural evidence preserved. The apparent foliation is defined by amphibole and biotite.  
350Some amphibole crystals are also oriented within shear bands filled with euhedral iron oxide. Quartz  
351shows undulose extinction. Plagioclase is sericitised. Epidote veins cross-cut the sample. Biotite is



352 mostly replaced by chlorite, and muscovite grains are again oriented perpendicular to the foliation.  
353 Garnet crystals are more abundant on the margins and contain quartz and Fe-Ti-oxides inclusions.  
354 Neither kyanite nor sillimanite was observed.

355 Kyanite-bearing schists shown in figures 3i and 6a-c, sampled ~50 m away from the contact, contain 5  
356 mm-large garnet, quartz, biotite, plagioclase, muscovite, apatite, rutile, epidote and late chlorite  
357 growing after biotite. Sillimanite, fibrolite and nanogranite-like inclusions have not been confidently  
358 identified in these samples. Staurolite is only found included in garnet (Fig. 6c), together with  
359 muscovite, apatite and biotite. Accidental 30  $\mu\text{m}$  monazite has been found.

360 In the deformed low-grade unit of the metamorphic sole, chlorite-mica-bearing quartzites show a well-  
361 developed foliation with oriented phyllosilicates. Crenulation cleavage is observed in all samples.  
362 Garnet is rare (5%, in one sample) and includes apatite and chlorite. Albite is found disseminated in  
363 thin sections, with calcite and epidote. Muscovite and chlorite are intergrown, with minor biotite.  
364 These are generally smaller than 20  $\mu\text{m}$ .

#### 3655. **MINERAL COMPOSITION**

366 Representative electron probe micro-analyses are provided in tables in appendix for amphibole (A1),  
367 clinopyroxene (A2), plagioclase (A3), micas (A4), epidote (A5), garnet (A6) and accessory phases  
368 (A7, including staurolite, chlorite, margarite, scapolite and pumpellyite).

#### 369 **5.1. Mafic rocks**

370 Garnet in high-grade mafic rocks is a solid solution with 40-60% almandine, 12-30% pyrope, 18-45%  
371 grossular and minor spessartine content ( $\leq 7\%$ ). Garnet zoning is bimodal, with homogeneous cores  
372 and spessartine - almandine-rich rims, best seen on the Mn map content (Fig. 7a-c). Mn-enriched  
373 zones correspond to the garnet rim with symplectic texture, crystallising with plagioclase and  
374 clinopyroxene. It is noteworthy that symplectic garnet is found surrounding homogeneous Mn-poor  
375 garnet. Mn enrichment is systematic around garnet cores and followed by Mn depletion in largest  
376 symplectites (Fig. 7c). The systematic pattern implies that garnet rims with symplectite texture were  
377 produced, not consumed, during symplectite growth, in contrast with kelyphite usually associated to  
378 garnet consumption during retrogressive decompression (Messiga and Bettini, 1990). In this view, Mn  
379 depletion is a reservoir effect during symplectite growth (as for classical Mn bell-shaped zoning in

380garnet) not necessarily related to changing pressure-temperature conditions (e.g. Kohn, 2003; Tropper  
381and Recheis, 2003).

382Clinopyroxene (Fig. 7c-d-e) is of diopside type with  $X_{Mg}$  (defined as  $Mg/(Mg+Fe^{2+})$  pfu) in the range  
3830.6-0.8, Na content between 0.04 and 0.06 apfu, and Al content between 0.10 and 0.35 apfu. Samples  
384closest to the contact have varying  $X_{Mg}$  (from 0.60 to 0.75) and highest jadeite content (sample MA-  
38514-35, ~2 metres off the contact). Further away from the contact, large clinopyroxene crystals within  
386the foliation have lowest Al. Al is high in small pyroxene crystals and in crystal cores, and low in the  
387pyroxene with symplectite texture (Fig. 7b and 8d).  $X_{Mg}$  increases with decreasing Al content.

388Figure 9 shows the compositional variation of amphibole in high and low-grade mafic units.  
389Amphibole close to the contact shows compositional zoning between ferroan pargasite and  
390tschermakitic hornblende (both sampled 5-8 m away of the contact) using the definition and site  
391repartition of Leake et al. (1997). Corresponding Ti content reaches 0.20 apfu for the pargasite and  
392decreases steadily with increasing Si content towards Ti-free actinolite. Amphibole in the low-grade  
393unit is often zoned, with Al-poor cores and Al-rich rims (corresponding to Si-rich, Ti-poor cores and  
394Si ~6.5, Ti~0.05 apfu rims, see Fig. 9a-b-c), consistently with colour variations marked by paler cores.  
395Feldspars mainly consist of plagioclase, orthoclase (or adularia) and albite (Fig. 9d). Extensive  
396retrogression of plagioclase in the garnet-clinopyroxene symplectite complicates EPMA  
397measurements and prevents studying zoning. Anorthite content in plagioclase ranges between 75 and  
39892% in the high-grade section with garnet and clinopyroxene. Further away from the contact and in  
399the low-grade section, plagioclase is of oligoclase type with anorthite content in the range 17-30%.  
400Albite, orthoclase and adularia are found in samples from the low-grade unit and unequivocally  
401associated to retrogression. Interstitial sanidine with complex twinning around ~40% orthoclase (Fig.  
4029d) was accidentally found in samples where plagioclase content is low (<5%, samples MA-14-22 and  
403MA-14-34).

404Epidote (Fig. 10) is a solid solution varying from a clinozoisite-rich component (maximum Al content  
405= 2.87 apfu found in our samples) to a pistacite-rich component ( $Fe^{3+} = 1$  apfu). The more aluminous  
406compositions are restricted to the high-grade section of the metamorphic sole, and ferric epidote is  
407observed in almost all mafic samples regardless of metamorphic grade, as individual crystals,

408 overgrowths and in veinlets cross-cutting the foliation (Fig. 10b-c). In high-grade rocks, Al-rich  
409 epidote is observed associated to retrogressed plagioclase (Fig. 7d), corundum-rich layers and with the  
410 garnet-clinopyroxene-amphibole symplectite. Allanite is sporadically found in low-grade mafics with  
411 ferric epidote overgrowths.

412 Chlorite is of chamosite type (mostly tri-trioctahedral with octahedral sum greater than 5.90) and has  
413  $X_{Mg}$  between 0.55 and 0.70, with highest values reached in corundum-epidote-bearing samples close to  
414 the contact and lowest  $X_{Mg}$  in the low-grade section of the sole. Only sample MA-14-22 shows zoning,  
415 with crystal cores at Si = 3.0 apfu and edges/rims at Si = 2.7 apfu. Other samples have Si content in  
416 the range 2.55-2.74 with little variations within sample.

## 417 5.2. Metasediments and “intrusion”

418 Figure 11 presents mineral compositions for garnet, biotite, feldspar and phengite for the metapelites  
419 and metacherts found in the metamorphic sole of Mont Albert.

420 Garnet in metapelites from the high-grade section is a solid solution between almandine (55-80%),  
421 grossular (5-25%), pyrope (10-25%) and minor spessartine component (<7%). Zoning is ubiquitous  
422 with concentric, oscillatory and fracture-sealing zoning best observed in Mn and Ca (Fig. 11 b,c). Ca-  
423 rich core in some garnet (Fig. 11b) is mantled by Ca-poor areas. Rims are Ca-rich and show partial  
424 resorption. Mn first increases in Ca-rich rims and decreases again in the external, Ca-richest parts of  
425 the rims. More classical concentric zoning with Mn-rich core and Ca-rich rims is also observed (Fig.  
426 11c), also with limited resorption. Garnet from the lower-grade section (found in veinlets in  
427 metacherts along the Cascapedia river, samples MA-14-24 and MA-14-31 on Fig. 11a) has higher  
428 pyrope (sample MA-14-31) and grossular (sample MA-14-24) content.

429 Biotite has  $X_{Mg}$  in the range 0.45-0.65, with highest Ti content associated with  $X_{Mg} \sim 0.55$  (Fig. 11d).

430 Feldspars consist of orthoclase and plagioclase varying between oligoclase and andesine (Fig. 11e).

431 Phengite is generally muscovite-rich (Fig. 11f) with up to 18% Tschermak substitution towards  
432 celadonite and limited pyrophyllitic substitution ( $\leq 6\%$  for most analyses).

433 Staurolite composition shows negligible solid solution with Mn ( $\leq 0.2$  MnO wt. %) and has  $X_{Mg}$  in the  
434 range 0.15-0.25, for crystals included in garnet as well as in the foliation. Staurolite at an angle with  
435 the foliation (Fig. 6g) and growing over garnet is homogeneous around  $X_{Mg} = 0.20$ .

436Scapolite is a sodian meionite with  $Si = 7.17$  apfu and  $Ca / (Ca+Na) = 0.71$  when structural formula is  
437calculated to compensate 50 negative charges (C and Cl were not measured).

438As for mafic rocks, chlorite is a chamosite with low sudoite content. It has  $X_{Mg}$  between 0.39 and 0.52,  
439lower than for mafic rocks but similar Si content in the range 2.55-2.65 apfu.

#### 4406. **PHASE EQUILIBRIA AND THERMOBAROMETRY**

441The petrological evolution of the sole is modelled here with the use of a pseudosection (phase diagram  
442for fixed bulk rock composition) representative of the mafic rocks. Despite progress in the  
443thermodynamic models for mafic compositions, uncertainties remain large for thermobarometry on  
444these rocks, especially compared to mineral assemblages in metapelites. To further constrain  
445conditions of crystallisation, we carried out empirical thermobarometry on all lithologies and multi-  
446equilibrium thermobarometry on selected assemblages in metapelites. This approach has been  
447preferred over building pseudo-sections as the observed metapelites are very thin beds (up to ~10 cm  
448thick within the mafic rocks) showing poly-metamorphic history with compositional banding,  
449retrogression and evidence for opening of the system and interaction with the mafic rocks. Therefore  
450assuming equilibrium at sample scale and close system has been deemed erroneous for the  
451metapelites.

#### 452 **6.1. Mafic rocks**

##### 453 *6.1.1. Phase equilibria*

454Figure 11 shows a pseudo-section modelled in the NCKFMASHTO system for the high-grade subunit,  
455using THERMOCALC version 3.45 (Holland and Powell, 1998, 2011) with the updated database  
456version (tc-ds62) of Holland and Powell (2011). The selected bulk rock composition is an average of  
457six samples of the garnet amphibolite measured by O'Beirne-Ryan et al. (1990), which has been  
458deemed representative of the large-scale composition of the high-grade subunit, reducing sampling  
459biases due to compositional banding. Water content was calculated through mass balance of  
460amphibole proportion over several thin sections and corresponds within error to the average loss on  
461ignition obtained by O'Beirne-Ryan et al. (1990). Activity models are after White et al. (2014b) for  
462orthopyroxene, biotite, chlorite and garnet, Green et al. (2016) for mafic melts, augite and hornblende,  
463Holland and Powell (2003) for plagioclase and K-feldspar, and White et al. (2000) for ilmenite-

464hematite. In the absence of magnetite or any other  $\text{Fe}^{3+}$  rich phase at peak conditions, rock oxidation  
465was set to 1 %, following previous studies on similar rocks (e.g., Guilmette et al., 2011; Palin et al.,  
4662014).

467Peak conditions were approximated based on the observed mineralogy and isopleths for garnet  
468(grossular fraction and  $X_{\text{Fe}} = \text{Fe}/(\text{Mg}+\text{Fe})$ , all in apfu), clinopyroxene ( $X_{\text{Fe}}$ ), and amphibole ( $X_{\text{Fe}}$ ), using  
469representative mineral compositions for the large, homogeneous crystal cores (not the symplectites)  
470given by O'Beirne-Ryan et al. (1990) and measured in this study. Garnet, clinopyroxene and  
471amphibole are stable throughout the pseudosection, with the amphibole-out reaction at temperatures  
472greater than 1000°C, which is consistent with the dehydration reaction of hornblende (Wolf and  
473Wyllie, 1994). Pressure-temperature conditions for the field best matching the mineralogy for the  
474high-grade subunit are around  $0.98 \pm 0.04$  GPa and  $825 \pm 25^\circ\text{C}$  (Fig. 12). They lie at supra-solidus  
475conditions where rutile is stable. Plagioclase is not predicted at peak conditions, also consistently with  
476observations where plagioclase is only very rarely found other than associated to the symplectites. In  
477this pseudosection, the plagioclase field does not extend to pressures above 0.8 GPa. Estimated modes  
478are in good agreement with sample modes for amphibole (44%), clinopyroxene (20%) and garnet (26  
479%), as for sample MA-14-35 (Fig. 4b). A melt proportion of 9 vol.% is predicted and broadly  
480consistent with previous estimates for mafic rocks at comparable conditions using similar activity  
481models (Palin et al., 2016 ; Soret et al., 2017). The Ti content of amphibole (0.08 apfu) is close to that  
482reported by O'Beirne-Ryan et al. (1990) (0.10 apfu), but in the low range of values document in this  
483study (0.05 up to 0.20 apfu; Fig. 9b). The  $X_{\text{Fe}}$  of amphibole at  $\sim 0.32$  compares well with the  
484compositions observed here and given by O'Beirne-Ryan et al. (1990).

#### 485       6.1.2. Garnet-clinopyroxene thermometry

486Garnet-clinopyroxene thermometry has been carried out on the two samples (MA-14-35 and MA-14-  
48738) where phase relations between garnet and clinopyroxene are clearest. In both cases garnet and  
488clinopyroxene are zoned, with relatively large, homogenous cores and variably-sized rims linked to  
489the garnet-clinopyroxene-epidote-plagioclase symplectite. Equilibrium is inferred between garnet and  
490clinopyroxene cores, and between minerals in the symplectitic rim. The Fe-Mg distribution coefficient

491  $\left( K_D = \frac{\text{Fe}_{\text{Grt}}^{2+} \cdot \text{Mg}_{\text{Cpx}}}{\text{Fe}_{\text{Cpx}}^{2+} \cdot \text{Mg}_{\text{Grt}}} \right)$  increases from core pairs (in the range  $K_D = 3.5 - 5$ ) to rim pairs ( $K_D \geq 7$ ). Figure

49213 shows the results of four empirical thermometers. The first three (Ellis and Green, 1979; Powell, 4931985; Krogh Ravn, 1988) give consistently higher temperatures than the more recent thermometer of 494Krogh Ravn (2000) which is retained, as it specifically addresses possible over-estimation by the 495other three thermometers in this type of samples. Selected crystallisation temperatures vary between 496820 and 900°C for equilibrium between garnet-clinopyroxene cores and between 680 and 720°C for 497equilibrium between rims.

### 498 6.1.3. Amphibole-plagioclase thermometry

499The amphibole–plagioclase thermometer of Holland and Blundy (1994) has been used on two samples 500(MA-14-38, MA-14-42) from the high-grade amphibolite and four samples (MA-14-22, 23, 26, 32) 501from the amphibolite of the low-grade unit. For the high-grade unit, equilibrium is inferred between 502pargasitic amphibole and anorthitic plagioclase (Fig. 9). For the low-grade unit, equilibrium is inferred 503between amphibole rim composed of Mg-hornblende and plagioclase of andesine type with anorthite 504content of 23% (Fig. 9). Pressure was assumed constant at 0.95 GPa. This method gave two clusters 505separated by ~200°C: the high-grade amphibolite yielded estimates of 875±40°C and the low-grade 506amphibolite yielded estimates of 680±40°C.

## 507 6.2. Metapelites

508Multi-equilibrium thermobarometry has been carried out on selected mineral assemblages in 509metapelites. Three main parageneses have been recognized and tested for thermodynamic equilibrium: 510 - kyanite – garnet cores – quartz – biotite – staurolite as seen in garnet inclusions (e.g. Fig. 6), for the 511prograde history  
512 - aluminosilicate – garnet mantle – plagioclase – biotite – quartz with kyanite or sillimanite depending 513on sample, for peak metamorphic conditions  
514 - sillimanite – staurolite – phengite, all crosscutting the foliation and associated in sample MA-15-5a 515(Fig. 6f-h).

516Multi-equilibrium thermobarometry was carried out using THERMOCALC (Holland and Powell, 5171998, 2011) version 3.33 with the thermodynamic database tc-ds55. Results are summarised in figure

51814. For sample MA-15-5a, the peak mineral assemblage garnet + biotite + muscovite + plagioclase +  
519quartz + sillimanite gives estimates of  $690 \pm 27^\circ\text{C}$  and  $0.85 \pm 0.1$  GPa. For sample MA-14-50, the  
520assemblage garnet + biotite + muscovite + plagioclase + quartz + kyanite yields conditions of  $750 \pm$   
521 $130^\circ\text{C}$  and  $0.92 \pm 0.1$  GPa. The same assemblage in sample MA-14-48a gives peak conditions of  $615 \pm$   
522 $65^\circ\text{C}$  and  $1.2 \pm 0.4$  GPa. For this sample, addition of staurolite (included in garnet with kyanite and  
523biotite) refines estimates for prograde metamorphism at  $633 \pm 32^\circ\text{C}$  and  $1.1 \pm 0.17$  GPa. For the  
524staurolite and aluminosilicate-free sample MA-14-52, the assemblage garnet + biotite + muscovite +  
525plagioclase + quartz yields  $640 \pm 40^\circ\text{C}$  and  $1.01 \pm 0.14$  GPa.

526Chlorite-phengite thermobarometry could not be systematically carried out due to the generally low  
527susoite content of the chlorite, which nevertheless indicates that chlorite likely crystallised over  $350^\circ\text{C}$   
528(see Bourdelle and Cathelineau, 2015). Chlorite thermometry (using the approach and thermodynamic  
529properties given in Vidal et al., 2006) yields values of  $457^\circ\text{C}$  and  $496^\circ\text{C}$  for two groups of chlorite in  
530sample MA-14-22, a mafic rock in the low-grade section of the sole. Unfortunately no phengite at  
531equilibrium were identified in this sample, therefore corresponding pressure could not be estimated.

532The Ti-in-biotite thermometer of Henry et al. (2005) yields estimates of  $695 \pm 23^\circ\text{C}$  and  $680 \pm 23^\circ\text{C}$   
533for the samples MA-15-5a and MA-14-50, respectively. The garnet-biotite thermometer of Holdaway  
534(2000) gives estimates of  $700 \pm 25^\circ\text{C}$  for these samples. Additional pressure estimates in metapelites  
535were obtained using the garnet-biotite-muscovite-plagioclase barometers of Wu (2015), yielding  $0.8 \pm$   
536 $0.12$  GPa and  $0.91 \pm 0.12$  GPa for samples MA-15-5a and MA-14-50. These are within uncertainties  
537of the garnet-biotite-muscovite-aluminosilicate-quartz barometer of Wu and Zhao (2007), yielding  $0.7$   
538 $\pm 0.08$  GPa and  $0.88 \pm 0.08$  GPa for samples MA-15-5a and MA-14-50, not shown on figure 14 for  
539readability.

540In the low-grade unit, the Ti-in-biotite thermometer gives  $610 \pm 23^\circ\text{C}$  for the sample MA-14-24 (the  
541only biotite-bearing sample in this subunit). In sample MA-14-31, the Ti-in- muscovite thermometer  
542of Wu and Chen (2015) yields  $515 \pm 65^\circ\text{C}$ , within uncertainties of the garnet-muscovite thermometer  
543of Wu and Zhao (2006) at  $555 \pm 16^\circ\text{C}$  on the same sample.

## 5447. **DISCUSSION**

### 545 **7.1. Petrological evolution of the metamorphic sole**

547 Close to the contact with the peridotite, metamorphic sole rocks are strained, sheared and lack relicts  
548 of original magmatic minerals so that the original nature of the rock is hard to assess: although the  
549 high-grade unit is indisputably of mafic origin, whether these rocks were gabbros or basalt-type lavas  
550 could not be deciphered. The presence of metasediments in the high-grade unit advocates oceanic  
551 floor origin, and the persistence of (strained) boudins and spherulites in the folded, lower-grade unit  
552 suggests basaltic lavas with a shallow oceanic crust origin, together with the absence of relicts of  
553 gabbro-derived clinopyroxene. This is consistent with a single geodynamic origin for the metamorphic  
554 sole, with the metasedimentary content increasing away from the structural top (as discussed by Agard  
555 et al., 2016). In this view the metamorphic sole of the Mont Albert ophiolitic complex represents a  
556 subducted portion of the Schick-Schock group units, which is consistent with the similarities in  
557 compositions reported for both mafic lithologies (O'Beirne-Ryan et al., 1990; Camiré et al., 1995).

559 Thermobarometric estimates carried out in this study are compiled in figure 14. For the high-grade  
560 unit, pressure estimates on metapelites cluster within uncertainties and indicate crystallisation  
561 pressures around 0.95(+/-0.10) GPa. Calculated temperatures range between 650°C and 950°C, with  
562 garnet-clinopyroxene estimates using crystal cores being highest in sample MA-14-38 and seemingly  
563 somewhat overestimated. Broadly speaking, mafic samples close to the contact with peridotites have  
564 reached temperatures between 850 and 900°C.

565 Estimates at lower temperatures for these samples, such as garnet-clinopyroxene rims, are interpreted  
566 as indicative of cooling along the retrograde path. Metasediments were not found less than ~25 m  
567 away from the contact and indicate lower temperatures in the range 750-650°C, matching  
568 crystallisation of the garnet-clinopyroxene rims. Kyanite and staurolite inclusions in garnet show that  
569 prograde metamorphism took place in the field of kyanite and staurolite, along a geothermal gradient  
570 of the order of 20°C/km (sample MA-14-52). For the lower-grade unit rocks, further away from the  
571 contact, estimated temperatures are distinctly lower than close to the contact, with some overlap with  
572 the lowest peak temperatures estimated in the high-range unit (~700°C).



573 In rocks from the lower-grade unit, equilibrium was probably not reached at sample scale at peak  
574 temperature, given that amphibole preserves Al-poor cores interpreted as crystallising along the  
575 prograde path. In these samples chlorite geothermometry gives temperatures below 500°C which are  
576 interpreted as crystallisation temperatures during cooling. Crystallisation pressures here are poorly  
577 constrained, apart from the lack of evidence of high-pressure or very-low pressure index minerals.  
578 Tectonic juxtaposition of the low- and high-grade units and peak metamorphic conditions of the low-  
579 grade unit suggest a retrograde path along a similar geothermal gradient for both units.

580 These results are consistent with step-wise accretion of two (or more) subunits of metamorphic soles.  
581 These units (and/or samples within the subunits) *do not* share an identical pressure-temperature path,  
582 as suggested by Gagnon and Jamieson (1986). Metamorphic rocks close to the contact with the  
583 peridotites record higher temperatures than further away, either because of step-wise accretion of  
584 subunits or due to slow thermal equilibration compared with exhumation. The obtained pressure-  
585 temperature paths appear clockwise, with burial largely in the field of kyanite and exhumation starting  
586 in that of sillimanite.

### 587       7.1.3. Compositional evolution and stability of epidote

588 The broad compositional range of epidote and its links with texture (with Al-rich cores and Fe<sup>3+</sup>-rich  
589 rims and late veins, Fig. 7 and 10), mineral assemblage and distance to the contact, allow further  
590 constraining the petrological history of the metamorphic sole. The composition of epidote is known to  
591 vary with temperature and oxygen fugacity ( $fO_2$ ), where increasing  $fO_2$  leads to increase the stability  
592 field of epidote towards higher temperature (e.g. Holdaway, 1972). In metasomatic veinlets from the  
593 garnet-bearing amphibolite with epidote-corundum assemblage (sample MA-14-2b, Fig. 6d-e and 10),  
594 the pistacite component of epidote is about 0.5. This indicates a maximum crystallisation temperature  
595 around 700°C (Holdaway, 1972). Variations of composition in the high-grade subunit where the Fe<sup>3+</sup>  
596 content of epidote increases at the expense of Al from crystal cores to rims (Fig. 7d) then to late veins  
597 (Fig. 10) are consistent with decreasing crystallisation temperatures as indicated by the clinozoisite  
598 component (Schmidt and Poli, 2004).

599 The texture of clinozoisite-rich epidote and its association to garnet, clinopyroxene, plagioclase and  
600 oxide in the symplectite point to high-grade metamorphic conditions. The presence of clinozoisite-rich

601epidote may reflect the involvement of magmatic fluids, as MORB melting gives epidote up to 800-  
602830°C at 0.9-1.2 GPa (see review of Schmidt and Poli, 2004) and magmatic epidote is also mentioned  
603in comparable assemblages with similar texture by Lardeaux and Spalla (1991) and Nicollet et al.  
604(1979). Higher temperature for epidote crystallisation in metamorphic soles is not impossible as  $fO_2$   
605and water content are only inferred here, and zoisite may have been missed in the field. The  
606amphibole-epidote-plagioclase-garnet assemblage is nevertheless regarded as representative of  
607conditions around 0.9-1.5 GPa and 700-830°C for reasons given by Schmidt and Poli (2004), in good  
608agreement with present thermobarometric estimates.

## 609 **7.2. Formation and structure of the metamorphic sole**

### 610 *7.2.1. Metamorphic sole and subduction initiation*

611The metamorphic sole of the Mont Albert ophiolitic complex appears broadly similar to other  
612metamorphic soles, hinting at a common formation process. The overall structure and petrology  
613reproduce that of the Semail ophiolite, yet with smaller differences between metamorphic grades for  
614the base of the high-grade unit and the top of the low-grade unit. However differences in deformation  
615between high and low-grade units are as striking as in the Semail ophiolite, where the low-grade unit  
616is thickened by numerous folds and faults (Hacker and Mosenfelder, 1996; Gray and Gregory, 2000).  
617Here, aluminous metasediments allow more accurate estimation of peak metamorphic pressure, and  
618confirm broadly similar peak conditions. Peak temperatures are in the range of those estimated in  
619Semail (~850°C), and compare well with estimations for the sole of the Bay of Islands complex, where  
620sillimanite is also reported (e.g., Suhr and Cawood, 1993). These estimates all fall well into stability  
621conditions of a metabasalt-derived melt (Fig. 12). In the model of Agard et al. (2016), subducted  
622metabasalts (future metamorphic soles) are “underplated” (accreted to upper plate peridotites) when  
623both units have similar effective viscosities and coupling is maximal between the two. Agard et al.  
624(2016) emphasize that conditions allowing accretion of the metamorphic sole are only transiently met,  
625because of the general cooling of the subduction system. This restricts the origin of the high-grade  
626section of the metamorphic sole to the tip of the forming slab (see Fig. 1a-b), and implies that the  
627mixed mafic-sedimentary protolith deposited close to the future trench – and further away from the

628continental margin than presented in e.g. the geodynamic reconstruction of Tremblay and Pinet (2016,  
629their figure 19).

630Figure 15 compares peak metamorphic conditions estimated in this study to the thermal structure of  
631oceanic lithosphere over time, from present-time modelling. Peak metamorphic conditions of 800 to  
632900°C in the metabasalt at ~33 km depth imply that the overriding oceanic lithosphere was less than  
633about 20 My-old. This is a maximum age as cooling of the slab/mantle interface due to slab  
634penetration would imply a younger age. The reconstructed ~33 km depth has geodynamic implications  
635for the distance of the trench/megathrust to the ridge. Assuming subduction took place at a  
636convergence rate of 2 cm/yr (consistent with kinematics estimated by e.g. Bradley, 1989) with a 25°  
637dip of the slab indicates that ~4 Ma were necessary to subduct the high-grade metabasalts to peak  
638pressure, which decreases to ~2.3 Ma for a 45° slab dip. In any case the time required to bury mafic  
639rocks of the future metamorphic sole to peak pressure is not insignificant but small compared to the  
640age of the overriding lithosphere during underplating of the sole. This time lapse is short yet sufficient  
641for heat transfer to the whole high-grade unit (always thinner than 100 m, to be compared with the  
642much larger lengths heat may travel in a Ma, e.g. Bickle and McKenzie, 1987). Overall, this model is  
643consistent with subduction initiating close to (within tens of kilometres) or at the ridge and with  
644metamorphic soles originating from ocean-floor rocks located close to the forming trench at the time  
645of subduction initiation (also within tens of kilometres). Greater distances, convergence rates below  
646cm/yr and shallow slab dipping require greater time for burial to peak pressure and become  
647inconsistent with the thermal structure of oceanic lithosphere shown in figure 15a due to cooling of the  
648mantle wedge. The supra-subduction zone origin of the ophiolitic complex proposed by many authors  
649(see Tremblay et al., 2011) suggests that the oceanic lithosphere where subduction initiated (within the  
650Iapetus ocean) could have been warmer than presented in figure 15a. This resonates with the global  
651scale analysis of Vaughan and Scarrow (2003) who link thermal rejuvenation of the oceanic  
652lithosphere to ophiolite obduction. Unfortunately testing for thermal rejuvenation is beyond the  
653resolution of the geological record of the Mont Albert ophiolitic complex, especially as peridotites  
654remain too poorly dated to compare with peak metamorphism ages in the sole.

655       7.2.2. *Clockwise pressure-temperature paths in a cooling geodynamic environment*

656The mineral record of the Mont Albert metamorphic sole argues for hair-pin yet clockwise pressure-  
657temperature paths with exhumation along a warmer geothermal gradient than during burial. Although  
658this is counter-intuitive, given the progressive cooling of the plate interface (and the trajectories of  
659Hacker and Gnos, 1997), this is explained by rapid vertical movements in comparison of thermal re-  
660equilibration of the overriding plate, as tentatively depicted in figure 15b-c.

661 Figure 15b and c show ocean-floor basalts buried below the plate interface, in a nascent subduction  
662zone concomitantly of downward advection of isotherms (heating below the plate interface is  
663comparatively slow: step 1 on Fig. 15b-c). Over time, isotherms in the lower plate are increasingly  
664parallel to the plate interface. The thermal gradient through the plate interface to the upper plate  
665increases with time, explaining the near-isobaric temperature increase of the high-grade unit during its  
666accretion (step 2 on Fig. 15b-c). Exhumation follows along the base of the upper plate together with  
667peridotites. Through the still sharp temperature gradient, exhumation explains initially rapid cooling  
668(step 3) continuing along a warmer thermal gradient than burial (via step 4). With time, the plate  
669interface has been cooling significantly (compare isotherms at t1 and t4). This schematic model is only  
670valid if the upper plate remains significantly warmer over a distance of several tens of meters above  
671the plate interface during the time of exhumation of the metamorphic sole (i.e. a few millions years, in  
672agreement with radiometric constraints discussed above). Preservation of peak temperature mineral  
673assemblages above 700°C and of subsequent parageneses without homogenization by diffusion are  
674also consistent with fast cooling.

### 675       7.2.3. *Melting... or not?*

676In the Mont Albert ophiolitic complex, absence of metasediments from the rocks less than 20 metres  
677away from to the contact with the peridotite is observed in a trend where the proportion of sediments  
678and their quartz content apparently increase towards the base of the sole. This has also been noted in  
679the Semail metamorphic sole (e.g. Soret et al., 2017). In their model, Agard et al. (2016) point out that  
680ocean-floor derived subducted rocks likely contain more sediments with time as distance to the margin  
681decreases (following closure of the basin).

682Alternatively, the absence of metasediments from the first 20 metres may be related to melting: close  
683to the contact, metamorphic conditions are well above 700°C and aluminous metapelites should have

684been molten at a significant degree (>30 %), consistently with observations of geochemical tracers of  
685subducted sediments within arc magmas (e.g. Labanieh et al., 2012; Plank et al., 2009). Melts  
686produced from the metasediments and from the amphibolite should have near granitic composition at  
687peak conditions (see Feisel et al., 2018 for open system amphibolite melting at 0.95 GPa) and should  
688produce easily identifiable leucosomes. However leucosomes and melt remnants are rare throughout  
689the sole and have not been found closer than about 20 metres from the contact or crosscutting the  
690peridotite. The restite of molten sediments may have been missed in the field (it is probably dark  
691within dark mafic rocks), especially as shearing has been intense and proportions of metasediments are  
692small in comparison to mafic rocks. Corundum-epidote-chlorite rocks found within the amphibolite  
693less than 10 metres away from the contact may record interactions between partially molten  
694metapelites and mafic rocks, but these are rare and cryptic.

695Generalized partial melting is predicted in all present rock types above 750°C. Soret et al. (2017)  
696argue that limited melting of the metabasalts may enhance accretion, with a threshold around 7%  
697partial melting, above which melting would cause too much weakening to allow accretion. This  
698suggests that metasediment-derived melts were mostly extracted parallel to the slab, and/or that melt-  
699rich lithologies were not accreted to the upper plate peridotite and subsequently subducted and lost to  
700the mantle. In this view, the absence of metasediments close to the contact would be explained (in the  
701model of Agard et al., 2016) as due to a too large decrease in effective viscosity (because of melting)  
702to allow coupling and accretion to the upper plate. It follows that what has been identified as the high-  
703grade metamorphic sole unit could be a more complex assemblage of small (tens of metres in  
704thickness at most) subunits, as in the Semail metamorphic sole (Soret et al., 2017). A possible  
705consequence is that mafic rocks located immediately at the contact with the peridotite and lacking  
706metapelites could have formed at higher pressure than estimated here (since pressure is possibly  
707estimated with larger uncertainties in mafic rocks). Pressure estimates in horizons with pelitic and  
708mafic lithologies nevertheless concur (e.g., figure 14a).

## 7098. CONCLUSION

710The metamorphic sole of the Mont Albert ophiolitic complex and its relicts of metasediments provide  
711clues to understand early subduction dynamics. As for the Semail ophiolite, a strong, seemingly

712inverted metamorphic gradient is observed within the two main subunits respectively characterized by  
713granulite / higher amphibolite facies and higher greenschist facies metamorphism. The metamorphic  
714sole appears derived from the Schick-Shock volcanics from the Dunnage zone, and its petrology  
715suggests a shallow, ocean-floor origin (basalt and sediments, although the absence of gabbro is hard to  
716prove unequivocally).

717Limited retrogression and presence of aluminous metapelites allow constraining the metamorphic  
718history of the high-grade unit to peak pressure around 0.95 GPa with peak temperatures up to about  
719850°C. These estimates are consistent with the model proposed by Agard et al. (2016), where the  
720metamorphic sole formed in a nascent subduction zone, below young (less than ~20 Ma) or  
721rejuvenated oceanic lithosphere, with burial along a geothermal gradient around 20°C/km. This study  
722provides evidence for a clockwise metamorphic path, with exhumation of the high-grade units along a  
723warmer geothermal gradient (~40°C/km), suggesting rapid exhumation (i.e., faster than thermal re-  
724equilibration and cooling of the mantle wedge above the plate interface). Cooling of the interface is  
725documented by successive underplating of subunits with progressively lower peak metamorphic  
726conditions (away from the contact with the peridotite). The necessarily fast pace of evolution of the  
727metamorphic sole of the Mont Albert ophiolitic complex (formation below warm oceanic lithosphere,  
728underplating and exhumation) is consistent with the narrow range of ages obtained by Tremblay et al.  
729(2011) for the Thetford-Mines ophiolitic complex along the same suture zone: oceanic magmatism (at  
730~480 Ma), formation of the high-grade metamorphic sole (at ~476 Ma), emplacement of sole-derived  
731melting products in the peridotite (at ~470 Ma) and cooling of the metamorphic sole (from ~466 Ma to  
732the end of obduction around 460 Ma), all took place within ~20 Ma. Although partial melting is  
733reported in Taconian ophiolitic soles (e.g. at the Thetford-Mines ophiolite: Tremblay et al., 2011; the  
734Bay of Islands complex: Suhr and Cawood, 1993), evidenced in metapelites and predicted by  
735thermodynamic modelling in mafic rocks (up to ~9 vol.%) at the Mont Albert ophiolitic complex, melt  
736remnants such as leucosomes, granitoids or felsic intrusions are sparse. This may relate to strain  
737localization in melt-rich lithologies, precluding coupling and favouring accretion of the mafic  
738lithologies now found close to the contact with the overlying peridotite. Strain localisation during  
739melting and melt drainage appear linked to stepwise accretion of subunits to form metamorphic soles,

740consistently with pulsatile melting during prograde metamorphism (e.g. Diener and Fagereng, 2014)  
741and with similar mechanisms observed in the metamorphic sole of the Semail ophiolite (Soret et al.,  
7422017).

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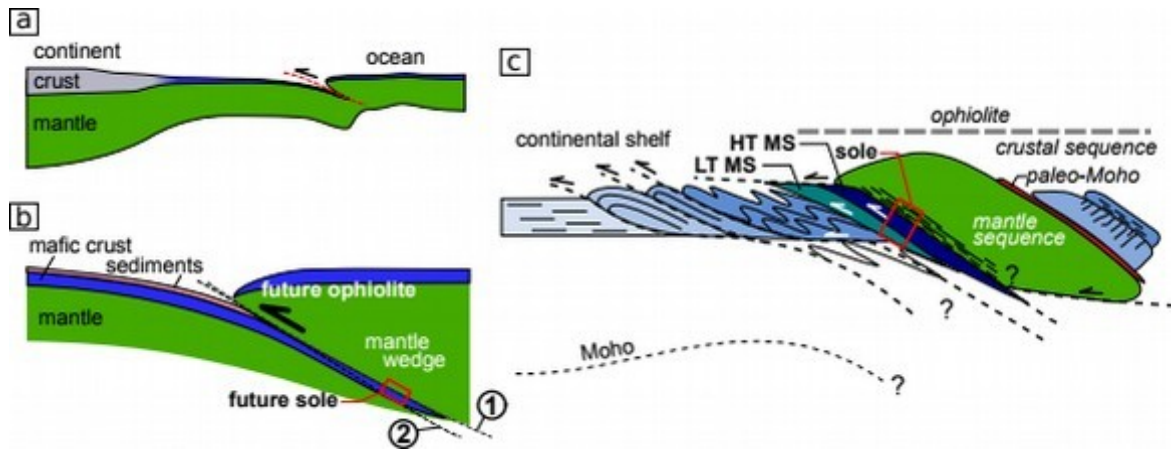
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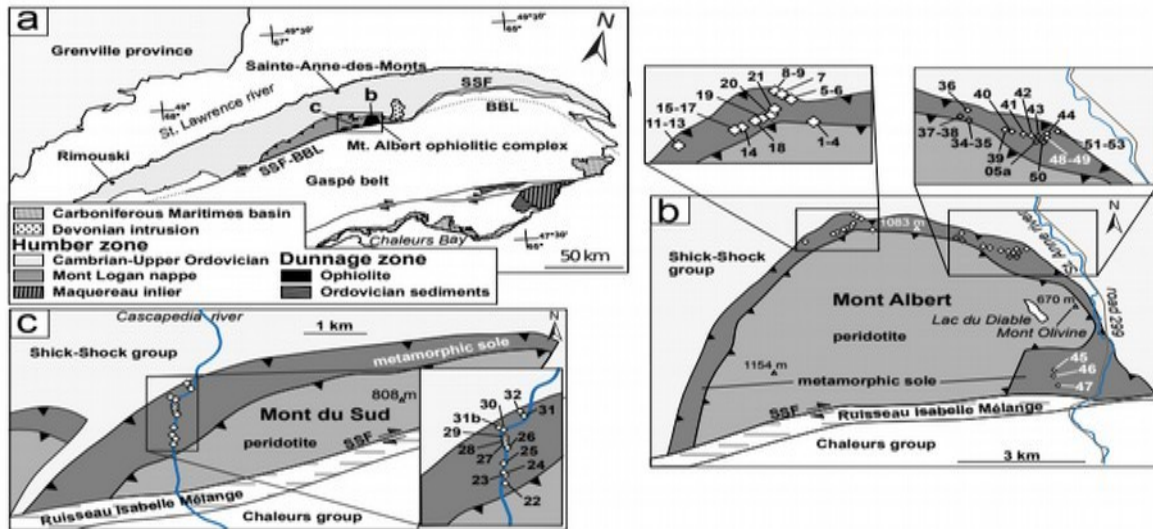
1034 **FIGURE CAPTIONS**

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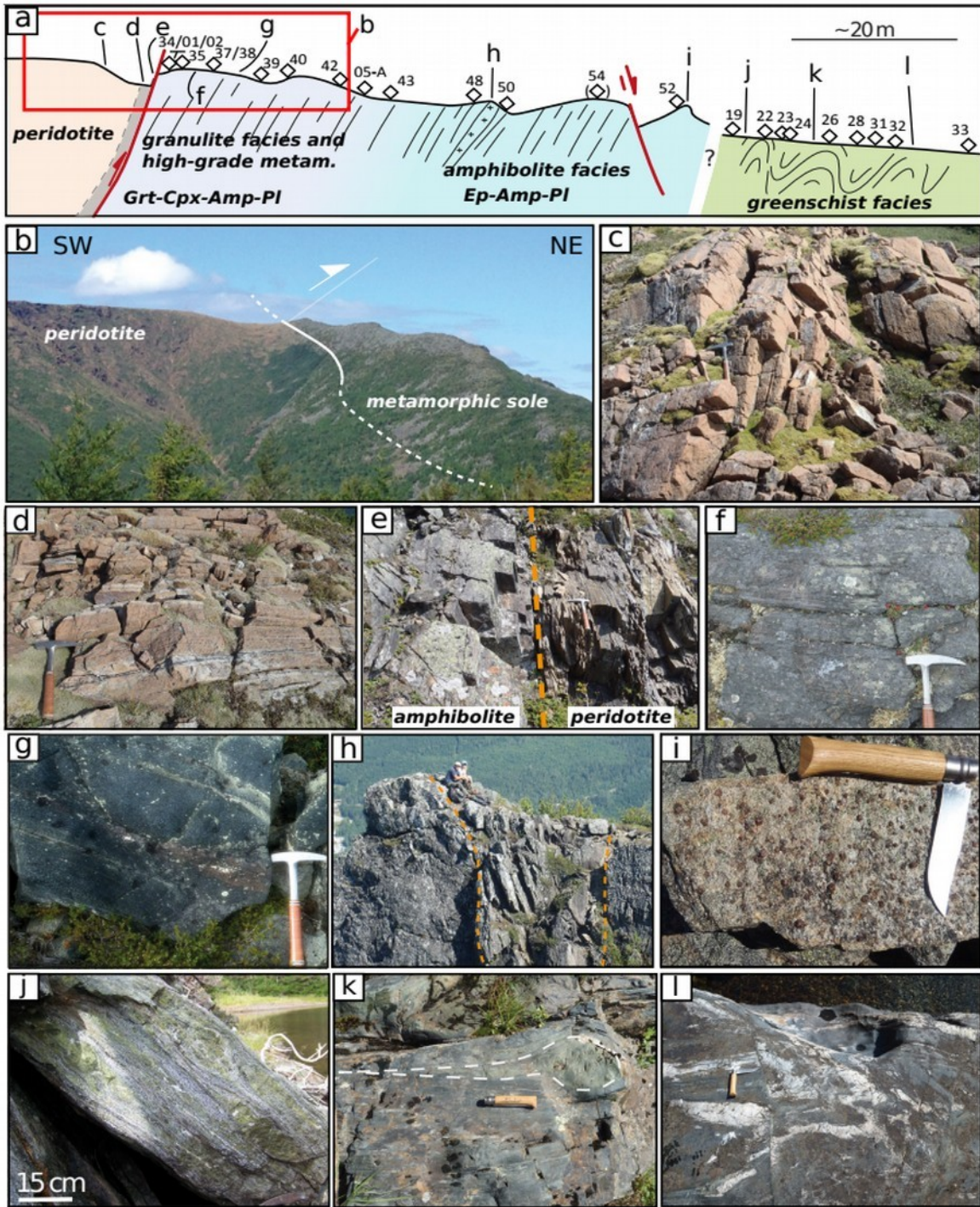


1036 Figure 1: Schematic cross-sections showing the general geodynamic setting and its evolution during  
 1037 subduction infancy and ophiolite obduction, with emphasis on the ophiolitic sole. Redrawn after  
 1038 Agard et al. (2016) and Searle et al. (2015). (a) Intra-oceanic subduction initiation, prior to ophiolite  
 1039 obduction. (b) Close-up view on the formation and accretion of the metamorphic sole to the mantle  
 1040 wedge. Accretion of crustal-derived material implies displacement of the subduction interface from  
 1041 thrust 1 to thrust 2. (c) Obduction of the ophiolite and its sole (red rectangle). The sole has an apparent  
 1042 inverted metamorphic gradient and includes, from bottom to top: greenschist- and lower amphibolite  
 1043 facies metamorphic rocks (LT MS: low temperature metamorphic sole), higher amphibole to granulite  
 1044 facies metamorphic rocks (HT MS: high temperature), and peridotite of mantle origin showing  
 1045 multiple deformation events (from ~1200°C to ~650°C: Linkens et al., 2011 ; Prigent et al., 2018).  
 1046 The Mont Albert ophiolitic complex lacks the crustal sequence.

1047



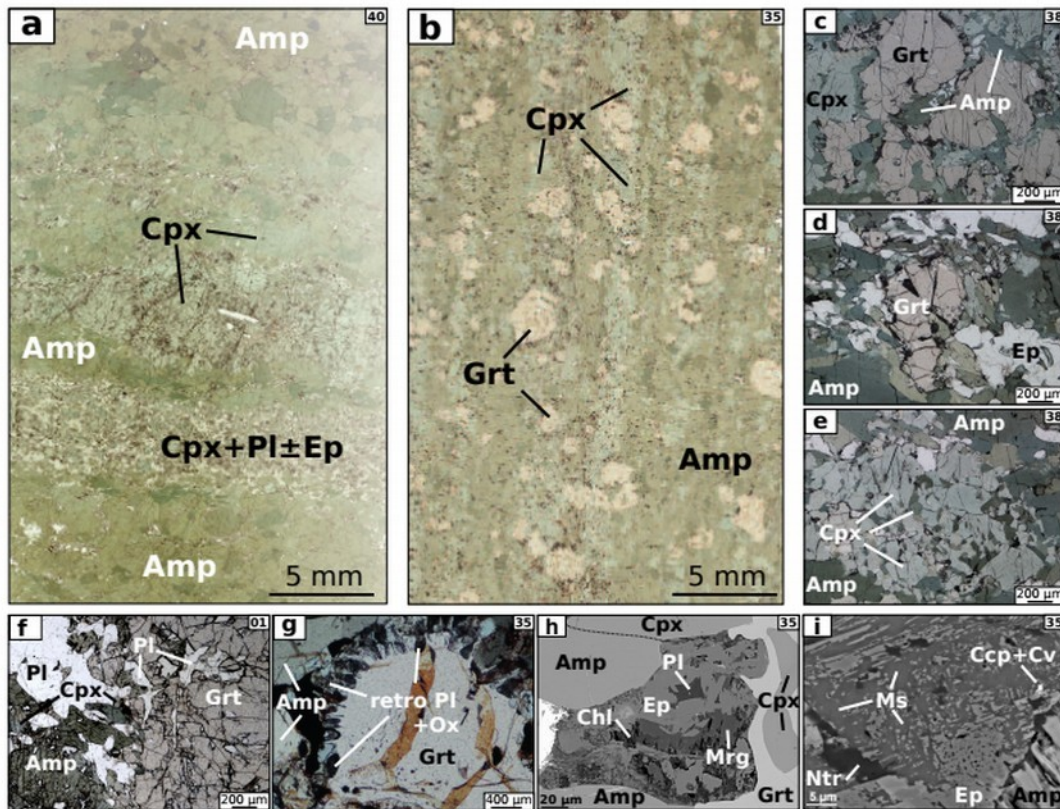
1049Figure 2: Geological maps of the Mont Albert ophiolitic complex and sample location. (a) Simplified  
 1050geological map of the Gaspé peninsula (modified after Malo et al., 2008 and Williams and Grant,  
 10511998). The Mont Albert ophiolitic complex is indicated by the central rectangle. (b) Simplified  
 1052geological map of the Mont Albert area (after MacGregor and Basu, 1979; Gagnon and Jamieson,  
 10531986). Numbers indicate sample location, as shown in insets for readability. (c) Geological map of the  
 1054Mont du Sud area (after the geological map available from SIGEOM <http://sigeom.mines.gouv.qc.ca>).  
 1055Sampling of the metamorphic sole was focused on the shore of the Cascapedia River. SSF: South  
 1056Schick-Schock Fault; BBL: Baie Verte-Brompton Line.



1059 Figure 3: Representative geology of the base of the Mont Albert ophiolitic complex. (a) Schematic  
 1060 cross-section, indicating the position of samples presented in this study (diamonds and numbers) and  
 1061 the position of fields photographs underneath (letters). (b) Large-scale view from the summit of Mont  
 1062 Olivine of the north-east ridge of Mont Albert, with peridotite on the left (brass colour) and

1063 amphibolite on the right (dark grey). The contact is partly hidden by vegetation and grey boulders  
1064 (dotted line). (c) Typical aspect of the peridotite away from the contact. (d) Serpentinite unit at the  
1065 base of the peridotite, with oxide-rich layers, north-east of the summit of Mont Albert. (e) The  
1066 peridotite / amphibolite contact as found on top of Mont Albert. (f) Typical aspect of the high-grade  
1067 garnet-clinopyroxene amphibolite. (g) Garnet-rich layer (left of hammer head) alternating with albite-  
1068 epidote rich layers (top of image) in the high-grade amphibolite. (h) View of a 'sill' (bounded by  
1069 orange dashes) along the north-east arête of Mont Albert, with quartz-plagioclase-hornblende in the  
1070 centre and quartz-mica-gedrite on the margins (samples MA-14-48-49 on Fig. 2b and 6j). Foliation is  
1071 subparallel to the intrusion. (i) Garnet-bearing metapelites along the 'Marches du Géant' normal fault  
1072 system,  $\geq 40$  m away from the contact with the peridotite (near sample MA-14-50, Fig. 2b, 6a). (j), (k)  
1073 and (l) are typical outcrops of the low-grade amphibolite. Deformation is highlighted by quartz-albite-  
1074 epidote assemblages found in shear zones, as layers, veinlets and around deformed pillows  
1075 (highlighted in k). (j): west of summit of Mont Albert, near sample MA-14-19 (Fig. 2b and 5c). (k):  
1076 south of Mont Albert (near sample MA-14-46, Fig. 2b). (l) south-west of Mont du Sud near sample  
1077 MA-14-24 (Fig. 2c).

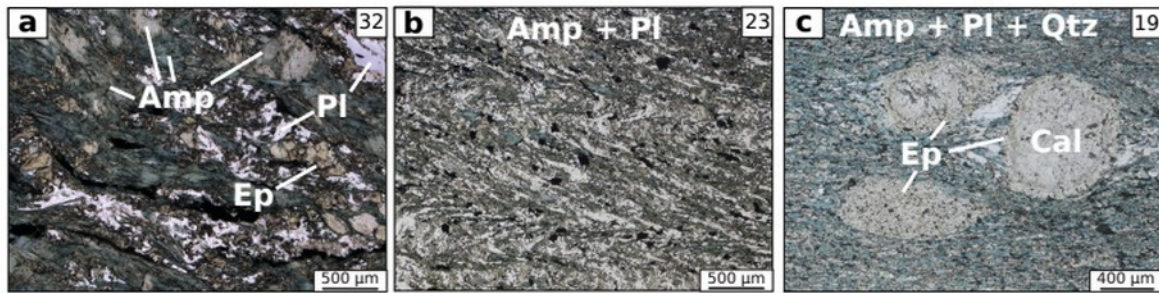
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1080 Figure 4: Typical aspect of high-grade amphibolite, with thin sections scans, microphotographs and  
 1081 SEM images. (a) Clinopyroxene-rich amphibolite, without garnet. Foliation is roughly horizontal.  
 1082 Amphibole varies from deep to paler green. Clinopyroxene (pale green, paler than amphibole) is often  
 1083 found forming layers where large, fractured and deformed clinopyroxene crystals are surrounded by  
 1084 smaller clinopyroxene crystals and plagioclase (translucent). (b) Garnet-clinopyroxene-epidote  
 1085 amphibolite. Foliation is subvertical. (c-d-e) close-up microphotographs of sample MA-14-38,  
 1086 showing ~500 µm anhedral garnet crystals and aggregated smaller (100-200 µm) euhedral garnet  
 1087 crystals, both often with symplectitic rim (e). Epidote is a crystallisation product in the symplectite.  
 1088 Clinopyroxene is found as ≥1mm crystals and as ~100µm crystals growing with amphibole. (e)  
 1089 Clinopyroxene-amphibole symplectite. (f) Plagioclase-garnet-amphibole symplectite with minor  
 1090 clinopyroxene. (g): sample MA-14-35; garnet rims with symplectite texture, retrogressed plagioclase  
 1091 and Fe-Ti oxides. (h-i) close-up views of phases associated with retrogressed plagioclase within the  
 1092 symplectite (note the texture of garnet, see also Fig. 7c). Plagioclase is preserved associated to epidote,

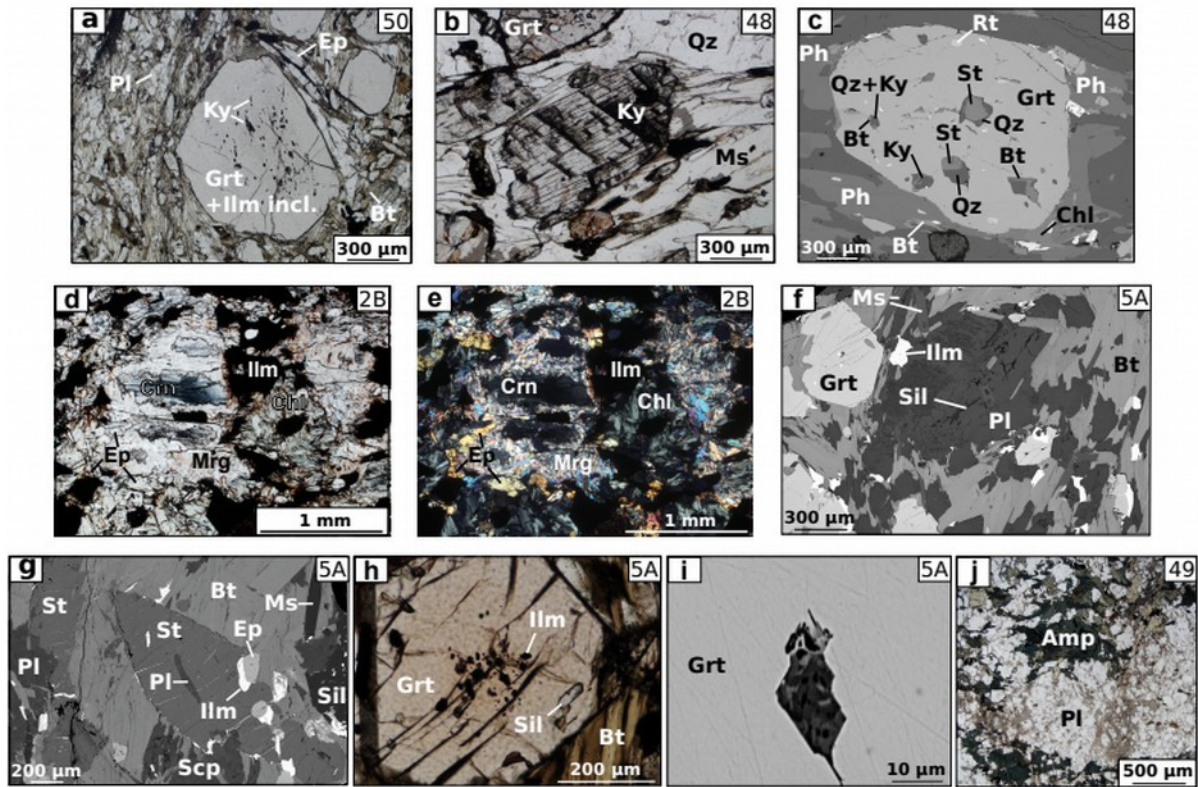
1093 and replaced by very fine epidote-muscovite intergrowths. Margarite, chlorite, sulfides and natrolite  
1094 appear as later alteration products.

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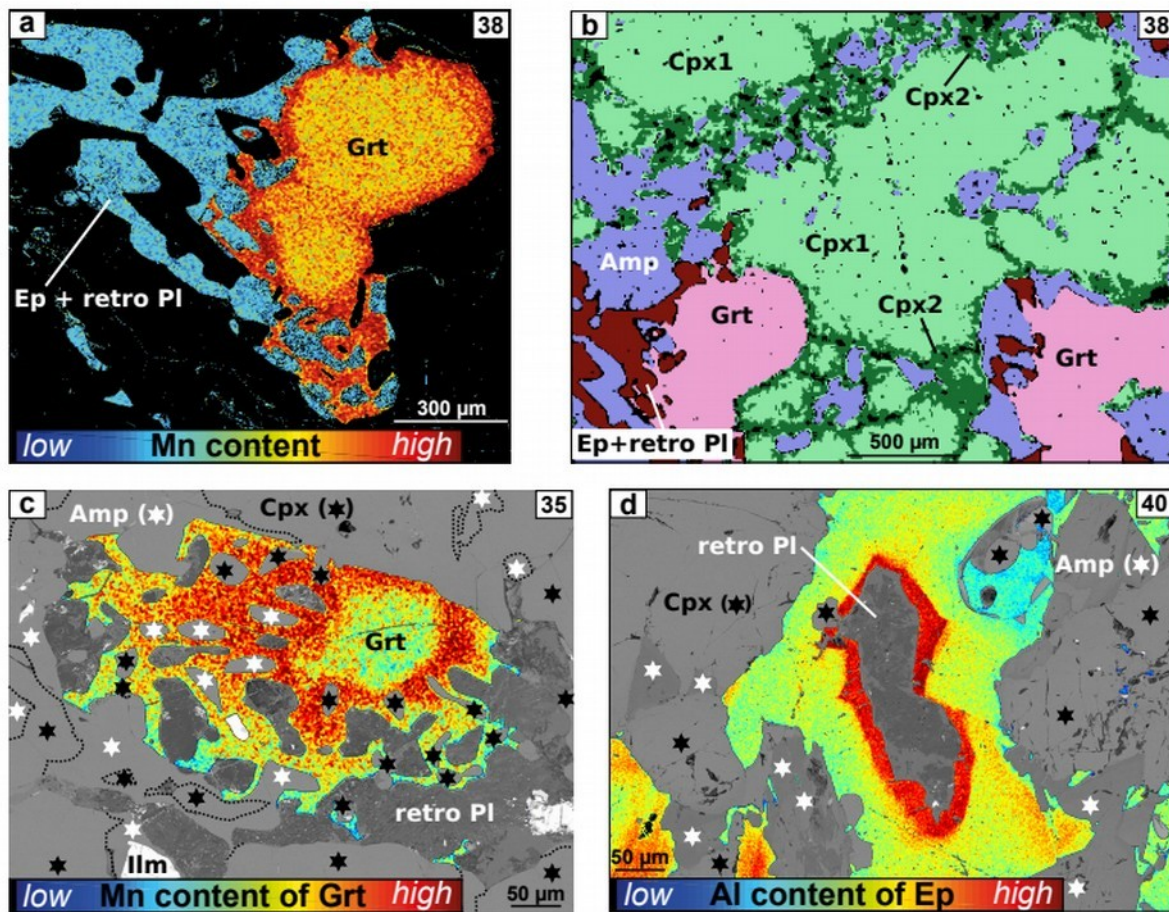
1097 Figure 5: Selected thin section microphotographs of the low-grade amphibolite. (a) Plagioclase-  
 1098 epidote amphibolite where amphibole shows pale green cores and darker blue-green rims. (b) Incipient  
 1099 crenulation cleavage in schistose amphibolite, as typically found along the Cascapedia river. (c)  
 1100 Calcite-epidote filled spherulites in amphibolite, with quartz and albite. Foliation is horizontal.



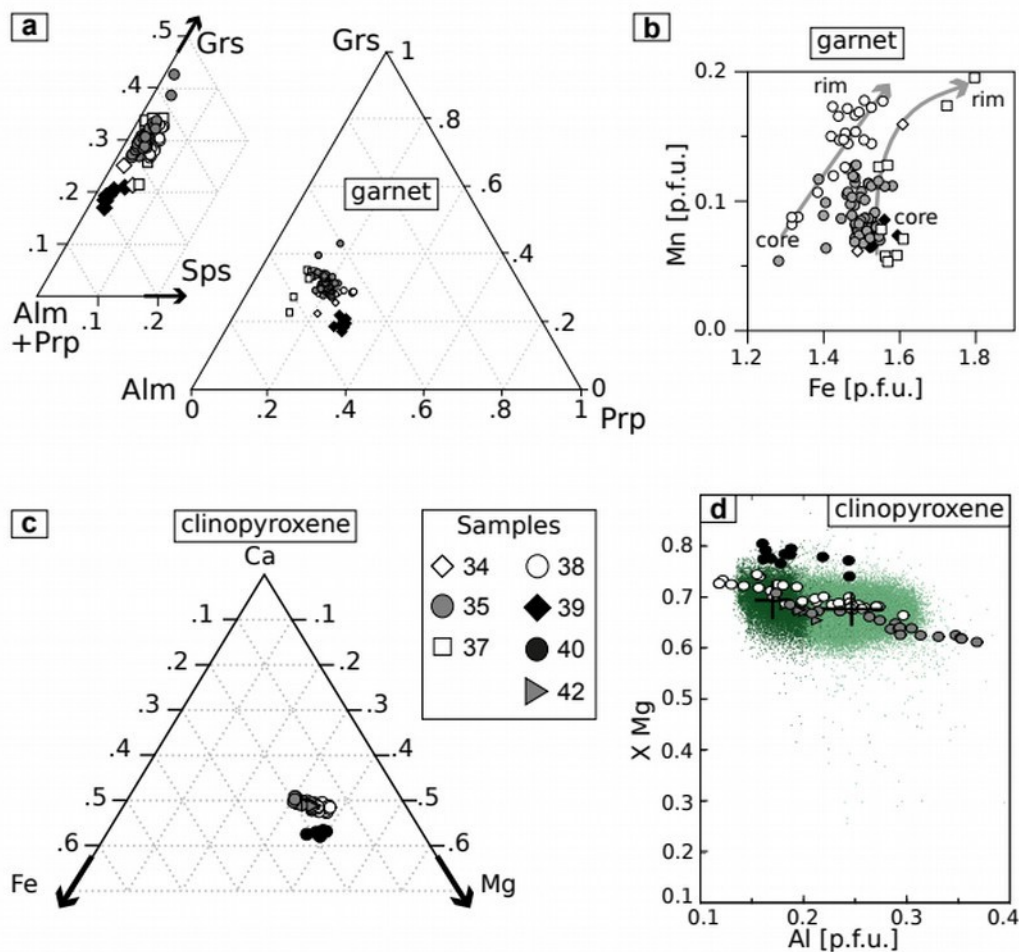


1103 Figure 6: Representative mineralogy of metapelites and associated rocks found in the metamorphic  
 1104 sole of Mont Albert. (a) Garnet-kyanite-biotite-plagioclase metapelite (see Fig. 3i). (b) Kyanite is  
 1105 found as a porphyroclast and included in garnet (SEM image c). Garnet also includes staurolite,  
 1106 biotite, quartz and rutile (c). (d – plane-polarized light) and (e – crossed polars) show  
 1107 microphotographs of corundum-epidote-ilmenite assemblage in red oxide-rich layers, retrogressed to  
 1108 margarite, chlorite, paragonite and diaspore (both too small to show on micrograph). (f-g-h-i) SEM  
 1109 images and microphotographs of sample MA-15-05A, found ~20 m away from the peridotite.  
 1110 Sillimanite is observed as abundant needles in plagioclase (f) and in prismatic form associated with  
 1111 scapolite and staurolite (g). These are both in the foliation and cross-cutting the foliation as in (g). (h)  
 1112 and (i) show inclusions in garnet from biotite-rich layers, with oxides in the core and sillimanite in the  
 1113 rim. SEM revealed that some inclusions have negative crystal shape and contain polycrystalline  
 1114 silicates (too small for determination) together with apparent porosity. (j) Texture of the retrogressed  
 1115 sill with millimetre-scale plagioclase and amphibole.

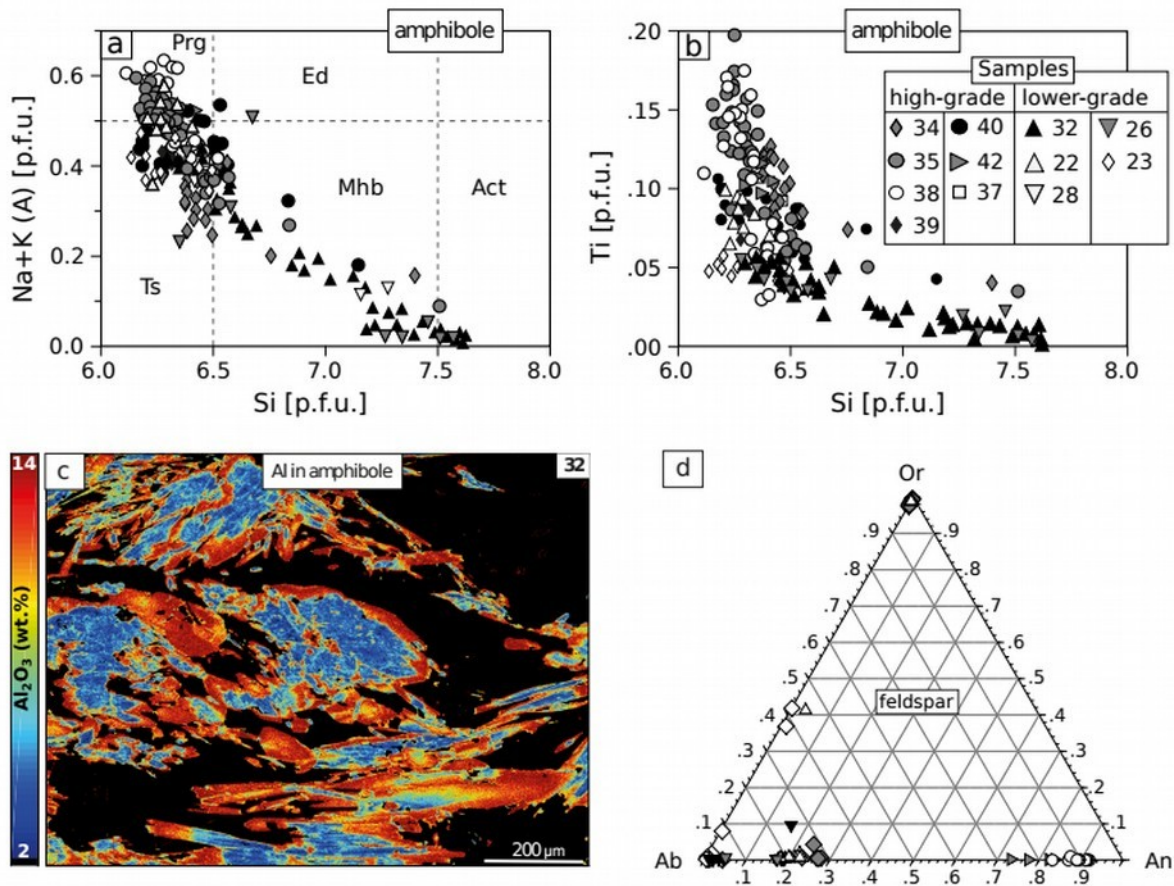




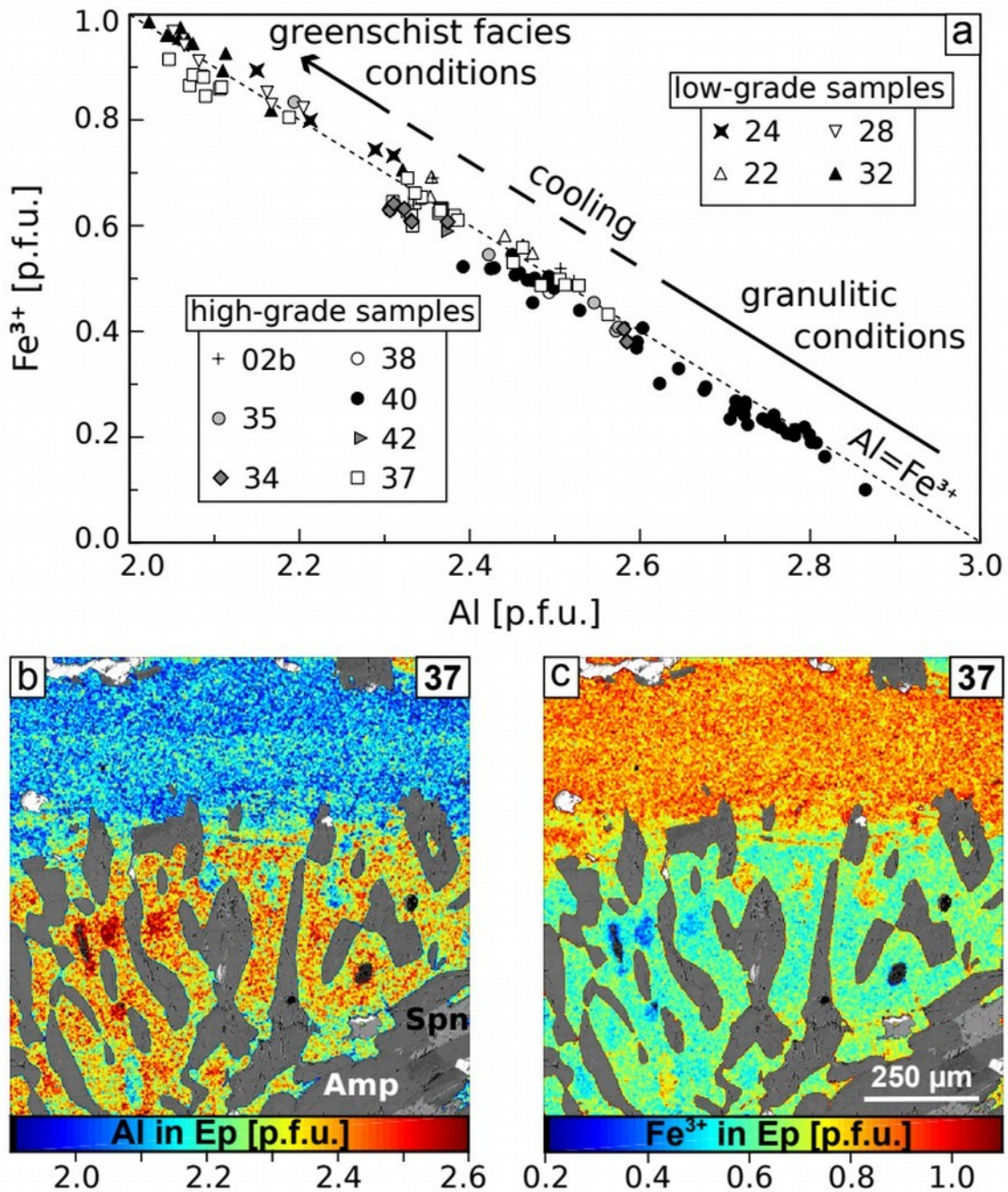
1118 Figure 7: Texture and composition of minerals associated with the garnet-amphibole-clinopyroxene  
 1119 symplectite. (a) and (b) Mineral assemblage and Mn content in sample MA-14-38. The symplectic  
 1120 garnet rim has high Mn, and is intimately associated to retrogressed plagioclase and epidote. Two  
 1121 generations of clinopyroxene are unambiguously evidenced from their Al content (see corresponding  
 1122 compositions in Fig. 8d). (c) Mn content of garnet over SEM image of texture of symplectite in  
 1123 sample MA-14-35. Garnet is associated with amphibole, clinopyroxene, oxide and retrogressed  
 1124 plagioclase (labelled “retro Pl”). Clinopyroxene and amphibole, hard to distinguish on SEM images,  
 1125 are labelled with black and white stars respectively, and contoured with dotted lines. (d) Al content of  
 1126 epidote over SEM image of epidote crystallised around retrogressed plagioclase. Clinopyroxene and  
 1127 amphibole are intergrown on each side of the image and labelled as in (c).



1130 Figure 8: composition of garnet and clinopyroxene from the mafic rocks. (a) and (b) show garnet  
 1131 composition, plotted with and without the spessartine component in (b). Arrows in (b) emphasize the  
 1132 increase in Mn in the symplectite rimming garnet cores (see also Fig. 7a-c), mostly at the expense of  
 1133 Fe. (c) and (d) show clinopyroxene composition, from point EPMA measurements as circles and from  
 1134 EPMA mapping as small dots coloured according to their Al content, corresponding to CPX1 (Al-rich  
 1135 cores) and CPX2 (Al-poor rims) in Fig. 7b (sample MA-14-38). Crosses in (d) indicate average  
 1136 composition and 2-sigma standard deviation of each clinopyroxene generation measured on the area of  
 1137 Fig. 7b.



1140Figure 9: Composition of amphibole and feldspar in high-grade and lower-grade mafic rocks of the  
 1141metamorphic sole of Mont Albert. (a) Alkali content of the A site of amphibole versus Si content,  
 1142linked to Ti content (b). Samples close to the contact with the peridotite have highest alkali and Ti. (c)  
 1143Al content of amphibole in sample MA-14-32 (top of lower-grade unit along the Cascapedia river)  
 1144showing actinolite-rich cores and pargasite-rich rims, measured with SEM. Numbers on the left-hand  
 1145side colour scale indicate concentration as obtained from EPMA point analysis. (d) Composition of  
 1146feldspar.



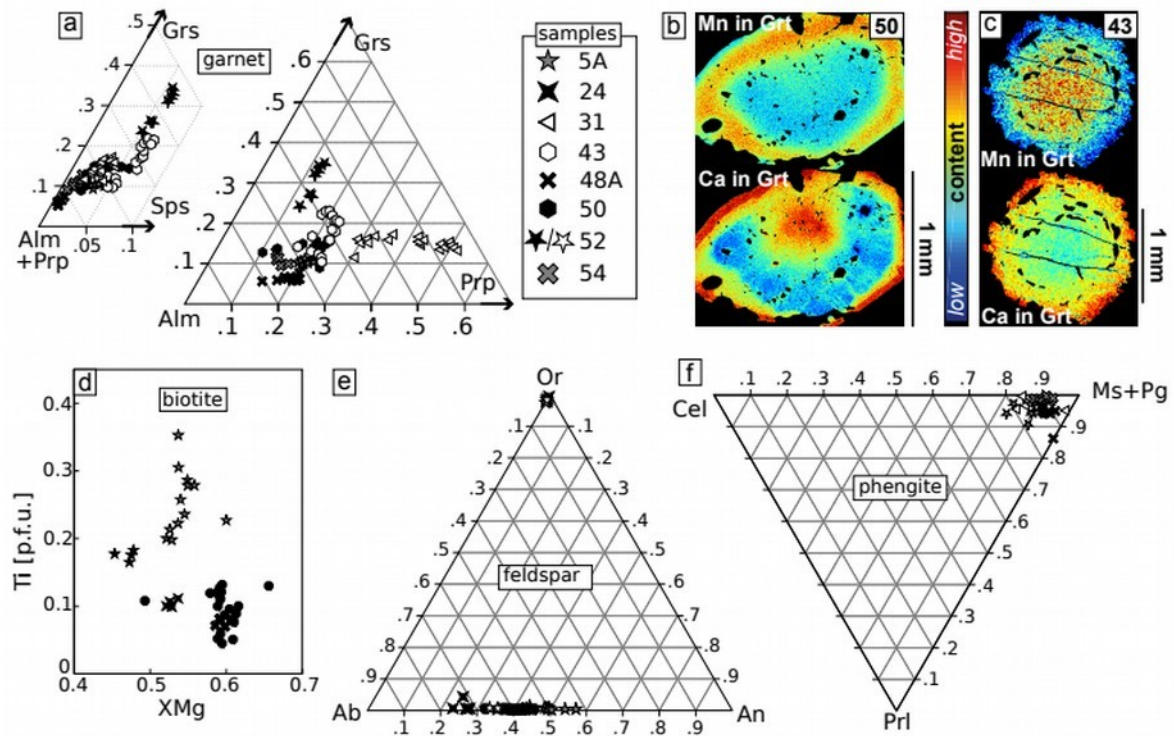
1149 Figure 10: Composition of epidote in high-grade and lower-grade mafic rocks of the metamorphic sole  
 1150 of Mont Albert. (a) Compilation of analyses showing Fe<sup>3+</sup> content versus Al content. (b) and (c) show  
 1151 map views of Al and Fe<sup>3+</sup> content of epidote in sample MA-14-37, laid over a back-scattered electron  
 1152 EPMA image of an amphibole-epidote symplectite cross-cut by an epidote vein (horizontal, on top).

1153  $\text{Fe}^{3+}$ -rich epidote is found in the vein, Al-rich epidote in the symplectite, with the cores of symplectite

1154 crystals being richest in Al.

1155

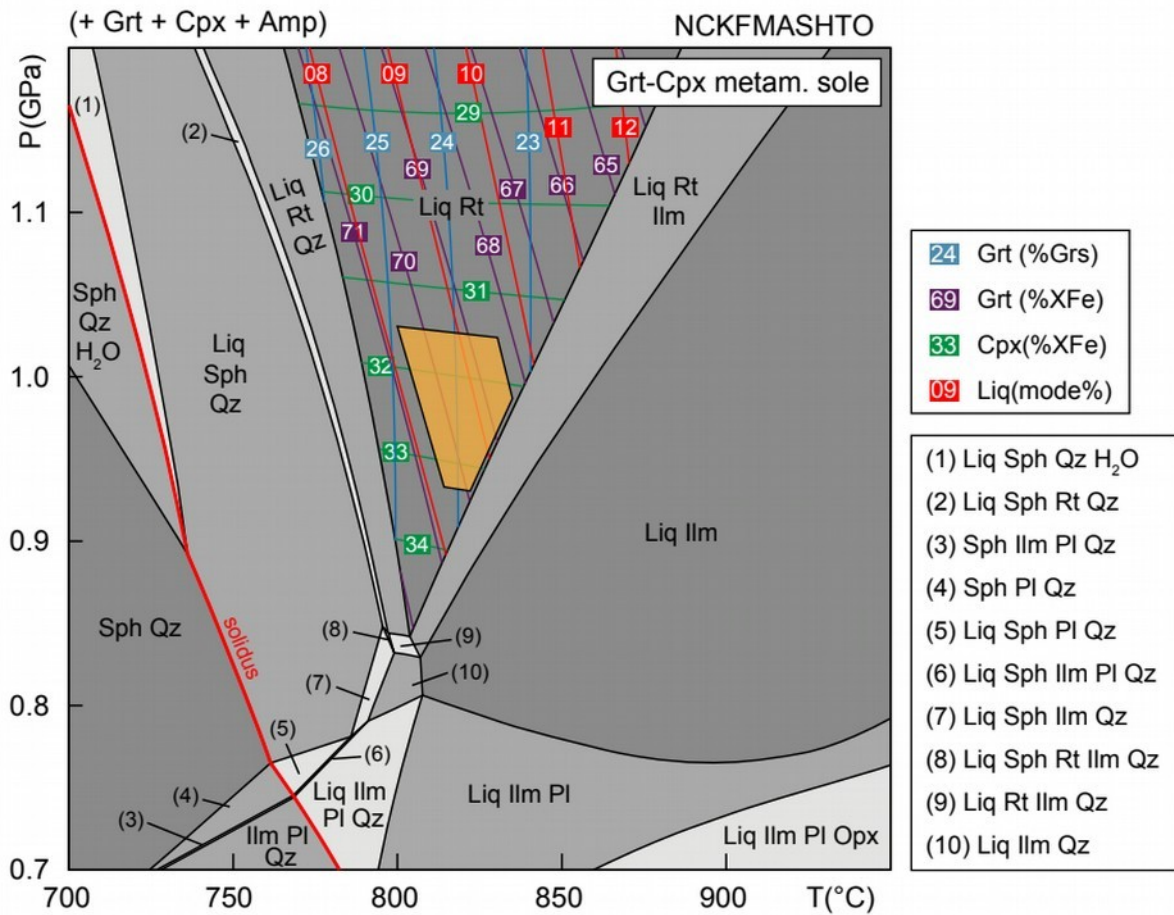
1156



1157Figure 11: Composition of minerals in metasediments from the metamorphic sole of the Mont Albert  
1158complex. (a) Garnet composition, plotted with and without the spessartine component. Zoning in  
1159garnet is shown as measured with SEM for Ca and Mn in high-grade samples in (b) and (c), all scaled  
1160on the colourbar in b. (d) Ti content versus XMg of biotite. (e) Composition of feldspar. (f)  
1161Composition of phengite.

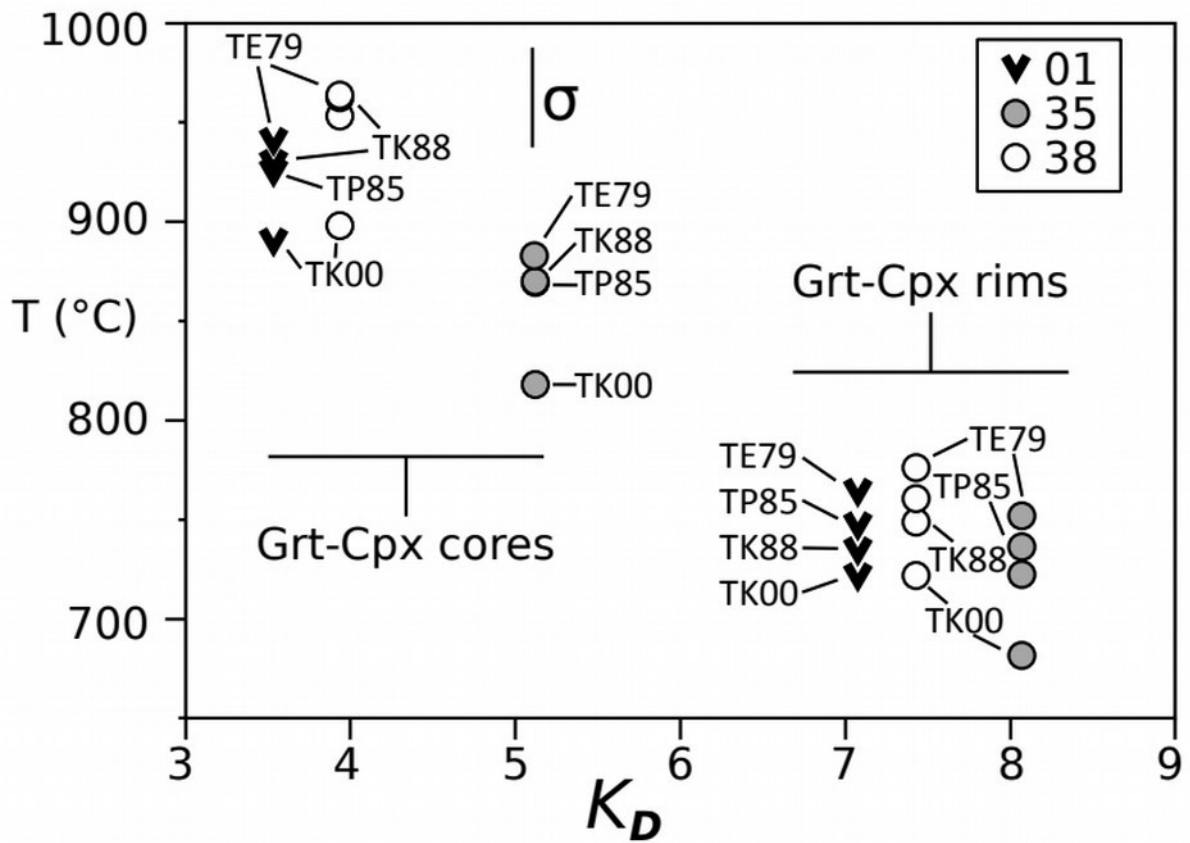
1162



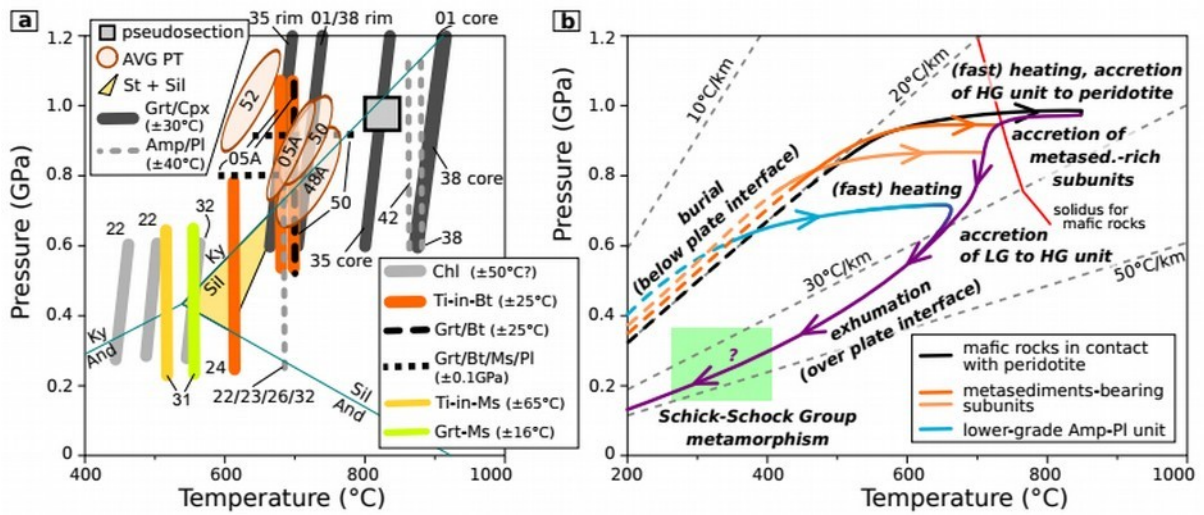


1164 Figure 12: pressure-temperature pseudosection in NCKFMASHTO for a mafic rock representative of  
 1165 the garnet-bearing high-grade unit. Garnet, clinopyroxene and amphibole are present throughout the  
 1166 pseudosection. The solidus is drawn with a red line and isopleths are shown for garnet, clinopyroxene  
 1167 and melt fraction as discussed in the text. The orange field highlights pressure-temperature conditions  
 1168 matching the petrography.

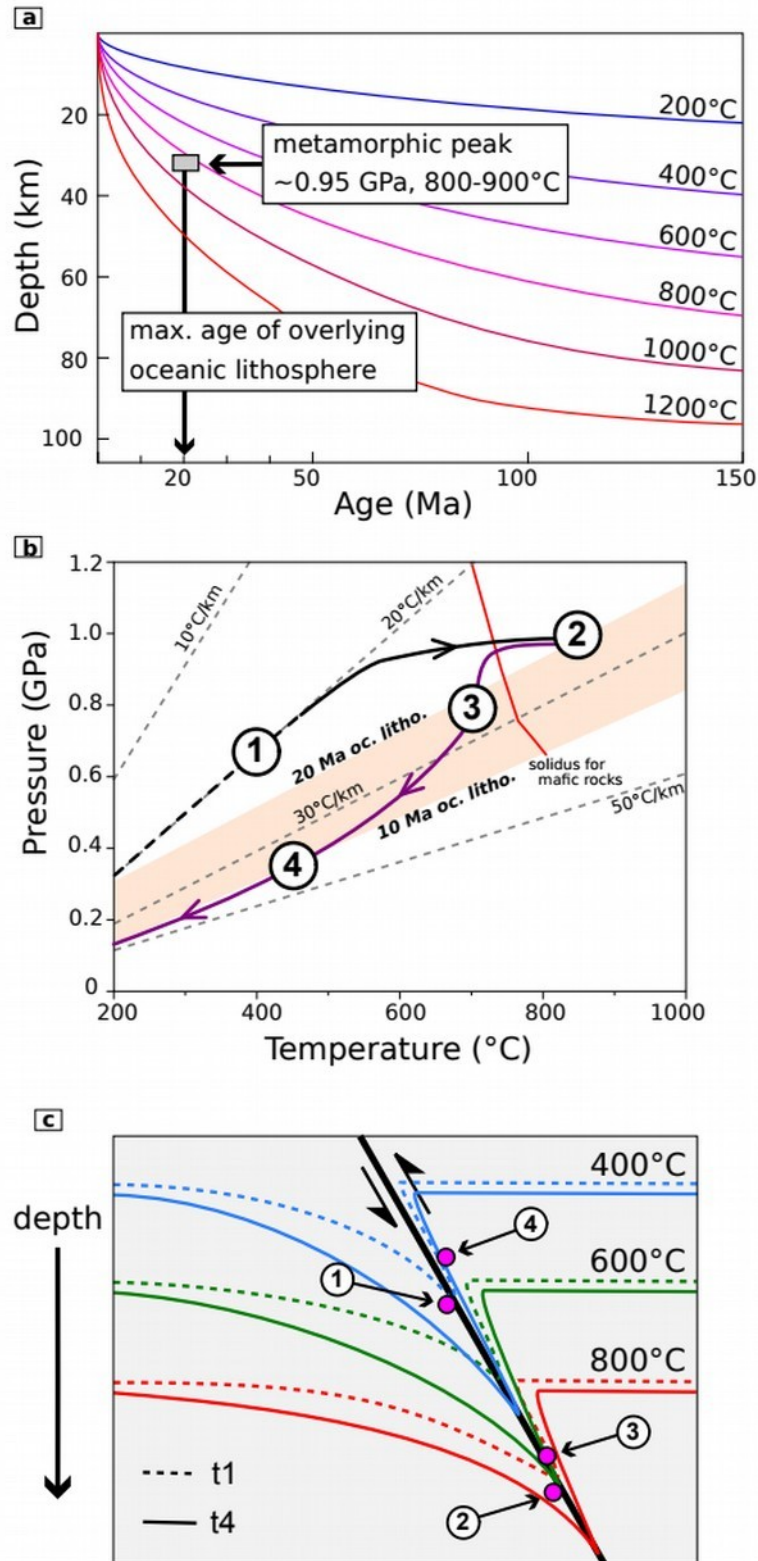
1169



1171 Figure 13: Results of garnet-clinopyroxene thermometry, calculated at fixed pressure of 0.95 GPa  
 1172 using the calibrations of Ellis and Green (1979, TE79), Powell (1985, TP85), Krogh Ravna (1988,  
 1173 TK88 ; 2000, TK00). Uncertainties on temperature estimates are consistently of the order of 50°C,  
 1174 including ~10°C uncertainty originating from pressure estimates.



1177Figure 14: Compilation of thermobarometric estimates obtained in this study and inferred pressure-  
 1178temperature paths. (a) Thermobarometry results for mafic rocks (grey shades) and metasediments  
 1179(orange / green), reported as envelopes for AVG-PT, a box for results from the pseudosection (Fig.  
 118011), and sticks for chlorite thermometry, empirical pair equilibria and Ti solubility. Stability of  
 1181alumina-silicates from White et al. (2014a). (b) Pressure-temperature paths of subunits from the  
 1182metamorphic sole, leading to an apparent inverted metamorphic gradient. Rocks on top of the  
 1183metamorphic sole are subject to higher peak conditions than rocks structurally further from the contact  
 1184to the peridotite. All rocks all exhumed along the same path. The total number of subunits is unknown  
 1185and shown as three subunits with the higher-grade unit for readability. Note the different temperature  
 1186scales in (a) and (b).



1189Figure 15: estimate of the evolution of the thermal structure of the lithosphere during metamorphic  
1190sole creation. (a) Peak metamorphic conditions compared to temperature-depth profile of the oceanic

1191lithosphere as a function of age (from McKenzie et al., 2005). (b) Pressure-temperature evolution of  
1192the high-grade unit, with four steps constraining the temperature evolution close to the interface, as  
1193schematized in (c), where the plate boundary is sketched in black and isotherms are shown for step 1  
1194( $t_1$ , dotted line) and step 4 ( $t_4$ , solid line).

**Table 1. Selected representative analyses of amphibole**

| Unit<br>Sample                 | High Grade Unit |          |          |          |          |          | MA-12-22 | MA-14-23 |
|--------------------------------|-----------------|----------|----------|----------|----------|----------|----------|----------|
|                                | MA-14-34        | MA-14-35 | MA-14-38 | MA-14-39 | MA-14-40 | MA-14-42 |          |          |
| Analysis #                     | 46              | 13       | 111      | 10       | 125      | 140      | 114      | 30       |
| SiO <sub>2</sub>               | 43,09           | 41,67    | 44,21    | 42,92    | 43,30    | 42,77    | 42,36    | 41,35    |
| TiO <sub>2</sub>               | 0,81            | 1,51     | 0,73     | 0,79     | 0,84     | 1,03     | 0,89     | 0,50     |
| Al <sub>2</sub> O <sub>3</sub> | 12,07           | 13,85    | 12,38    | 14,19    | 13,72    | 12,74    | 14,12    | 12,88    |
| Cr <sub>2</sub> O <sub>3</sub> | 0,05            | 0,01     | 0,10     | 0,04     | 0,56     | 0,04     | 0,08     | 0,09     |
| FeO                            | 15,19           | 14,74    | 13,47    | 12,49    | 9,60     | 15,32    | 15,85    | 19,63    |
| MnO                            | 0,24            | 0,06     | 0,14     | 0,07     | 0,40     | 0,21     | 0,28     | 0,43     |
| MgO                            | 10,70           | 10,51    | 11,82    | 11,77    | 12,85    | 10,52    | 10,37    | 8,68     |
| CaO                            | 11,58           | 11,84    | 11,67    | 11,86    | 12,27    | 11,61    | 11,21    | 10,89    |
| Na <sub>2</sub> O              | 1,84            | 1,92     | 1,73     | 1,49     | 1,76     | 1,91     | 2,02     | 1,79     |
| K <sub>2</sub> O               | 0,26            | 0,30     | 0,21     | 0,72     | 0,40     | 0,43     | 0,92     | 0,52     |
| Σ                              | 95,84           | 96,42    | 96,46    | 96,37    | 95,71    | 96,59    | 98,10    | 96,74    |
| Ox.                            | 23              | 23       | 23       | 23       | 23       | 23       | 23       | 23       |
| Si                             | 6,45            | 6,21     | 6,50     | 6,32     | 6,39     | 6,37     | 6,21     | 6,20     |
| Aliv                           | 1,55            | 1,79     | 1,50     | 1,68     | 1,61     | 1,63     | 1,79     | 1,80     |
| Alvi                           | 0,58            | 0,65     | 0,64     | 0,78     | 0,78     | 0,61     | 0,65     | 0,48     |
| Ti                             | 0,09            | 0,17     | 0,08     | 0,09     | 0,09     | 0,12     | 0,10     | 0,06     |
| Cr                             | 0,01            | 0,00     | 0,01     | 0,00     | 0,07     | 0,01     | 0,01     | 0,01     |
| Fe <sup>3+</sup>               | 0,48            | 0,40     | 0,47     | 0,42     | 0,12     | 0,44     | 0,67     | 1,08     |
| Fe <sup>2+</sup>               | 1,43            | 1,44     | 1,19     | 1,11     | 1,07     | 1,47     | 1,27     | 1,38     |
| Mn                             | 0,03            | 0,01     | 0,02     | 0,01     | 0,05     | 0,03     | 0,04     | 0,05     |
| Mg                             | 2,39            | 2,34     | 2,59     | 2,58     | 2,83     | 2,34     | 2,27     | 1,94     |
| Ca                             | 1,86            | 1,89     | 1,84     | 1,87     | 1,94     | 1,85     | 1,76     | 1,75     |
| Na                             | 0,53            | 0,56     | 0,49     | 0,43     | 0,50     | 0,55     | 0,57     | 0,52     |
| K                              | 0,05            | 0,06     | 0,04     | 0,14     | 0,08     | 0,08     | 0,17     | 0,10     |
| Σ cat.                         | 15,44           | 15,50    | 15,37    | 15,43    | 15,52    | 15,49    | 15,51    | 15,37    |
| [Na+K] <sup>A</sup>            | 0,44            | 0,50     | 0,37     | 0,43     | 0,52     | 0,49     | 0,51     | 0,37     |
| XMg                            | 0,63            | 0,62     | 0,69     | 0,70     | 0,73     | 0,61     | 0,64     | 0,58     |

Low Grade Unit

| MA-14-26 |       | MA-14-28 |       | MA-14-32 |       |
|----------|-------|----------|-------|----------|-------|
| 88       | 78    | 61       | 56    | 127      | 125,1 |
| 42,58    | 52,68 | 43,36    | 50,68 | 43,61    | 53,47 |
| 0,50     | 0,07  | 0,54     | 0,16  | 0,47     | 0,12  |
| 12,70    | 3,20  | 11,48    | 5,42  | 12,81    | 3,25  |
| 0,05     | 0,00  | 0,03     | 0,04  | 0,01     | 0,00  |
| 16,84    | 11,73 | 17,81    | 13,06 | 16,29    | 11,90 |
| 0,36     | 0,24  | 0,26     | 0,25  | 0,27     | 0,34  |
| 10,65    | 16,53 | 10,33    | 14,86 | 10,70    | 15,97 |
| 10,91    | 11,70 | 11,01    | 12,07 | 11,17    | 11,65 |
| 2,03     | 0,66  | 2,00     | 0,90  | 2,03     | 0,74  |
| 0,37     | 0,11  | 0,26     | 0,12  | 0,38     | 0,14  |
| 97,01    | 96,90 | 97,07    | 97,55 | 97,74    | 97,59 |
| 23       | 23    | 23       | 23    | 23       | 23    |
| 6,27     | 7,51  | 6,42     | 7,28  | 6,38     | 7,60  |
| 1,73     | 0,49  | 1,58     | 0,72  | 1,62     | 0,40  |
| 0,48     | 0,05  | 0,42     | 0,20  | 0,59     | 0,15  |
| 0,06     | 0,01  | 0,06     | 0,02  | 0,05     | 0,01  |
| 0,01     | 0,00  | 0,00     | 0,00  | 0,00     | 0,00  |
| 1,03     | 0,65  | 0,92     | 0,50  | 0,78     | 0,45  |
| 1,04     | 0,75  | 1,28     | 1,07  | 1,22     | 0,96  |
| 0,05     | 0,03  | 0,03     | 0,03  | 0,03     | 0,04  |
| 2,34     | 3,52  | 2,28     | 3,18  | 2,33     | 3,39  |
| 1,72     | 1,79  | 1,75     | 1,86  | 1,75     | 1,77  |
| 0,58     | 0,18  | 0,57     | 0,25  | 0,58     | 0,20  |
| 0,07     | 0,02  | 0,05     | 0,02  | 0,07     | 0,03  |
| 15,37    | 14,99 | 15,37    | 15,13 | 15,40    | 15,00 |
| 0,37     | 0,02  | 0,37     | 0,13  | 0,40     | 0,03  |
| 0,69     | 0,82  | 0,64     | 0,75  | 0,66     | 0,78  |

**Table 2. Selected representative analyses of clinopyroxene.**

| Unit<br>Sample                 | High Grade Unit |       |       |          |       |       |          |          |       |
|--------------------------------|-----------------|-------|-------|----------|-------|-------|----------|----------|-------|
|                                | MA-14-35        |       |       | MA-14-38 |       |       | MA-14-40 | MA-14-42 |       |
| Analysis #                     | 23              | 30    | 41    | 80       | 84    | 100   | 102      | 111      | 135   |
| SiO <sub>2</sub>               | 47,70           | 50,37 | 47,82 | 48,35    | 50,39 | 51,40 | 51,30    | 51,12    | 50,09 |
| TiO <sub>2</sub>               | 0,50            | 0,37  | 0,62  | 0,55     | 0,27  | 0,07  | 0,13     | 0,25     | 0,34  |
| Al <sub>2</sub> O <sub>3</sub> | 6,92            | 3,96  | 6,80  | 6,61     | 4,08  | 3,54  | 3,94     | 4,11     | 4,43  |
| Cr <sub>2</sub> O <sub>3</sub> | 0,04            | 0,11  | 0,01  | 0,26     | 0,17  | 0,07  | 0,08     | 0,07     | 0,01  |
| FeO                            | 10,66           | 8,77  | 10,68 | 9,53     | 9,58  | 8,00  | 8,55     | 6,63     | 9,76  |
| MnO                            | 0,18            | 0,15  | 0,20  | 0,17     | 0,22  | 0,26  | 0,24     | 0,54     | 0,28  |
| MgO                            | 9,89            | 12,15 | 10,50 | 10,43    | 11,64 | 12,51 | 12,35    | 13,04    | 11,05 |
| CaO                            | 22,03           | 23,10 | 22,65 | 22,42    | 22,79 | 23,14 | 22,75    | 23,20    | 22,74 |
| Na <sub>2</sub> O              | 0,76            | 0,62  | 0,62  | 0,79     | 0,60  | 0,54  | 0,62     | 0,72     | 0,76  |
| K <sub>2</sub> O               | 0,02            | 0,00  | 0,00  | 0,00     | 0,01  | 0,01  | 0,00     | 0,01     | 0,01  |
| Σ                              | 98,69           | 99,61 | 99,91 | 99,12    | 99,76 | 99,54 | 99,95    | 99,68    | 99,47 |
| Ox.                            | 6               | 6     | 6     | 6        | 6     | 6     | 6        | 6        | 6     |
| Si                             | 1,83            | 1,90  | 1,81  | 1,84     | 1,90  | 1,93  | 1,92     | 1,91     | 1,90  |
| Ti                             | 0,01            | 0,01  | 0,02  | 0,02     | 0,01  | 0,00  | 0,00     | 0,01     | 0,01  |
| Al <sub>tot</sub>              | 0,31            | 0,18  | 0,30  | 0,30     | 0,18  | 0,16  | 0,17     | 0,18     | 0,20  |
| Cr                             | 0,00            | 0,00  | 0,00  | 0,01     | 0,00  | 0,00  | 0,00     | 0,00     | 0,00  |
| Fe <sub>tot</sub>              | 0,34            | 0,28  | 0,34  | 0,30     | 0,30  | 0,25  | 0,27     | 0,21     | 0,31  |
| Mn                             | 0,01            | 0,00  | 0,01  | 0,01     | 0,01  | 0,01  | 0,01     | 0,02     | 0,01  |
| Mg                             | 0,56            | 0,68  | 0,59  | 0,59     | 0,65  | 0,70  | 0,69     | 0,72     | 0,62  |
| Ca                             | 0,90            | 0,93  | 0,92  | 0,91     | 0,92  | 0,93  | 0,91     | 0,93     | 0,92  |
| Na                             | 0,06            | 0,05  | 0,05  | 0,06     | 0,04  | 0,04  | 0,05     | 0,05     | 0,06  |
| K                              | 0,00            | 0,00  | 0,00  | 0,00     | 0,00  | 0,00  | 0,00     | 0,00     | 0,00  |
| Σ cat.                         | 4,03            | 4,03  | 4,04  | 4,03     | 4,02  | 4,01  | 4,01     | 4,02     | 4,02  |
| XMg                            | 0,62            | 0,71  | 0,64  | 0,66     | 0,68  | 0,74  | 0,72     | 0,78     | 0,67  |



**Table 3. Selected representative analyses of feldspar.**

| Mineral                        | Pl              | Pl       | Pl       | Or       | Or       | Pl       | Pl       | Pl       | Pl       |
|--------------------------------|-----------------|----------|----------|----------|----------|----------|----------|----------|----------|
| Unit                           | High Grade Unit |          |          |          |          |          |          |          |          |
| Sample                         | MA-14-34        | MA-14-38 | MA-14-39 | MA-14-40 | MA-14-42 | MA-12-22 | MA-14-23 | MA-14-23 | MA-14-23 |
| Analysis #                     | 60              | 89       | 73       | 12       | 109      | 134      | 104      | 20       | 41       |
| SiO <sub>2</sub>               | 68,87           | 47,26    | 45,71    | 64,39    | 64,74    | 47,21    | 61,96    | 62,61    | 60,42    |
| TiO <sub>2</sub>               | 0,00            | 0,00     | 0,00     | 0,00     | 0,00     | 0,00     | 0,00     | 0,00     | 0,00     |
| Al <sub>2</sub> O <sub>3</sub> | 19,89           | 33,52    | 34,93    | 18,50    | 18,53    | 33,10    | 24,14    | 23,34    | 24,83    |
| Cr <sub>2</sub> O <sub>3</sub> | 0,00            | 0,01     | 0,00     | 0,00     | 0,03     | 0,03     | 0,01     | 0,00     | 0,01     |
| FeO                            | 0,00            | 0,00     | 0,00     | 0,00     | 0,00     | 0,00     | 0,08     | 0,48     | 0,25     |
| MnO                            | 0,00            | 0,00     | 0,00     | 0,00     | 0,00     | 0,00     | 0,00     | 0,00     | 0,00     |
| MgO                            | 0,00            | 0,00     | 0,00     | 0,00     | 0,00     | 0,00     | 0,00     | 0,00     | 0,00     |
| CaO                            | 0,22            | 17,06    | 18,99    | 0,00     | 0,02     | 17,10    | 4,99     | 4,48     | 5,85     |
| Na <sub>2</sub> O              | 11,42           | 1,91     | 0,98     | 0,04     | 0,08     | 1,83     | 9,36     | 9,47     | 8,81     |
| K <sub>2</sub> O               | 0,04            | 0,00     | 0,01     | 16,23    | 15,61    | 0,02     | 0,14     | 0,07     | 0,11     |
| Σ                              | 100,43          | 99,75    | 100,61   | 99,15    | 99,01    | 99,29    | 100,67   | 100,46   | 100,29   |
| Ox.                            | 8               | 8        | 8        | 8        | 8        | 8        | 8        | 8        | 8        |
| Si                             | 2,99            | 2,17     | 2,09     | 2,99     | 3,00     | 2,18     | 2,74     | 2,77     | 2,69     |
| Ti                             | 0,00            | 0,00     | 0,00     | 0,00     | 0,00     | 0,00     | 0,00     | 0,00     | 0,00     |
| Al <sub>tot</sub>              | 1,02            | 1,81     | 1,89     | 1,01     | 1,01     | 1,80     | 1,26     | 1,22     | 1,30     |
| Cr                             | 0,00            | 0,00     | 0,00     | 0,00     | 0,00     | 0,00     | 0,00     | 0,00     | 0,00     |
| Fe <sub>tot</sub>              | 0,00            | 0,00     | 0,00     | 0,00     | 0,00     | 0,00     | 0,00     | 0,00     | 0,00     |
| Mn                             | 0,00            | 0,00     | 0,00     | 0,00     | 0,00     | 0,00     | 0,00     | 0,00     | 0,00     |
| Mg                             | 0,00            | 0,00     | 0,00     | 0,00     | 0,00     | 0,00     | 0,00     | 0,00     | 0,00     |
| Ca                             | 0,01            | 0,84     | 0,93     | 0,00     | 0,00     | 0,85     | 0,24     | 0,21     | 0,28     |
| Na                             | 0,96            | 0,17     | 0,09     | 0,00     | 0,01     | 0,16     | 0,80     | 0,81     | 0,76     |
| K                              | 0,00            | 0,00     | 0,00     | 0,96     | 0,92     | 0,00     | 0,01     | 0,00     | 0,01     |
| Σ cat.                         | 4,98            | 5,00     | 5,00     | 4,98     | 4,95     | 5,00     | 5,04     | 5,02     | 5,04     |
| XAn                            | 0,01            | 0,83     | 0,91     | 0,00     | 0,00     | 0,84     | 0,23     | 0,21     | 0,27     |
| XAb                            | 0,99            | 0,17     | 0,09     | 0,00     | 0,01     | 0,16     | 0,77     | 0,79     | 0,73     |
| XOr                            | 0,00            | 0,00     | 0,00     | 1,00     | 0,99     | 0,00     | 0,01     | 0,00     | 0,01     |

| Or             | Pl       | Pl       | Pl       | Pl     |
|----------------|----------|----------|----------|--------|
| Low Grade Unit |          |          |          |        |
| 14-24          | MA-14-25 | MA-14-26 | MA-14-32 |        |
| 49             | 56       | 86       | 147      | 133    |
| 63,57          | 63,95    | 63,14    | 62,90    | 68,37  |
| 0,00           | 0,00     | 0,00     | 0,00     | 0,00   |
| 18,19          | 23,14    | 22,71    | 24,04    | 20,58  |
| 0,01           | 0,00     | 0,00     | 0,00     | 0,02   |
| 0,18           | 0,17     | 0,31     | 0,27     | 0,31   |
| 0,00           | 0,00     | 0,00     | 0,00     | 0,00   |
| 0,00           | 0,00     | 0,00     | 0,00     | 0,00   |
| 0,00           | 4,16     | 3,92     | 5,00     | 0,74   |
| 0,20           | 10,13    | 10,24    | 9,33     | 11,82  |
| 16,85          | 0,09     | 0,05     | 0,07     | 0,05   |
| 99,00          | 101,63   | 100,36   | 101,60   | 101,89 |
| 8              | 8        | 8        | 8        | 8      |
| 2,98           | 2,79     | 2,79     | 2,75     | 2,95   |
| 0,00           | 0,00     | 0,00     | 0,00     | 0,00   |
| 1,01           | 1,19     | 1,18     | 1,24     | 1,04   |
| 0,00           | 0,00     | 0,00     | 0,00     | 0,00   |
| 0,00           | 0,00     | 0,00     | 0,00     | 0,00   |
| 0,00           | 0,00     | 0,00     | 0,00     | 0,00   |
| 0,00           | 0,00     | 0,00     | 0,00     | 0,00   |
| 0,00           | 0,19     | 0,19     | 0,23     | 0,03   |
| 0,02           | 0,86     | 0,88     | 0,79     | 0,99   |
| 1,01           | 0,00     | 0,00     | 0,00     | 0,00   |
| 5,02           | 5,04     | 5,05     | 5,02     | 5,02   |
| 0,00           | 0,18     | 0,17     | 0,23     | 0,03   |
| 0,02           | 0,81     | 0,82     | 0,77     | 0,96   |
| 0,98           | 0,00     | 0,00     | 0,00     | 0,00   |

**Table 4. Selected representative analyses of micas**

| Min.                           | Bt               | Ms       | Ms    | Bt           | Bt    | Ms    | Bt       | Ms    |
|--------------------------------|------------------|----------|-------|--------------|-------|-------|----------|-------|
| Loc.                           | Lower Grade Unit |          |       | Metasediment |       |       |          |       |
| Smpl.                          | MA-14-24         | MA-14-31 |       | MA-14-05a    |       |       | MA-14-50 |       |
| Anal.                          | 37               | 8        | 9     | 16           | 36    | 34    | 74       | 80    |
| SiO <sub>2</sub>               | 36,14            | 46,20    | 45,59 | 34,62        | 35,43 | 48,14 | 37,04    | 45,83 |
| TiO <sub>2</sub>               | 1,94             | 0,26     | 0,24  | 3,03         | 2,53  | 0,00  | 2,36     | 0,27  |
| Al <sub>2</sub> O <sub>3</sub> | 17,80            | 31,83    | 33,46 | 18,60        | 19,07 | 34,52 | 18,20    | 33,87 |
| Cr <sub>2</sub> O <sub>3</sub> | 0,01             | 0,02     | 0,02  | 0,03         | 0,05  | 0,00  | 0,09     | 0,00  |
| FeO                            | 17,25            | 3,10     | 3,35  | 16,17        | 16,79 | 1,32  | 15,54    | 2,99  |
| MnO                            | 0,20             | 0,05     | 0,00  | 0,06         | 0,08  | 0,04  | 0,10     | 0,01  |
| MgO                            | 11,21            | 1,28     | 0,96  | 10,52        | 11,46 | 0,31  | 12,80    | 1,05  |
| CaO                            | 0,01             | 0,06     | 0,02  | 0,07         | 0,00  | 0,50  | 0,09     | 0,00  |
| Na <sub>2</sub> O              | 0,10             | 1,14     | 1,16  | 0,30         | 0,25  | 1,03  | 0,16     | 1,13  |
| K <sub>2</sub> O               | 9,67             | 9,75     | 9,71  | 8,99         | 9,35  | 9,20  | 8,89     | 9,58  |
| Σ                              | 94,33            | 93,68    | 94,50 | 92,41        | 95,01 | 95,07 | 95,27    | 94,74 |
| Ox.                            | 22               | 11       | 11    | 22           | 22    | 11    | 22       | 22    |
| Si                             | 5,51             | 3,16     | 3,09  | 5,36         | 5,34  | 3,18  | 5,51     | 3,09  |
| Ti                             | 0,22             | 0,01     | 0,01  | 0,35         | 0,29  | 0,00  | 0,26     | 0,01  |
| Al <sub>tot</sub>              | 3,20             | 2,56     | 2,67  | 3,39         | 3,39  | 2,69  | 3,19     | 2,69  |
| Cr                             | 0,00             | 0,00     | 0,00  | 0,00         | 0,01  | 0,00  | 0,01     | 0,00  |
| Fe <sub>tot</sub>              | 2,20             | 0,18     | 0,19  | 2,09         | 2,12  | 0,07  | 1,93     | 0,17  |
| Mn                             | 0,03             | 0,00     | 0,00  | 0,01         | 0,01  | 0,00  | 0,01     | 0,00  |
| Mg                             | 2,55             | 0,13     | 0,10  | 2,43         | 2,58  | 0,03  | 2,84     | 0,11  |
| Ca                             | 0,00             | 0,00     | 0,00  | 0,01         | 0,00  | 0,04  | 0,01     | 0,00  |
| Na                             | 0,03             | 0,15     | 0,15  | 0,09         | 0,07  | 0,13  | 0,05     | 0,15  |
| K                              | 1,88             | 0,85     | 0,84  | 1,78         | 1,80  | 0,78  | 1,69     | 0,82  |
| Σ cat.                         | 15,62            | 7,05     | 7,06  | 15,52        | 15,61 | 6,92  | 15,50    | 7,04  |
| XMg                            | 0,54             | -        |       | 0,54         | 0,55  | -     | 0,59     | -     |
| XPrI                           | -                | 0,00     | 0,01  | -            | -     | 0,06  | -        | 0,03  |
| XM <sub>s</sub> +XPg           | -                | 0,84     | 0,91  | -            | -     | 0,82  | -        | 0,91  |
| Cel                            | -                | 0,16     | 0,08  | -            | -     | 0,13  | -        | 0,06  |

Abbreviations after Whitney and Evans (2010).

**Table 5. Selected representative analyses of epidote.**

| Unit                           | Low grade |       | Low grade |       | High grade |       | Low ; |
|--------------------------------|-----------|-------|-----------|-------|------------|-------|-------|
| Sample                         | MA-14-32  |       | MA-14-22  |       | MA-14-02   |       | MA-1  |
| Analysis #                     | 135       | 136   | 90        | 107   | 7          | 70    | 46    |
| SiO <sub>2</sub>               | 37,37     | 37,41 | 38,06     | 38,19 | 37,89      | 37,40 | 37,23 |
| TiO <sub>2</sub>               | 0,03      | 0,04  | 0,19      | 0,09  | 0,14       | 0,12  | 0,10  |
| Al <sub>2</sub> O <sub>3</sub> | 21,02     | 22,11 | 26,72     | 25,63 | 27,23      | 25,13 | 24,27 |
| Cr <sub>2</sub> O <sub>3</sub> | 0,03      | 0,00  | 0,10      | 0,19  | 0,01       | 0,02  | 0,00  |
| FeO                            | 14,87     | 14,20 | 8,62      | 10,62 | 7,37       | 10,37 | 11,13 |
| MnO                            | 0,12      | 0,21  | 0,13      | 0,32  | 0,25       | 0,49  | 0,37  |
| MgO                            | 0,00      | 0,00  | 0,00      | 0,00  | 0,12       | 0,03  | 0,02  |
| CaO                            | 23,24     | 23,39 | 23,48     | 23,07 | 23,17      | 22,56 | 22,76 |
| Na <sub>2</sub> O              | 0,02      | 0,00  | 0,04      | 0,01  | 0,00       | 0,05  | 0,02  |
| K <sub>2</sub> O               | 0,00      | 0,00  | 0,01      | 0,00  | 0,01       | 0,00  | 0,01  |
| Σ                              | 96,71     | 97,37 | 97,35     | 98,12 | 96,19      | 96,18 | 95,90 |
| Ox.                            | 12,5      | 12,5  | 12,5      | 12,5  | 12,5       | 12,5  | 12,5  |
| Si                             | 3,00      | 2,98  | 2,98      | 2,98  | 2,99       | 2,97  | 2,98  |
| Ti                             | 0,00      | 0,00  | 0,01      | 0,01  | 0,01       | 0,01  | 0,01  |
| Al <sub>tot</sub>              | 1,99      | 2,07  | 2,46      | 2,35  | 2,53       | 2,36  | 2,29  |
| Cr                             | 0,00      | 0,00  | 0,01      | 0,01  | 0,00       | 0,00  | 0,00  |
| Fe <sup>3+</sup>               | 1,00      | 0,94  | 0,56      | 0,69  | 0,49       | 0,69  | 0,74  |
| Mn                             | 0,01      | 0,01  | 0,01      | 0,02  | 0,02       | 0,03  | 0,02  |
| Mg                             | 0,00      | 0,00  | 0,00      | 0,00  | 0,01       | 0,00  | 0,00  |
| Ca                             | 2,00      | 2,00  | 1,97      | 1,93  | 1,96       | 1,92  | 1,95  |
| Na                             | 0,00      | 0,00  | 0,01      | 0,00  | 0,00       | 0,01  | 0,00  |
| K                              | 0,00      | 0,00  | 0,00      | 0,00  | 0,00       | 0,00  | 0,00  |
| Σ cat.                         | 8,00      | 8,01  | 8,00      | 7,99  | 8,00       | 8,00  | 8,00  |

| grade | Low grade |       | High grade |       | High grade |       |
|-------|-----------|-------|------------|-------|------------|-------|
| l4-24 | MA-14-28  |       | MA-14-35   |       | MA-14-38   |       |
| 47    | 58        | 59    | 36         | 39    | 54         | 57    |
| 36,66 | 37,48     | 36,99 | 39,17      | 39,09 | 38,38      | 38,69 |
| 0,05  | 0,09      | 0,12  | 0,02       | 0,05  | 0,30       | 0,00  |
| 22,53 | 22,98     | 21,58 | 28,35      | 28,27 | 24,92      | 28,19 |
| 0,03  | 0,02      | 0,01  | 0,00       | 0,01  | 0,00       | 0,01  |
| 13,19 | 12,45     | 14,47 | 6,23       | 6,31  | 9,75       | 6,22  |
| 0,42  | 0,10      | 0,08  | 0,10       | 0,12  | 0,13       | 0,23  |
| 0,00  | 0,00      | 0,00  | 0,02       | 0,04  | 0,13       | 0,04  |
| 22,59 | 23,11     | 22,82 | 24,26      | 23,73 | 23,40      | 23,91 |
| 0,00  | 0,00      | 0,00  | 0,01       | 0,00  | 0,00       | 0,00  |
| 0,03  | 0,00      | 0,01  | 0,02       | 0,02  | 0,00       | 0,02  |
| 95,49 | 96,23     | 96,07 | 98,18      | 97,65 | 97,03      | 97,32 |
| 12,5  | 12,5      | 12,5  | 12,5       | 12,5  | 12,5       | 12,5  |
| 2,97  | 3,00      | 2,98  | 3,02       | 3,02  | 3,02       | 3,00  |
| 0,00  | 0,01      | 0,01  | 0,00       | 0,00  | 0,02       | 0,00  |
| 2,15  | 2,17      | 2,05  | 2,57       | 2,57  | 2,31       | 2,58  |
| 0,00  | 0,00      | 0,00  | 0,00       | 0,00  | 0,00       | 0,00  |
| 0,89  | 0,83      | 0,98  | 0,40       | 0,41  | 0,64       | 0,40  |
| 0,03  | 0,01      | 0,01  | 0,01       | 0,01  | 0,01       | 0,02  |
| 0,00  | 1,98      | 1,97  | 0,00       | 0,00  | 0,02       | 0,01  |
| 1,96  | 0,00      | 0,00  | 2,00       | 1,96  | 1,97       | 1,99  |
| 0,00  | 0,00      | 0,00  | 0,00       | 0,00  | 0,00       | 0,00  |
| 0,00  | 0,00      | 0,00  | 0,00       | 0,00  | 0,00       | 0,00  |
| 8,01  | 7,99      | 8,00  | 8,00       | 7,99  | 7,99       | 8,00  |

| High grade |       |       |       | High grade |       |       |
|------------|-------|-------|-------|------------|-------|-------|
| MA-14-40   |       |       |       | MA-14-37   |       |       |
| 120        | 121   | 122   | 51    | 3          | 9     | 11    |
| 38,95      | 39,21 | 38,99 | 37,81 | 37,47      | 38,23 | 38,33 |
| 0,05       | 0,02  | 0,17  | 0,28  | 0,09       | 0,25  | 0,01  |
| 29,54      | 31,67 | 28,68 | 22,01 | 21,44      | 25,30 | 27,73 |
| 0,00       | 0,03  | 0,25  | 0,02  | -0,01      | 0,04  | -0,01 |
| 3,60       | 1,56  | 4,64  | 12,97 | 13,52      | 9,82  | 6,59  |
| 0,18       | 0,05  | 0,19  | 0,18  | 0,16       | 0,09  | 0,16  |
| 0,08       | 0,00  | 0,09  | 0,02  | -0,03      | 0,07  | 0,03  |
| 24,08      | 24,57 | 23,96 | 23,51 | 22,70      | 23,75 | 23,60 |
| 0,00       | 0,05  | 0,03  | 0,01  | 0,01       | 0,04  | 0,02  |
| 0,00       | 0,02  | 0,02  | 0,01  | 0,00       | 0,02  | -0,02 |
| 96,49      | 97,19 | 97,02 | 96,82 | 95,34      | 97,62 | 96,44 |
| 12,5       | 12,5  | 12,5  | 12,5  | 12,5       | 12,5  | 12,5  |
| 3,03       | 3,01  | 3,03  | 3,02  | 3,03       | 2,99  | 3,01  |
| 0,00       | 0,00  | 0,01  | 0,02  | 0,01       | 0,01  | 0,00  |
| 2,71       | 2,86  | 2,62  | 2,07  | 2,05       | 2,34  | 2,56  |
| 0,00       | 0,00  | 0,02  | 0,00  | 0,00       | 0,00  | 0,00  |
| 0,23       | 0,10  | 0,30  | 0,87  | 0,92       | 0,64  | 0,43  |
| 0,01       | 0,00  | 0,01  | 0,01  | 0,01       | 0,01  | 0,01  |
| 0,01       | 0,00  | 0,01  | 0,00  | 0,00       | 0,01  | 0,00  |
| 2,01       | 2,02  | 1,99  | 2,01  | 1,97       | 1,99  | 1,98  |
| 0,00       | 0,01  | 0,01  | 0,00  | 0,00       | 0,01  | 0,00  |
| 0,00       | 0,00  | 0,00  | 0,00  | 0,00       | 0,00  | 0,00  |
| 8,00       | 8,01  | 8,00  | 8,00  | 7,98       | 8,00  | 8,00  |

**Table 6. Selected representative analyses of garnet.**

| Unit                           | Mafic rocks, high grade unit |       |          |       |          |          |          |       |
|--------------------------------|------------------------------|-------|----------|-------|----------|----------|----------|-------|
| Sample                         | MA-14-39                     |       | MA-14-35 |       | MA-14-38 | MA-14-34 | MA-14-37 |       |
| Analysis #                     | 4                            | 5     | 5        | 46    | 92       | 3        | 78       | 31    |
| SiO <sub>2</sub>               | 39,39                        | 38,97 | 38,64    | 38,09 | 38,77    | 38,93    | 38,64    | 37,70 |
| TiO <sub>2</sub>               | 0,00                         | 0,00  | 0,04     | 0,07  | 0,02     | 0,03     | 0,01     | 0,06  |
| Al <sub>2</sub> O <sub>3</sub> | 21,65                        | 21,59 | 20,66    | 20,65 | 21,04    | 21,76    | 21,01    | 20,92 |
| Cr <sub>2</sub> O <sub>3</sub> | 0,03                         | 0,05  | 0,03     | 0,00  | 0,02     | 0,08     | 0,00     | -0,02 |
| FeO                            | 23,79                        | 23,60 | 22,76    | 23,75 | 21,85    | 20,85    | 24,48    | 26,96 |
| MnO                            | 1,08                         | 1,00  | 1,24     | 1,68  | 2,63     | 1,35     | 2,40     | 2,90  |
| MgO                            | 7,69                         | 7,66  | 5,49     | 4,69  | 4,74     | 7,15     | 5,17     | 3,35  |
| CaO                            | 6,72                         | 6,72  | 10,97    | 10,83 | 10,86    | 10,44    | 7,55     | 7,56  |
| Na <sub>2</sub> O              | 0,00                         | 0,00  | 0,03     | 0,00  | 0,00     | 0,00     | -0,02    | -0,01 |
| K <sub>2</sub> O               | 0,01                         | 0,01  | 0,02     | 0,00  | 0,00     | 0,00     | -0,01    | 0,02  |
| Σ                              | 100,36                       | 99,60 | 99,88    | 99,75 | 99,93    | 100,59   | 99,24    | 99,46 |
| Ox.                            | 12                           | 12    | 12       | 12    | 12       | 12       | 12       | 12    |
| Si                             | 3,02                         | 3,01  | 3,01     | 2,99  | 3,02     | 2,98     | 3,04     | 3,00  |
| Ti                             | 0,00                         | 0,00  | 0,00     | 0,00  | 0,00     | 0,00     | 0,00     | 0,00  |
| Al <sub>tot</sub>              | 1,96                         | 1,96  | 1,90     | 1,91  | 1,93     | 1,96     | 1,95     | 1,97  |
| Cr                             | 0,00                         | 0,00  | 0,00     | 0,00  | 0,00     | 0,00     | 0,00     | 0,00  |
| Fe <sub>tot</sub>              | 1,52                         | 1,52  | 1,48     | 1,56  | 1,42     | 1,33     | 1,61     | 1,80  |
| Mn                             | 0,07                         | 0,07  | 0,08     | 0,11  | 0,17     | 0,09     | 0,16     | 0,20  |
| Mg                             | 0,88                         | 0,88  | 0,64     | 0,55  | 0,55     | 0,81     | 0,61     | 0,40  |
| Ca                             | 0,55                         | 0,56  | 0,92     | 0,91  | 0,91     | 0,86     | 0,64     | 0,65  |
| Na                             | 0,00                         | 0,00  | 0,00     | 0,00  | 0,00     | 0,00     | 0,00     | 0,00  |
| K                              | 0,00                         | 0,00  | 0,00     | 0,00  | 0,00     | 0,00     | 0,00     | 0,00  |
| Σ cat.                         | 8,00                         | 8,01  | 8,04     | 8,04  | 8,01     | 8,04     | 7,99     | 8,01  |





**Table 6. Selected representative analyses of minor phases.**

| Mineral                        | St           | Scp      | Mrg-rich Phg | Mrg-rich Phg | Mrg-rich Phg | Pmp        | Chl   |
|--------------------------------|--------------|----------|--------------|--------------|--------------|------------|-------|
| Unit                           | Metasediment |          | High grade   |              |              | High grade | High  |
| Sample                         | MA-14-14     | MA-14-12 | MA-14-02     |              |              | MA-14-34   | MA-1  |
| Analysis #                     | 27           | 13       | 9            | 10           | 72           | 64         | 84    |
| SiO <sub>2</sub>               | 27,04        | 45,17    | 41,86        | 36,14        | 44,38        | 36,51      | 26,26 |
| TiO <sub>2</sub>               | 0,65         | 0,04     | 0,09         | 0,01         | 0,32         | 0,04       | 0,04  |
| Al <sub>2</sub> O <sub>3</sub> | 53,76        | 24,84    | 42,50        | 45,69        | 39,69        | 21,67      | 20,85 |
| Cr <sub>2</sub> O <sub>3</sub> | 0,00         | 0,00     | 0,00         | 0,01         | 0,00         | 0,03       | 0,03  |
| FeO                            | 12,84        | 0,17     | 0,86         | 1,02         | 1,12         | 8,91       | 22,90 |
| MnO                            | 0,18         | 0,00     | 0,02         | 0,00         | 0,00         | 0,13       | 0,37  |
| MgO                            | 1,78         | 0,00     | 0,18         | 0,38         | 0,14         | 2,27       | 17,49 |
| CaO                            | 0,00         | 16,54    | 3,06         | 7,02         | 1,16         | 22,64      | 0,03  |
| Na <sub>2</sub> O              | 0,00         | 4,04     | 6,43         | 4,18         | 6,43         | 0,02       | 0,00  |
| K <sub>2</sub> O               | 0,00         | 0,00     | 0,73         | 0,42         | 1,61         | 0,00       | 0,04  |
| Σ                              | 96,25        | 90,80    | 95,74        | 94,86        | 94,85        | 92,22      | 88,02 |
| Ox.                            | 22           | 24       | 11           | 11           | 11           | 12         | 14    |
| Si                             | 3,63         | 6,94     | 2,71         | 2,39         | 2,89         | 2,99       | 2,72  |
| Ti                             | 0,07         | 0,00     | 0,00         | 0,00         | 0,02         | 0,00       | 0,00  |
| Al <sub>tot</sub>              | 8,52         | 4,50     | 3,24         | 3,56         | 3,04         | 2,09       | 2,55  |
| Cr                             | 0,00         | 0,00     | 0,00         | 0,00         | 0,00         | 0,00       | 0,00  |
| Fe <sub>tot</sub>              | 1,44         | 0,02     | 0,05         | 0,06         | 0,06         | 0,61       | 1,98  |
| Mn                             | 0,02         | 0,00     | 0,00         | 0,00         | 0,00         | 0,01       | 0,03  |
| Mg                             | 0,36         | 0,00     | 0,02         | 0,04         | 0,01         | 0,28       | 2,70  |
| Ca                             | 0,00         | 2,72     | 0,21         | 0,50         | 0,08         | 1,98       | 0,00  |
| Na                             | 0,00         | 1,20     | 0,81         | 0,54         | 0,81         | 0,00       | 0,00  |
| K                              | 0,00         | 0,00     | 0,06         | 0,04         | 0,13         | 0,00       | 0,00  |
| Σ cat.                         | 14,04        | 15,40    | 7,10         | 7,11         | 7,05         | 7,97       | 10,00 |
| XMg                            | 0,20         | -        | 0,27         | 0,40         | 0,19         | 0,31       | 0,58  |

| <hr/> | Chl   |
|-------|-------|
| grade |       |
| 14-22 | 85    |
|       | 26,33 |
|       | 0,06  |
|       | 20,44 |
|       | 0,02  |
|       | 23,18 |
|       | 0,43  |
|       | 17,50 |
|       | 0,06  |
|       | 0,03  |
|       | 0,02  |
|       | 88,07 |
|       | 14    |
|       | 2,73  |
|       | 0,00  |
|       | 2,50  |
|       | 0,00  |
|       | 2,01  |
|       | 0,04  |
|       | 2,71  |
|       | 0,01  |
|       | 0,01  |
|       | 0,00  |
| <hr/> | 10,01 |
| <hr/> | 0,57  |