

Strain localization *via* mechanical mixing and metasomatism: an example from the metagabbros of Marine de Giottani, Alpine Corsica, France

Bénédicte Cenki^{1,*}, Emilien Oliot¹, Frédéric Gueydan¹, Lucille Nègre¹
and José Alberto Padrón-Navarta^{1,2}

¹ Géosciences Montpellier, UMR5243 Université de Montpellier, CNRS, 34095 Montpellier cedex 5, France

² Instituto Andaluz de Ciencias de la Tierra (IACT), CSIC-UGR, Av. Palmeras 4, 18100 Armilla, Granada, Spain

Received: 23 February 2024 / Accepted: 20 February 2025 / Publishing online: 9 June 2025

Abstract – Alpine deformation in the meta-ophiolitic nappe of the Upper Oceanic Unit of Corsica occurs under greenschist facies conditions. It is notably characterized by a series of shear zones in metagabbros. These shear zones are centimetre- to decimetre-size and are composed of amphibole ± chlorite schists. This occurrence offers a unique opportunity to study mechanisms of low-grade shear zone formation, extensive fluid/rock interaction and weakening processes controlled by mineralogical changes in the metamorphosed oceanic crust in the shallow part of a subduction system. A detailed sampling of undeformed metagabbros, protomylonitic metagabbros, as well as mylonitic schists allows tackling several finite strain states that involved rare occurrence of serpentinite clasts within the fault zones. Petrological observations combined with thermodynamic and geochemical modelling indicate that the metagabbro to amphibole-chlorite schist transformation involved mass transfer and occurred under open-system and water-saturated conditions. The main chemical features of this metasomatic process are significant gains in MgO, H₂O, SiO₂ and Fe₂O₃ accompanied by an almost complete loss of Na₂O. The transformation of metagabbros into schists occurs under water-saturated open-system conditions and is triggered by strain localization *via* mechanical mixing (with serpentinite clasts) and Mg-rich metasomatic fluids. Deciphering the softening processes controlled by the transformation of metagabbros into low-grade schistose rocks are of major importance to understand the seismogenic behavior of the mafic crust during subduction.

Keywords: fluid-rock interactions / oceanic crust / metagabbros / metasomatism / Alpine Corsica / open-system thermodynamics

Résumé – **Localisation de la déformation par mélange mécanique et métasomatisme: exemple des métagabbros de la Marine de Giottani, Corse alpine, France.** La déformation alpine dans la nappe métagabbroïque de l'Unité Océanique Supérieure de Corse se produit dans des conditions de faciès schiste vert. Elle est notamment caractérisée par une série de zones de cisaillement dans les métagabbros. Ces zones de cisaillement sont centimétriques à décimétriques et sont composées de schistes à amphiboles ± chlorite. Ces objets géologiques exceptionnels offrent une occasion unique d'étudier les mécanismes de formation des zones de cisaillement à bas degré métamorphique, les interactions fluide-roche associées et les processus d'affaiblissement contrôlés par les changements minéralogiques dans la croûte océanique métamorphosée dans la partie peu profonde d'un système de subduction. Un échantillonnage minutieux de métagabbros non déformés, de métagabbros protomylonitiques, ainsi que de schistes mylonitiques permet d'examiner plusieurs états de déformation finie qui impliquent la présence rare de clastes de serpentinite dans les zones de faille. Les observations pétrologiques combinées à la modélisation thermodynamique et géochimique indiquent que la transformation du métagabbro en schiste à amphibole-chlorite implique un transfert de masse et se produit dans des conditions de système ouvert et de saturation en eau. Les principales caractéristiques chimiques de ce processus métasomatique sont des gains significatifs en MgO, H₂O et Fe₂O₃ accompagnés d'une perte presque

*Corresponding author: benedicte.cenki@umontpellier.fr

totale en Na₂O. Le décryptage des processus d'adoucissement contrôlés par la transformation des métagabbros en roches schisteuses de faible degré métamorphique est d'une importance majeure pour comprendre le comportement sismogénique de la croûte mafique au cours de la subduction.

Mots clés : interactions fluide-roche / croûte océanique / métagabbros / métasomatisme / Corse Alpine / thermodynamique des systèmes ouverts

1 Introduction

Understanding metamorphic reactions and associated chemical mass-transfers within shear zones and faults is essential to predict weakening and/or strengthening processes within portions of the crust and their ability to generate or inhibit earthquakes (e.g. Dipple and Ferry, 1992; Mancktelow and Pennacchioni, 2020). The thermodynamic stability of mineral phases occurring during fluid-rock interactions controls their production or consumption within the deforming crust in response to geodynamics (Goncalves *et al.*, 2012, 2016). Common processes controlling the formation of shear zones may occur both under closed- or open-system conditions. Processes occurring in closed-system conditions, with local and limited fluid flow, include metamorphic reactions and phase changes, that modifies the local mechanical behavior of the rocks (e.g. Gueydan *et al.*, 2003, 2014; Oliot *et al.*, 2010; Leydier *et al.*, 2019). Open-system conditions processes imply large-scale fluid flow, the addition or leaching of elements and the massive development of new mineral phases that also modifies the rock rheology (Putnis and Austrheim, 2010; Oliot *et al.*, 2014).

Unravelling metasomatic processes and quantifying fluid flow as well as mass-transfer within shear zones in quartzofeldspathic systems have been the focus of intensive previous research (e.g., Goncalves *et al.*, 2012, and references therein). The hydration of ultramafic systems dominated by serpentinization processes has been also well studied (see Guillot *et al.*, 2015, for a review). Serpentinites exhibit unique rheological properties which play a major role in weakening the lithosphere and/or contributing to the exhumation of subducted rocks. For example, talc-bearing serpentinites are invoked to explain the creeping section of the San Andreas strike-slip continental Fault (Moore and Rymer, 2007; Klein *et al.*, 2022). In addition, the subduction history prior to strike slip faulting implies a mélange of metasediments, metabasites (gabbros and basalts) and serpentinites (e.g. Franciscan Complex) that may modify and control the overall rheological behavior of the fault (Moor and Rymer, 2007). As major earthquakes occur in subduction zone settings within the oceanic crust, understanding metamorphic reactions that may induce rheological changes or weakness in metagabbros is of major importance (Zihlmann *et al.*, 2018; Harigane *et al.*, 2019).

Deciphering in a quantitative manner the fluid-rock interactions and thermodynamic triggers of these metamorphic reactions is essential in order to assess the associated rheological changes of the oceanic crust. To tackle these issues, we present in this study novel data on the strain regime, petrology, mineralogy, thermodynamic modelling and chemistry of metagabbros transformed into amphibole-chlorite schists within a domain of highly-localized deformation in Alpine Corsica.

2 Geological setting

Alpine Corsica consists of a nappe stack of units resulting from the Alpine convergence at Cretaceous to Eocene times (Fig. 1a; Molli, 2008; Gueydan *et al.*, 2017). Continental as well as oceanic units are present (Fig. 1b, c; Vitale Brovarone *et al.*, 2013, Gueydan *et al.*, 2017). The “Schists Lustrés” in Alpine Corsica correspond to oceanic-derived nappes with slices of continental slivers and are composed from bottom to top of three main units (Fig. 1c, tectonic logs, from Gueydan *et al.*, 2017): the Castagniccia unit (mainly oceanic metasediments with some patches of metagabbros and serpentinites, at blueschists metamorphic conditions, Vitale Brovarone *et al.*, 2013), the Lower Oceanic unit (mainly serpentinites, metabasalts and metagabbros with the highest P-T conditions recorded in Alpine Corsica, blueschist to eclogitic peak metamorphism, Vitale Brovarone *et al.*, 2013) and the Upper Oceanic unit (serpentinites, metagabbros and some continental slivers, at greenschists to blueschists metamorphic conditions, Vitale Brovarone *et al.*, 2013). The Schist Lustrés record a complex deformation history, starting with subduction, followed by exhumation and late normal faulting (Gueydan *et al.*, 2017). Ductile deformation during both subduction and exhumation is marked by an Alpine regional foliation trending NNE and dipping to the SW in the western side of Cap Corse (Fig. 1b and 2a,b). Foliation trajectories define broad antiforms (Cap Corse Antiform, Fig. 1b and 2a,b, Castagniccia antiform) and synform (St-Florent synform) associated with late extensional deformation events (Gueydan *et al.*, 2017). Lineations are trending NNE and are associated with two senses of shear: top to SSW during prograde deformation (e.g. subduction, marked as D1 in Fig. 1d) and top to NNE during retrograde deformation (e.g. exhumation, marked as D2 in Fig. 1d; Jolivet *et al.*, 1990; Fournier *et al.*, 1991).

The studied area at Marine de Giottani is located in the Upper Oceanic Units (Gratera, Pigno, Inzecca, Figure 1b,c; Lahondère *et al.*, 1992; Gueydan *et al.*, 2017) that are marked by low blueschist to greenschist facies metamorphism. The observed oceanic material are metabasalts (prasinities), serpentinites, and retrogressed greenschist metagabbros (Fig. 2a), that thrust serpentinites with lenses of eclogitic glaucophanite (Lower Oceanic Unit, Fig. 2a). In the retrogressed greenschist metagabbros in Marine de Giottani, meter-scale amphibole-chlorite-rich bearing low-grade shear zones are observed at several places and are the subject of the present study (Fig. 2).

3 Structural data and field observations

The studied shear zones are observed in the retrogressed (greenschists) metagabbros of the Upper Oceanic Unit. We have acquired 225/169 foliations/lineations measurements in

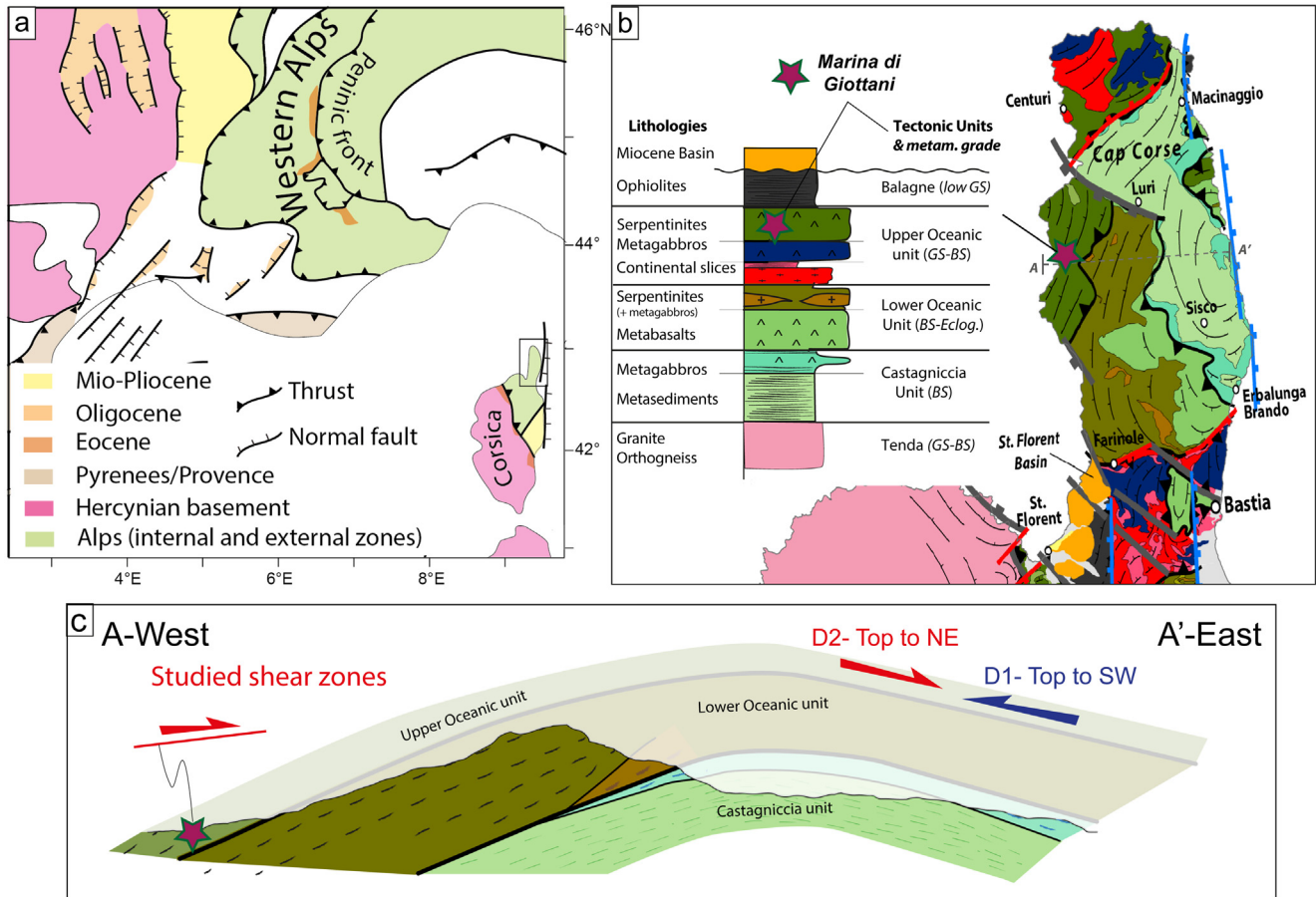


Fig. 1. Key geological features of Alpine Corsica (modified from Gueydan *et al.*, 2017). a. Schematic sketch of Western Alps and Corsica, showing the Alpine wedge, the major thrusts and basins, as well as Oligo-Miocene extensional basins in South-East France, in the Lyon Gulf and in Corsica. b. Regional geological map of Alpine Corsica with major lithological units shown in the tectonic log in inset. The “Schistes Lustrés” are composed from bottom to top of three main units *i.e.* Castagniccia (mainly meta-sediments), Lower Oceanic Unit (serpentinities and metabasalts) and Upper Oceanic Unit (serpentinities, metagabbros, and continental slices). The contacts between units are thrusts. The studied zone (violet star in both the tectonic log and the map) is in Marina di Giotanni and occurs in metagabbros in the Upper oceanic units. Oligo-Miocene brittle-ductile normal faults are shown (grey for Oligocene, red for early Miocene and blue for late Miocene, see details in Gueydan *et al.*, 2017). c/ East-West schematic cross section (location in b/ as AA' profile in dark grey dashed line) showing the tectonic nappe piles acquired during subduction (associated with top to NE shearing, blue arrow). Red arrows for exhumation sense of shearing. See text for references and explanations. The studied shear zones (violet star) is on top of the tectonic nappe piles (Upper Oceanic unit) and with top to E/NE shearing (red arrow).

the metagabbros, prasinites and serpentinites (Fig. 2b) and 126 measurements of the shear zones in the metagabbros (Fig. 2c).

The metagabbro generally presents a granoblastic texture with cm-size pyroxene in a recrystallized foliated albitic matrix (Fig. 3e). It can be slightly foliated to mylonitic. The measured foliation trends N40°E dipping to the NW (Fig. 2a,b) and is consistent with the regional Alpine foliation (Fig. 1b). It is often associated with sheath folds and a sub-horizontal stretching lineation trending N30°E and marked by greenschist facies minerals (amphiboles and chlorite). As an example, pyroxene is locally entirely transformed into green-amphibolite (smaragdite), giving the name of these white gabbros in Corsica (“Smaragdite gabbros”). The gabbroic unit is wrapped by prasinites (*i.e.* which corresponds here to greenschist facies metabasalts) and serpentinites that share the same structural features (folds, foliation planes and stretching lineation) with

the underlying metagabbros. In the metagabbros, indications for sense of shear are widespread and show top to NE shearing, associated with retrogressed greenschist paragenesis.

In the metagabbros of Marine de Giotanni, a series of low-grade localised zones of deformation (tens to hundreds of meters in length; Figure 2a for the locations on map and Fig. 3 for one outcrop example) are observed, striking N40°E and dipping to the NW (10 to 20° or 50° to 60°), forming an anastomosed lozenge-shaped network of shear zones. The shear zones present a mylonitic foliation defined by elongate amphibole and/or chlorite crystals (Fig. 3a, b, c, d and f). These amphibole-chlorite bearing shear zones can reach a meter in thickness and tens of meters in length (one outstanding example is provided in Fig. 3a–d). In metagabbro, a marked strain localization occurs at the boundary between foliated metagabbros and amphibolite-chlorite-rich schists (Fig. 3a and b).

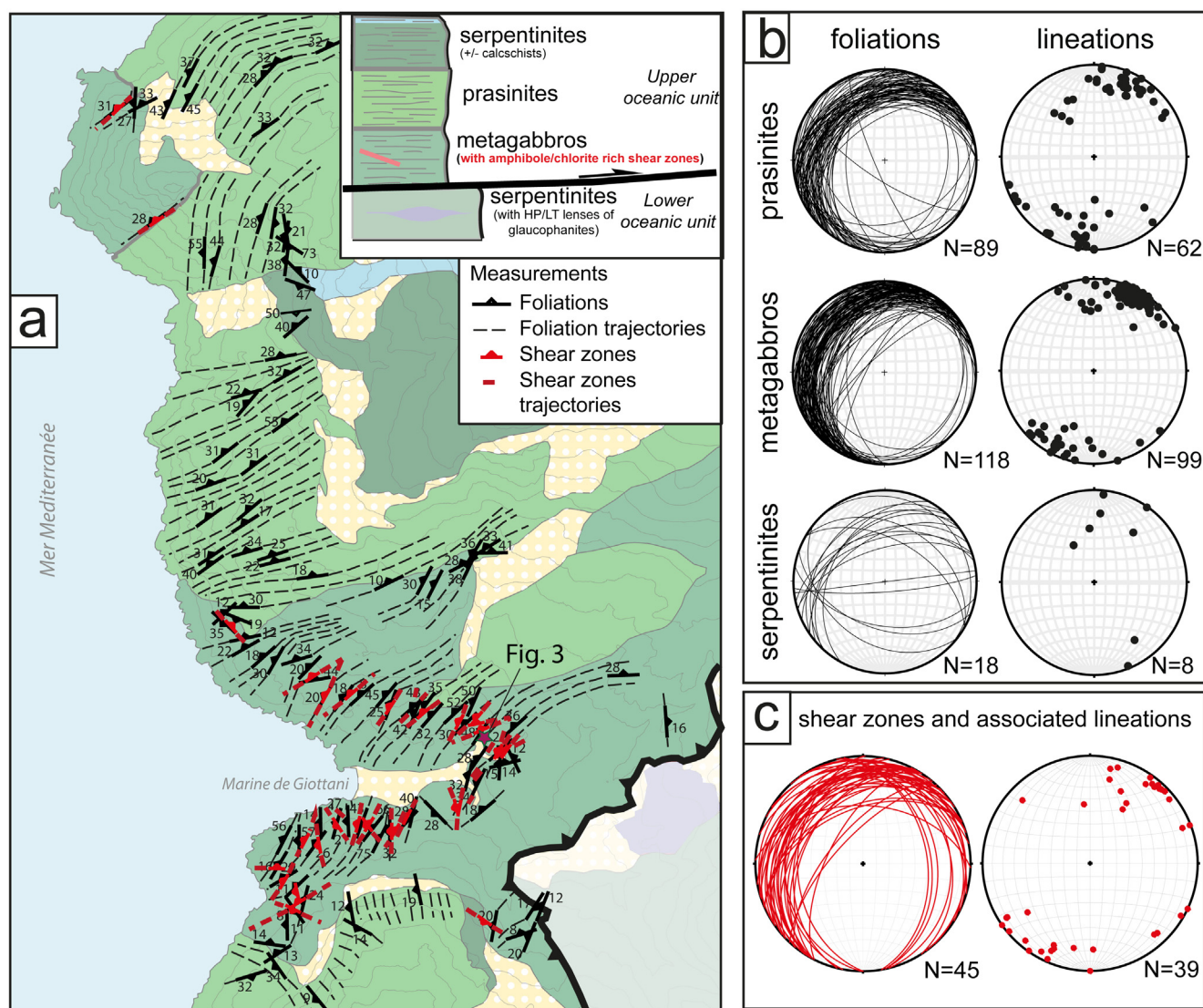


Fig. 2. Tectonic map and main amphibole-chlorite shear zones in Marine de Giottani metagabbros (see location on Fig. 1). A. Geological map (from BRGM) with foliation measurements and trajectories (in black) and with observed amphibole-chlorite shear zones (in red). Violet star for the location of key outcrops shown in Fig. 3. B. Stereoplots of foliation and lineation measurements in metabasalts (prasinities), metagabbros and serpentinites (lithologies of the Upper Oceanic Unit (Fig. 1) in Marine de Giottani). C. Stereoplots of amphibole-chlorite shear zones and associated lineations.

These shear zones are composed by schistose rocks, rich in chlorite and amphibolite with lenses of metagabbros and some lenses of ultramafic materials (Fig. 3d). Mylonitic foliation is well developed in the shear zone and S-C type of structure indicates a top to NE sense of shearing. Figure 3d is an interpreted zoomed view of the outcrop which presents the massive coarse-grained metagabbros cross-cut by the secondary anastomosed network of shallow dipping cm- to dm-size shear zones. The occurrence of lenses of metagabbros wrapped by amphibole and chlorite-rich schists inside the shear zone suggest that the schists developed at the expense of the metagabbros. In addition, meter-size rounded serpentinite clasts (Fig. 3a, b, e) occur locally within the shear zones and are also wrapped by amphibole-chlorite schists. Metagabbros and serpentinite clasts are never found in direct contact. This suggests a potential chemical and mechani-

cal mixing between metagabbros and serpentinite in the presence of fluids (*e.g.* leading to amphibole formation) during deformation, leading to the total transformation of the metagabbro into chlorite-amphibole rich schists. The aim of the following petrological and geochemical study is to identify and quantify such interactions.

4 Petrological and geochemical analytical methods

Mineral compositions were determined with a Cameca SX100 electron probe micro-analyzer (EPMA) at the University of Montpellier, operating at 20 kV accelerating voltage and 15 nA beam current.

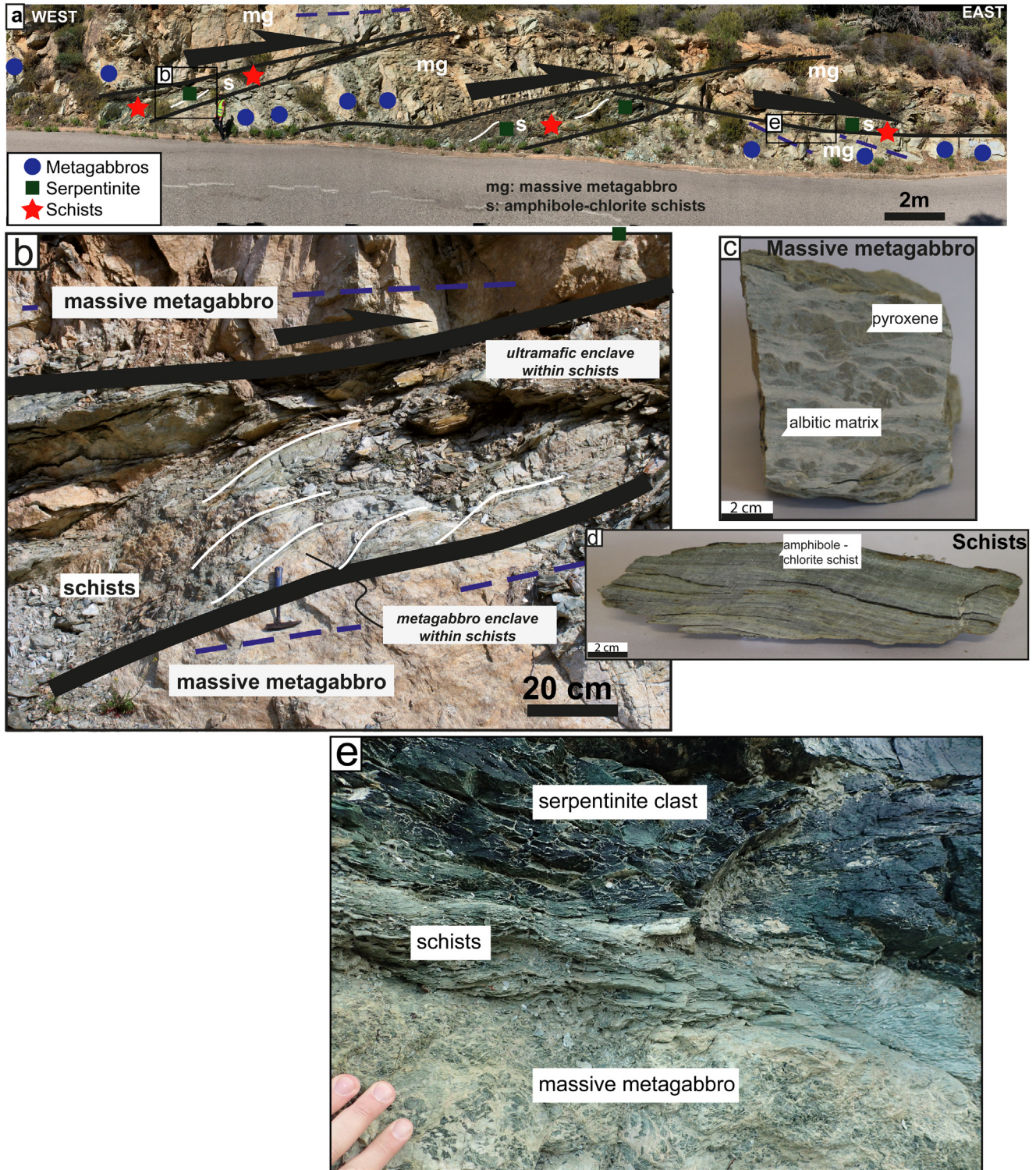


Fig. 3. Key outcrop features of amphibole-chlorite shear zones developing in metagabbros (locations in Fig. 2, along the D80 Cap Corse Road. The precise latitude and longitude are respectively 42.867808° and 9.349849°). A/. Meter scale characteristic examples of amphibole-chlorite shear zones cross-cutting foliated metagabbros (near D80 road). Shear zones (in black) are marked by strongly deformed schists (cleavage in white) with sigmoid shape constraining the top to NE sense of shear (black arrows). The thickness of these shear zones is variable, from cm- to pluri- meters. Colorful symbols indicate sample location. B/ Close-up picture showing the sharp contact between massive metagabbros, schists and clasts of metagabbros and serpentinite within the shear zone. C/ and D/ Hand sample microphotographs of metagabbro and schists, respectively. E/ Close up picture showing the contact between a serpentinite clast, schists and massive metagabbros.

Table 1. Representative analyses of constitutive minerals.

PYROXENE								
	metagabbro	metagabbro	metagabbro	metagabbro	metagabbro	metagabbro	metagabbro	metagabbro
<i>Sample</i>	CO1305core	CO1305rim	CO1423	CO1421	CO1429	CO1408	CO1408	CO1408
SiO ₂	52.79	52.31	51.11	52.31	52.12	56.77	55.35	55.03
Al ₂ O ₃	3.02	3.06	3.28	3.11	4.15	1.61	7.86	7.64
TiO ₂	0.51	0.55	0.58	0.36	0.42	0.02	0.04	0.10
Cr ₂ O ₃	0.21	0.15	0.47	0.50	0.26	0.02	0.00	0.00
NiO	0.02	0.01	0.02	0.02	0.02	0.00	0.00	0.00
Fe ₂ O ₃	0.26	0.00	3.24	1.70	4.60	0.00	7.96	10.02
FeO	5.14	5.02	2.13	3.91	0.00	4.77	0.00	0.00
MgO	16.29	15.87	15.93	17.01	15.41	21.44	9.47	8.26
MnO	0.15	0.17	0.18	0.00	0.18	0.16	0.20	0.24
CaO	21.30	21.70	22.79	21.08	22.05	12.66	14.00	12.41
Na ₂ O	0.42	0.37	0.36	0.35	1.47	0.74	6.84	7.78
K ₂ O	0.00	0.00	0.01	0.01	0.00	0.02	0.00	0.00
<i>Total</i>	100.11	99.22	100.10	100.34	100.68	98.22	101.73	101.48
<i>WB-cpx de pyroxene-norm (4 cations)</i>								
Si	1.93	1.93	1.87	1.91	1.89	2.07	1.96	1.96
Al	0.13	0.13	0.14	0.13	0.18	0.07	0.33	0.32
Ti	0.01	0.02	0.02	0.01	0.01	0.00	0.00	0.00
Cr	0.01	0.00	0.01	0.01	0.01	0.00	0.00	0.00
Ni	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe ³⁺	0.01	0.00	0.09	0.05	0.12	0.00	0.21	0.27
Fe ²⁺	0.16	0.16	0.07	0.12	0.00	0.15	0.00	0.00
Mg	0.89	0.87	0.87	0.92	0.83	1.16	0.50	0.44
Mn	0.00	0.01	0.01	0.00	0.00	0.01	0.01	0.01
Ca	0.83	0.86	0.90	0.82	0.85	0.49	0.53	0.47
Na	0.03	0.03	0.03	0.02	0.10	0.05	0.47	0.54
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
X Mg	0.84	0.85	0.85	0.85	0.87	0.89	0.70	0.62
AMPHIBOLE								
	metagabbro	metagabbro	metagabbro	metagabbro	metagabbro	schist	schist	
<i>Sample</i>	CO1305	CO1423	CO1421	CO1418core	CO1418rim	CO1312	CO1312	
SiO ₂	56.52	57.09	56.56	56.81	56.97	58.13	58.19	
Al ₂ O ₃	1.59	1.72	1.26	0.81	0.23	0.02	0.02	
TiO ₂	0.05	0.00	0.00	0.01	0.00	0.01	0.00	
Cr ₂ O ₃	0.18	0.00	0.01	0.16	0.08	0.00	0.00	
NiO	0.01	0.04	0.06	0.08	0.14	0.12	0.14	
FeO	5.29	4.96	5.28	5.50	4.77	2.80	2.68	
MgO	20.28	20.60	20.29	20.31	21.38	22.49	22.50	
MnO	0.09	0.18	0.18	0.14	0.13	0.09	0.11	
CaO	12.67	11.64	12.47	12.37	13.29	12.79	12.76	
Na ₂ O	0.41	1.19	0.66	0.70	0.38	0.14	0.13	
K ₂ O	0.04	0.06	0.04	0.04	0.02	0.01	0.01	
<i>Total</i>	97.11	97.47	96.82	96.93	97.39	96.62	96.53	
<i>CAMP NORM (stoichiometric, Sum(Cations) = 15+Na+K)</i>								
Si	7.93	8.03	7.98	8.02	7.94	8.08	8.09	
Al	0.26	0.28	0.21	0.13	0.04	0.00	0.00	
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Cr	0.02	0.00	0.00	0.02	0.01	0.00	0.00	
Ni	0.00	0.00	0.01	0.01	0.02	0.01	0.02	
Fe ²⁺	0.62	0.58	0.62	0.65	0.56	0.33	0.31	
Mg	4.24	4.32	4.27	4.27	4.44	4.66	4.66	
Mn	0.01	0.02	0.02	0.02	0.02	0.01	0.01	
Ca	1.91	1.75	1.89	1.87	1.98	1.90	1.90	

Table 1. (continued).

AMPHIBOLE							
Na	0.11	0.32	0.18	0.19	0.10	0.04	0.03
K	0.01	0.01	0.01	0.01	0.00	0.00	0.00
X Mg	0.87	0.88	0.87	0.87	0.89	0.93	0.94
	Actinolite	Actinolite	Actinolite	Actinolite	Actinolite	Tremolite	Tremolite
ALBITE							
	metagabbro			metagabbro		metagabbro	
Sample	CO1305			CO1423		CO1421	
SiO ₂	68.52			68.17		64.77	
Al ₂ O ₃	20.22			20.01		20.93	
TiO ₂	0.00			0.00		0.01	
FeO	0.07			0.01		0.13	
MgO	0.03			-0.01		0.26	
MnO	0.00			0.00		0.02	
CaO	0.16			0.23		3.22	
Na ₂ O	11.74			11.06		10.99	
K ₂ O	0.02			0.03		0.02	
Total	100.74			99.48		100.36	
Cations (normalised to 8 oxygens)							
Si	2.97			2.99		2.86	
Al	1.03			1.03		1.09	
Ti	0.00			0.00		0.00	
Fe	0.00			0.00		0.00	
Mg	0.00			0.00		0.02	
Mn	0.00			0.00		0.00	
Ca	0.01			0.01		0.15	
Na	0.99			0.94		0.94	
K	0.00			0.00		0.00	
% Ab	99.15			98.68		85.96	
% An	0.74			1.14		13.93	
% Or	0.11			0.18		0.11	
EPIDOTE-CLINOZOISITE							
	metagabbro			metagabbro		metagabbro	
	CO1305			CO1305		CO1423	
SiO ₂	39.03			39.32		37.95	
Al ₂ O ₃	30.82			29.50		28.60	
TiO ₂	0.02			0.02		0.05	
FeO	4.74			6.16		7.43	
MgO	0.03			0.03		0.00	
MnO	0.05			0.05		0.06	
CaO	23.66			23.66		24.56	
Na ₂ O	0.02			0.00		0.00	
Total	98.38			98.73		98.66	
Normalized to 8 cations and 25 charges							
Si	2.99			3.02		2.93	
Al	2.78			2.67		2.60	
Ti	0.00			0.00		0.00	
Fe2+	0.04			0.07		0.00	
Fe3+	0.23			0.28		0.43	
Mg	0.00			0.00		0.00	
Mn	0.00			0.00		0.00	
Ca	1.94			1.95		2.03	
Na	0.01			0.01		0.00	
XFe3+	0.08			0.10		0.14	

CHLORITE

	metagabbro	metagabbro	metagabbro	metagabbro	schist	schist
<i>Sample</i>	CO1305	CO1423	CO1421	CO1418	CO1312	CO1312
SiO ₂	29.78	30.05	29.53	30.06	33.14	31.66
Al ₂ O ₃	20.20	20.47	20.80	18.04	14.53	13.42
TiO ₂	0.02	0.01	0.01	0.00	0.01	0.02
Cr ₂ O ₃	0.18	0.03	0.26	0.52	2.90	4.32
NiO	0.10	0.17	0.09	0.38	0.34	0.38
FeO	10.26	9.42	10.92	10.48	6.68	7.09
MgO	26.21	27.88	26.17	26.82	30.89	30.06
MnO	0.13	0.12	0.15	0.12	0.06	0.09
CaO	0.10	0.05	0.08	0.03	0.01	0.01
Na ₂ O	0.00	0.01	0.01	0.01	0.02	0.01
K ₂ O	0.01	0.01	0.00	0.00	0.00	0.00
<i>Total</i>	86.99	88.21	88.00	86.46	88.58	87.04
<i>Normalized to 28 oxygens</i>						
Si	5.81	5.76	5.72	5.93	6.30	6.19
Ti	0.00	0.00	0.00	0.00	0.00	0.00
Cr	0.03	0.00	0.04	0.08	0.44	0.67
Al	4.65	4.62	4.75	4.20	3.25	3.09
Fe ²⁺	1.68	1.51	1.77	1.73	1.06	1.16
Mn	0.02	0.02	0.02	0.02	0.01	0.02
Ni	0.02	0.03	0.01	0.06	0.05	0.06
Mg	7.62	7.96	7.55	7.89	8.75	8.75
Ca	0.02	0.01	0.02	0.01	0.00	0.00
Na	0.00	0.00	0.00	0.00	0.01	0.00
K	0.00	0.00	0.00	0.00	0.00	0.00
X Mg	0.82	0.84	0.81	0.82	0.89	0.88

Mafic**to****Ultramafic****SERPENTINE**

	ultramafite	ultramafite
<i>Sample</i>	CO1414	CO1414
SiO ₂	41.65	41.47
Al ₂ O ₃	3.28	2.90
TiO ₂	0.01	0.00
Cr ₂ O ₃	0.04	0.07
NiO	0.24	0.23
FeO	6.66	6.22
MgO	34.60	35.61
MnO	0.09	0.09
CaO	0.01	0.03
Na ₂ O	0.00	0.01
K ₂ O	0.00	0.00
<i>Total</i>	86.58	86.65
<i>Normalized to 9 cations</i>		
Si	2.56	2.54
Ti	0.00	0.00
Cr	0.00	0.00
Al	0.24	0.21
Fe ²⁺	0.34	0.32
Mn	0.00	0.00
Ni	0.01	0.01
Mg	3.17	3.26
Ca	0.00	0.00
Na	0.00	0.00
K	0.00	0.00
X Mg	0.90	0.91

XMg = Mg/(Mg+Fe) for pyroxene, amphibole and chlorite; XFe³⁺ = Fe³⁺/(Fe³⁺ + Al) for epidote.

Table 2. Modal abundances of constitutive minerals in the studied rocks.

Samples	Metagabbros						Schists		
	CO1305	CO1429	CO1421	CO1423	CO1418	CO1416	CO1417	CO1312	CO1315
Minerals									
Cpx	18	34	36	23	<1	–	–	–	–
Amphibole	30	20	18	31	77	74	75	93	84
Chlorite	2.5	5	1.5	3.5	22	25	24	6	15
Albite	34	27	29	19	–	–	–	–	–
Epidote	15	13	15	23	–	–	–	–	–
Pumpellyite	<1	<1	<1	<1	–	–	–	–	–
White mica	<1	<1	<1	<1	–	–	–	–	–
Opaque	–	–	–	–	<1	<1	<1	<1	<1

Table 3. Average bulk chemical compositions of the metagabbros ($n=10$), schists ($n=4$) and serpentinite clasts ($n=4$).

Samples	metagabbros Protoliths C^0 ($n=10$)		chl-amph-schists Altered rocks C^A ($n=4$)		serpentinites Ultramafic enclaves ($n=4$)	
	geom. mean	stand. dev.	geom. mean	stand. dev.	geom. mean	stand. dev.
Wt%						
SiO ₂	48.30	0.56	45.03	1.83	41.00	0.44
Al ₂ O ₃	17.11	0.92	8.12	0.69	1.74	0.31
Fe ₂ O ₃	4.23	0.53	6.57	1.03	8.69	1.22
MgO	10.74	0.75	26.53	1.76	36.38	1.09
CaO	13.19	1.20	6.68	0.86	0.08	0.20
Na ₂ O	2.31	0.37	0.19	0.08	0.09	0.29
K ₂ O	0.07	0.03	0.06	0.00	0.11	0.20
TiO ₂	0.20	0.03	0.14	0.03	0.04	0.01
MnO	0.09	0.01	0.10	0.01	0.11	0.01
P ₂ O ₅	0.03	0.01	0.02	0.01	0.00	0.01
L.O.I.	3.11	0.16	5.70	0.97	10.80	0.63
Total	99.38	0.25	99.14	0.24	99.03	0.27
Density	2.96	0.07	2.83	0.01	2.61	0.10

Representative mineral analyses of pyroxene, amphibole, plagioclase, epidote and chlorite are presented in Table 1. Modal abundances of major minerals (Tab. 2) have been derived from optical microscope images analysis using the Image J software and maps of entire thin sections.

Absolute chemical mass transfer and related volume changes between the metagabbro and schists in shear zones have been estimated using the statistical Isocon method of Baumgartner and Olsen (1995). Considering the metagabbro as the main protolith as the shear zones are localized within this cartographic unit, its chemical composition has been calculated by averaging ten bulk-rock chemical compositions (Tab. 3). Samples were decimetric in size and considered representatively larger than the magmatic chemical heterogeneities. The 1σ standard deviations calculated on each oxide highlight these initial chemical heterogeneities and are used as errors on each chemical element in mass balance calculations. In the same way, four bulk rock compositions of schists taken from the shear zone cores have been used to estimate mass and volume changes that occurred during strain localization process and schists formation in shear zones. Average bulk rock chemical compositions and measured

sample densities are presented in Table 3. During mass transfer calculations, immobile chemical components are statistically selected by an algorithm that identifies the number of chemical components that are compatible, within their 1σ uncertainties, with the same isocon. The best-fit isocon is carefully chosen in relation with the petrological analyses (Durand *et al.*, 2015). Thus, the chosen isocon line is defined by the equation:

$$\log C_i^A = \log \left(\frac{M^0}{M^A} \right) + \log C_i^0 \quad (1)$$

where C_i^A and C_i^0 are the concentrations (wt%) of an element (i) in the altered rock (A) and in the unaltered protolith (0), respectively; M^A and M^0 are the mass (g) of reference amount of the altered rock and of the protolith, respectively. Mass transfers are estimated from the isocon line and results of the calculations are portrayed in log-log isocon diagrams (Baumgartner and Olsen, 1995). Absolute mass changes are expressed in $\text{g} \cdot 100 \text{ g}^{-1}$ of the initial metagabbro and relative mass changes are expressed in% (Tab. 4).

Table 4. Result of mass balance calculations, calculated with the statistical Isocon method of Baumgartner and Olsen (1995), between the ‘altered’ schists in shear zones and the ‘host’ metagabbros.

	value	1 σ	value (%)	1 σ (%)
M ⁰ /M ^A	0.50	0.04		
χ^2	1.36			
$\chi^2 / (n-1)$	0.45			
Q	0.51			
$n_i / 11$	4.00			
Mass change	1.02	0.16	101.59	16.37
Dens. change	-0.04	0.00	-4.39	0.35
Vol. change	1.11	0.61	110.85	61.44
Mass change (g.100g ⁻¹)				
SiO ₂	42.96	8.33	88	17
Al ₂ O ₃	-0.71	2.15	-4	12
Fe ₂ O ₃	9.11	2.42	214	57
MnO	0.12	0.03	135	31
MgO	43.15	5.71	399	53
CaO	0.32	2.39	2	18
Na ₂ O	-1.94	0.41	-83	17
K ₂ O	0.05	0.03	71	44
TiO ₂	0.08	0.08	38	38
P ₂ O ₅	0	0.02	12	69
L.O.I.	8.46	2.19	270	70

For thermodynamic calculations in the simplified model system Na₂O-CaO-FeO-MgO-Al₂O₃-SiO₂-H₂O, the database of Holland and Powell (1998) (thermodynamic database of THERMOCALC, version 3.21) was used including updates (Baldwin *et al.*, 2005; Kelsey *et al.*, 2005; White *et al.*, 2007). Solution models for feldspar and chlorite are taken from Holland and Powell (1998), orthopyroxene is from White *et al.*, (2002), amphibole is from Diener *et al.* (2007) and clinopyroxene from Green *et al.* (2007). Oxygen is considered in excess (*i.e.* symbol O(?)) used in the bulk rock compositions. Rock-specific equilibrium assemblage diagrams (*i.e.* pseudo-sections) were calculated with the free energy minimization programs THERIAK and DOMINO (de Capitani and Petrakakis, 2010). Mineral abbreviations used are from Whitney and Evans (2010).

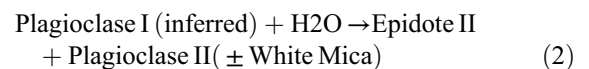
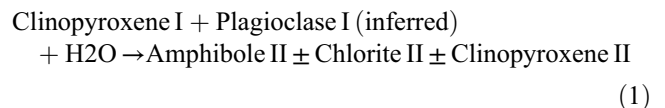
5 Petrological and geochemical results

In what follows, the amphibole-chlorite bearing shear zones will be called schists for the sake of simplicity.

5.1 Petrography

The studied rocks are metagabbros that present various degrees of ductile deformation. At the outcrop scale, this rock is massive, presenting an alternation of cm-size leucocratic bands of altered plagioclase and elongated and fractured brown-greenish minerals that can still be macroscopically recognized as magmatic clinopyroxene (Fig. 3e). In the next sections, minerals labelled I are magmatic (*i.e.* related to the magmatic evolution of the rocks) and II or III are metamorphic (*i.e.* related to the tectonic evolution of the rocks).

Locally, undeformed metagabbros (*e.g.*, CO1429, CO1420 and CO1305) preserve magmatic textures even though metasomatic and metamorphic minerals are widespread. Cm-size relics of magmatic clinopyroxene (cpx I) are frequent (Fig. 4a). These are often fractured and present embayments filled with euhedral amphibole (amp II), which crystallized within fractures, cleavages and locally form palisade around cpx I (Fig. 4a). Metamorphic clinopyroxene (cpx II) is locally present as aggregates of very fine-grained grains (<10 μ m) associated to amp II and chl II within embayments and fractures of cpx I. Magmatic plagioclase (pl I) is fully transformed into a very fine-grained (<10 μ m) aggregate of epidote and metamorphic plagioclase (pl II) and rare white mica and pumpellyite (Fig. 4b). Chlorite (chl II) is locally associated to amp II aggregates around cpx I and often forms a palisade between magmatic cpx I and pl I pseudomorphs (Fig. 4a). The following well-known unbalanced reactions can be deduced from the observed textures:



In the foliated metagabbros (*e.g.*, CO1419, CO1421, CO1430, CO1407, CO1412, CO1410, CO1423 and CO1408)

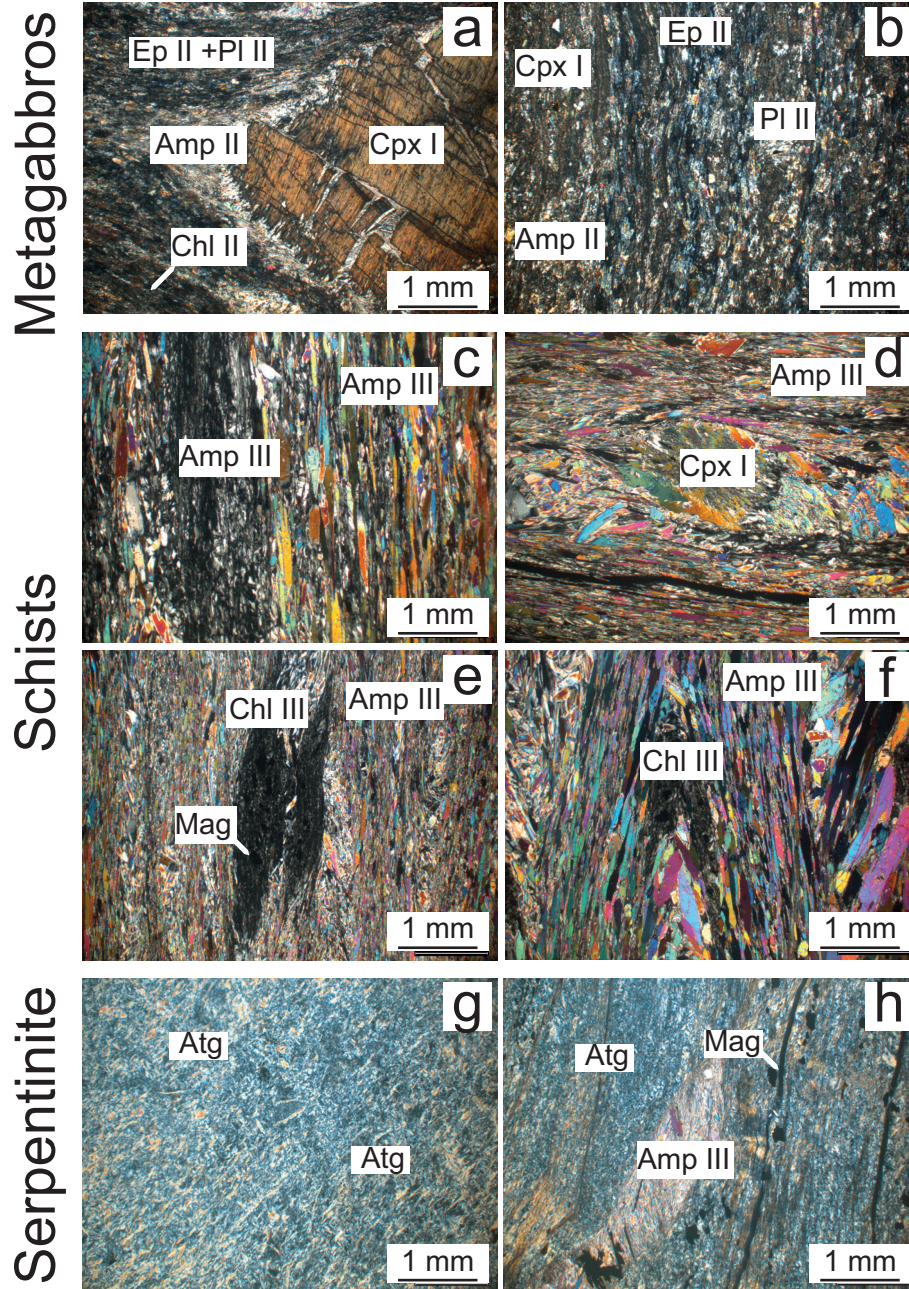


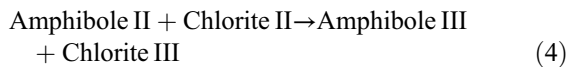
Fig. 4. Thin section microphotographs in plane polarized light. a. Undeformed metagabbros. The epidote and albite aggregate is a pseudomorph after magmatic plagioclase. b. Mylonitic metagabbros. c. Schist dominated by amphibole with a chlorite-rich pod. d. Schist with relic of magmatic clinopyroxene, locally transformed into amphibole along fractures and cleavages. e. Serpentinite clast dominated by antigorite. f. Local occurrence of amphibole with serpentinite clast. Abbreviations after [Whitney and Evans \(2010\)](#).

and mylonitic metagabbros (CO1422 and CO1432) the same mineralogy can be recognized, though with a finer grain size ([Fig. 4b](#)). Modal abundance of major minerals can be summarized as follow ([Tab. 2](#)): clinopyroxene (cpx I and II, 18–36%), amphiboles (18–31%), albite (19–34%), epidote (13–23%), chlorite (<4%) and pumpellyite (<1%). All the metagabbros regardless of their tectonic fabrics (undeformed, slightly foliated and mylonitic) have similar bulk rock

compositions, only displaying minor chemical heterogeneities on each oxide ([Tab. 3](#)).

Within shear zones, schists (*e.g.*, CO1416, CO1417, CO1418 and CO1312) can be described as metasomatized rocks composed of alternating amphibole-rich and chlorite-rich millimetre-size bands ([Fig. 4c](#)). The grain size is generally small (<100 μm) and reflects intense and pervasive deformation. Rare clinopyroxene I porphyroclasts can be found

(Fig. 4d). Minerals resulting from the hydrated breakdown of magmatic plagioclase (epidote and white mica) are absent. Amphibole makes *ca.* 75 vol% of the rock and chlorite the remaining about 25 vol% (Tab. 2). Locally, schists can be completely recrystallized and mostly composed of euhedral amphibole, with rare chlorite (Tab. 2). Chlorite generally appears as distinct pods or elongated patches (*ca.* 300 μm to few mm in length) within the foliation (Fig. 4e) and is often associated with opaque minerals (magnetite). The highly localized deformation (shear bands, C/S structures and axial-planar crenulation cleavage, Fig. 4f) controls amphibole grain size in general (from hundreds of μm in preserved domains to tens of μm in shear bands). The following transformation can be suggested (§5.2 highlights differences in chemistry of both generations):



Metre-size serpentinite clasts are locally observed within these low-grade shear zones. These rocks appear slightly more massive and darker than the surrounding schists. These are mostly composed of serpentine (>90%, Fig. 4g). Locally pods of amphibole and oxides are preserved (Fig. 4h).

5.2 Mineral composition

Amphiboles are calcic amphiboles within the tremolite-ferro-actinolite solid solution (Tab. 1; Leake *et al.*, 1997). Amphibole II (in metagabbros and schists) has actinolite composition with an X_{Mg} ratio that ranges between 0.85 to 0.90, no TiO_2 and Cr_2O_3 , Al_{tot} content is between 0.04 and 0.38 (p.f.u.) and Na contents between 0.04 and 0.36 (p.f.u.), both values decreasing from actinolite in metagabbros to schists. Amphibole III (in schists and serpentinite) has tremolite composition with X_{Mg} ratio higher than 0.90 (Tab. 1, Fig. 5a), Al_{tot} below 0.01 (p.f.u.) and Na below 0.04 (p.f.u.). Hornblende relics are absent.

Most clinopyroxene (cpx I and II) shows augite-diopside compositions with X_{Mg} equal to 0.83–0.84, Al_{tot} content ranging between 0.02 and 0.20 and Na (p.f.u.) < 0.10 (Tab. 1; Fig. 5b). Still in some deformed metagabbros (CO1408; Fig. 5b), cpx I coexists with crystals of cpx II enriched in jadeite component in which Na (p.f.u.) is higher (0.47–0.54) and X_{Mg} lower (0.62–0.78).

Chlorite in metagabbros and schists shows large compositional variations. Clinocllore is present in metagabbros (Si p.f.u. ranging between 5.7 and 5.9; Fig. 5c). Chlorite II has X_{Mg} between 0.81 and 0.83 as well as Al_{tot} between 4.41 and 4.81. Cr_2O_3 and NiO contents are low (<0.64 wt% and <0.17 wt%, respectively). Chlorite III in schists is highly variable (clinocllore and penninite are locally present; Fig. 4c) and can have higher X_{Mg} ratio (0.89) and lower Al_{tot} at 3.10–3.31 (p.f.u.). Cr_2O_3 and NiO increase drastically (up to 4.72 wt% and 0.42 wt%, respectively).

Plagioclase II is mostly albite (An_{0-2}) and rarely oligoclase (An_{14}).

Epidote belongs to the epidote-clinozoisite series and shows a moderate variability in $X_{\text{Fe}^{3+}}$ ratio ranging between 0.06 and 0.18.

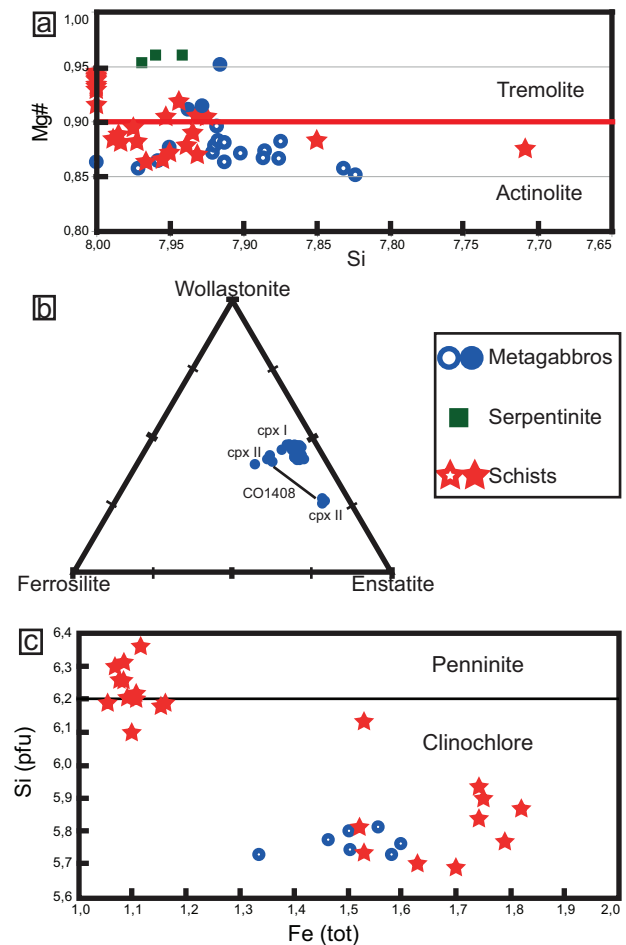


Fig. 5. Mineral chemistries. a. Mg# versus Si content of amphibole showing the trend between tremolite ($\text{Si} > 0.90$) and actinolite ($\text{Si} < 0.90$). Amp III in filled symbols. b. Wollastonite-Ferrosilite-Enstatite triangular diagram representing pyroxene chemistry. Cpx II in filled symbols. d. Si (p.f.u.) versus Fe_{tot} of chlorite showing the trend between penninite and clinocllore ($\text{Si p.f.u.} < 6.2$).

5.3 Whole rock composition

Figure 6a is an ACF diagram representing the chemical composition of the three rock types (Tab. 3). Metagabbro compositions cluster around 20% Al_2O_3 , 40% ($\text{FeO} + \text{MgO}$) and 40% CaO. Serpentine contains low amounts of Al_2O_3 and no CaO, therefore, plots at the near ($\text{FeO} + \text{MgO}$) apex of the triangle. Schist compositions are located at an intermediated position between metagabbros and serpentinite and present moderate variations in CaO (20% to 30%) and Al_2O_3 (0% to 15%).

Figure 6b is a binary plot showing a linear correlation between the Al_2O_3 and TiO_2 contents (in wt%) of the three studied groups of rocks. Those elements are considered relatively fluid immobile (see below §5.5). The groups showing the lowest and highest values are serpentinite and metagabbros, respectively, whereas values for schists are intermediate.

5.4 Closed-system thermodynamic modelling of metagabbros

Thermodynamic modelling has been used to estimate the P-T-fluid conditions of the isochemical (except for H₂O) shear zone formation within the oceanic crustal metagabbros. We have followed the reasoning and assumptions of [Oliot *et al.* \(2010\)](#) and [Goncalves *et al.* \(2012, 2013, 2016\)](#) deduced from deformed metagranites. [Figure 7a](#) is a T-X_{H₂O} binary phase diagram of the average metagabbros composition ([Tab. 3](#)), calculated from anhydrous to water-saturated conditions in the CNFMASH chemical system. The chosen temperature range is from 300 °C to 600 °C and pressure has been fixed at 4.5 kbars in agreement with [Caron *et al.* \(1981\)](#) and [Lahondère *et al.* \(1992\)](#). The amphibole – clinopyroxene – clinozoisite – chlorite – albite assemblage is stable between 310 °C and 450 °C under water-saturated conditions. As observed in thin sections from the slightly deformed metagabbros to the schists, the modal abundance of amphibole increases with temperature (as shown by the isopleths in [Fig. 7b](#)) until water saturation. Increasing the water content does not allow the complete disappearance of albite and epidote which marks the transition from metagabbros to schists. The fact that the petrography of schists cannot be fully explained by the sole addition of water (*i.e.*, from water-undersaturated conditions up to saturation as evidenced by [Fig. 7](#)) indicates that the system must have been chemically open in order to allow schist formation. Therefore hydrating the gabbro (with no mass transfer) is not sufficient to form the schists. This is corroborated by a distinct difference in the major bulk composition of the schists and the metagabbros ([Fig. 6](#)). We can therefore conclude that this transformation occurs under open system conditions, where mass transfer occurs due to chemical and mechanical interactions between a metamorphic aqueous-fluid phase, the surrounding metagabbros and the serpentinite clasts. In addition, the observation in the T-XH₂O phase diagram of two clinopyroxenes occurs slightly below water saturation (grey field in [Fig. 7c](#)). This water fraction (XH₂O=0.64) is therefore chosen for the P-T diagram in [Figure 8](#).

[Figure 8](#) is an equilibrium assemblage diagram (computed with the amount of water allowing the occurrence of two pyroxenes) presenting possible parageneses for the bulk composition of the average non-metasomatized metagabbros composition. The observed assemblage of two clinopyroxenes – amphibole – chlorite – clinozoisite – albite is stable over a large pressure but narrow temperature range (250–400 °C and 3–6 kbars). If the formation of Cpx II is considered a continuous process involving cooling and deformation we cannot exclude that it has started at a slightly higher T (450 °C) in the light grey field ([Fig. 8](#)) where only one clinopyroxene is present in the assemblage. The presence, in small quantities, of pumpellyite in metagabbros is attributed to retrograde equilibration upon cooling. In this equilibrium assemblage diagram, the predicted stability field of the observed assemblage is mostly temperature-dependent. The chosen pressure range (3–6 kbars) is constrained by literature data and the presence of Cpx II: testing [Figure 7c](#) at different pressures indicates that the 2 clinopyroxenes field disappears with increasing pressure (>6 kbars). Finally, for example, at 4.5 kbars and 350 °C, the phase equilibrium model reasonably

predicts modal abundances of 20% chlorite (clinochlore), 19% amphibole (tremolite), 8% two clinopyroxenes (diopside and Na-rich-clinopyroxene), 21% albite, 28% clinozoisite, which is in accordance with our thin section observations for the metagabbros.

5.5 Open-system geochemical modelling for the formation of amphibole-chlorite schists

The thermodynamical modelling results presented above indicate that deformation within metagabbros taking place under greenschist facies and water-saturated conditions occurs (at least initially) in a closed system (except for the H₂O intake) as the bulk chemical composition of metagabbros is quite homogeneous independent of their degree of deformation ([Sect. 5.3](#) and [Table 3](#)). However, [section 5.4](#) shows that the formation of schists in shear zones cannot be explained by a continuation of this process because [Figure 7](#) shows that the sole hydration of a metagabbro does not allow the formation of the schist assemblage and suggests that an opening of the system to an external influx of other elements occurs at higher fluid-rock ratios, and geochemical arguments are presented below.

The results of chemical mass-balance calculations are presented in [Table 4](#) and [Figure 9](#). Modal abundance of hydrated Mg(-Fe)-bearing phases strongly increases in the schists, as well as MgO(-FeO)-contents in these minerals. Looking at the bulk rock compositions ([Tab. 3](#)), and as a consequence of normalizations during bulk rock compositions measurements, the relative contents of MgO, L.O.I. (mostly H₂O fluid) and Fe₂O₃* (total iron expressed as ferric iron) seem to increase in the schists, whereas Al₂O₃, SiO₂, CaO and Na₂O seems to decrease. However, these trends cannot reflect the true mass transfer operating during metasomatic processes (see [Durand *et al.*, 2015](#), for an explanation).

Thus during mass-balance calculations, based on the calculation methodology ([Baumgartner and Olsen, 1995](#)), petrographic observations and the chemical environment, the isocon line passing through the higher number of immobile elements has been chosen: Al₂O₃, CaO, TiO₂, and P₂O₅. ([Fig. 9a](#)). Thus, isocon log-log diagram and the chosen isocon line display that the most mobile chemical components during low-grade shear zone formation in the studied metagabbro are MgO, H₂O (*i.e.* L.O.I.), Fe₂O₃* (gains) and Na₂O (loss) ([Fig. 9a,b](#)). Al₂O₃ and TiO₂ have been chosen as immobile here because they are commonly considered as such insoluble and immobile element during alteration processes ([Grant, 1986](#); [Streit and Cox, 1998](#); [Barnes *et al.*, 2004](#); [Rossi *et al.*, 2005](#); [Oliot *et al.*, 2010](#), and reference therein). In detail, alteration via dissolution of serpentinite clasts followed by precipitation promotes local gains of MgO (+399% ; +43.15 g·100g⁻¹), H₂O (+270% ; +8.46 g·100g⁻¹), Fe₂O₃* (+214% ; +9.11 g·100g⁻¹), SiO₂ (+88% ; +42.96 g·100g⁻¹) and MnO (+135% ; +0.12 g·100g⁻¹) during shear zones formation. On the other side, loss of Na₂O reaches -83% (-1.94 g·100g⁻¹). Finally, the total mass change is +101.59±16.37 g·100g⁻¹ and related volume changes is +110.85±61.44%, during schistose rocks formation in the studied metagabbros.

Mass balance equation can be written as follows ([Tab. 4](#)):

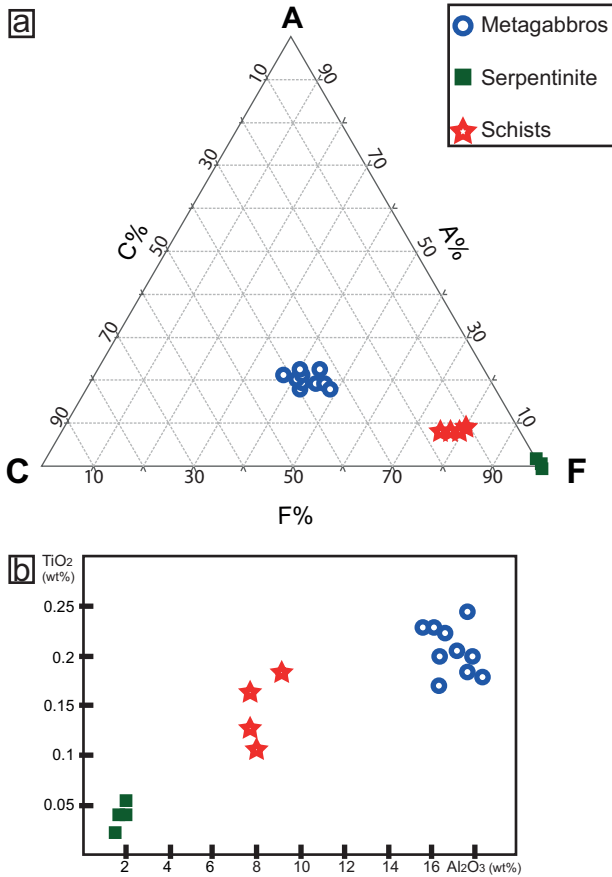


Fig. 6. a. ACF diagram representing the composition of the three rock types considered: metagabbros, schists and serpentinite. A is corrected for sodium and potassium ($A = Al_2O_3 - Na_2O - K_2O$), C is corrected for phosphorus ($C = CaO - P_2O_3$) and F is corrected for manganese and titanium ($F = FeO_1 + MgO - MnO - TiO_2$ with $FeO_1 = 0.8998 \times Fe_2O_3$). b. Binary diagram representing the trend of Al_2O_3 vs TiO_2 in the bulk rocks.

[100g Parent rock + amounts gained during the process
 → altered rock + amounts lost during the process]

100g metagabbro + 43.15 ± 5.71 g MgO + 42.96 ± 8.33 g
 SiO_2 + 9.11 ± 2.42 g $Fe_2O_3^*$ + 8.46 ± 2.19 g H_2O + $0.12 \pm$
 0.03 g MnO + 0.05 ± 0.03 g K_2O → **201.59 ± 16.37g**
schistose rock + 1.94 ± 0.41 g Na_2O

5.6 Thermodynamic modelling of mechanical mixing under open-system conditions

Figure 10 is a T-X equilibrium assemblage diagram calculated in order to represent changes in assemblages for mixture compositions ranging between the average composition of metagabbros ($X=0$, Tab. 3) and serpentinite clasts ($X=1$, Tab. 3). The representative assemblage for the metagabbros (Chl – Amp – Cpx – Czo – Ab – H_2O) is stable below 450 °C for $X < 0.50$ with metamorphic clinopyroxene occurring at compositions between 0.50 and 0.55. The high variance assemblage of the schists is stable (Chl – 2 Amp – H_2O) at temperature > 450 °C and $X > 0.60$. This field is additionally constrained by the absence of Opx

(appearing at $T > 580$ °C) and Talc (appearing at $T < 440$ °C). This model of physical and chemical mixing successfully reproduces: i) the appearance of high variance assemblages observed in schists dominated by amphiboles (tremolite and actinolite) and chlorite; ii) the disappearance of minerals forming after magmatic plagioclase (albite and clinozoisite) towards serpentinite clast composition (around 0.5).

6 Discussion

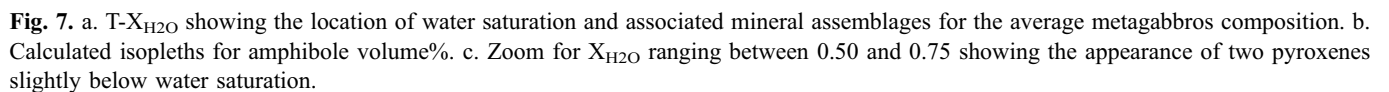
6.1 Structural and petrological aspects of the amphibole-chlorite schists shear zones formed in Alpine metagabbros.

Our results suggest that the low-grade shear zones studied here are formed during the late stage of exhumation during Alpine subduction for the three following reasons. Firstly, the studied metagabbros have a foliation that is fully concordant with the regional foliation of Alpine Corsica, which is unequivocally associated with HP/LT metamorphism and Alpine subduction (see § 2. and Fig. 1 and 2). Metagabbros were thus formed during the Alpine subduction/exhumation cycle. The amphibole-chlorite schists cross-cut this main foliation (Fig. 2), suggesting that they represent the last stage of exhumation. Secondly, the absence of hornblende suggests that the process was discontinuous and does not record continuous deformation and cooling from HT to greenschist at the oceanic ridge (e.g., Atlantis Massif, Schroeder and John, 2004; Allard *et al.*, 2021). Thirdly, our thermodynamic and P - T calculations indicate low pressure and temperature conditions (300–400 °C and 3–6 kbars) as well as the large variability of the chemistry of amphibole and chlorite in the schists. These conditions are consistent with previous estimates of the metamorphic conditions of the retrograde overprint are 400–500 °C and 3–6 kbar (Caron *et al.*, 1981 and Lahondère *et al.*, 1992).

From a chemical point of view, chlorite chemistry is largely variable and may reflect the polyphase character of the rocks. Chlorite composition in metagabbros shows low XMg (0.81–0.84) and high Al contents (4.2–4.6) which may correspond to primary oceanic chlorite. On the other hand, chlorite in schists is probably metamorphic with lower Al contents (3.0–3.2) and higher XMg (0.89–0.90). At low temperatures (ca. 400 °C), the appearance of talc is chemically controlled by the proximity of ultramafic clasts (Picazo *et al.*, 2012) or by a lowering of water activity of the fluid linked to the presence of CO₂. As talc is not observed in the studied schists, it can be concluded that the chemistry of fluid is probably initially dominated by the metagabbros (with little influence or low volume of serpentinite available for reaction during the initial stages of the hydration of the metagabbro).

6.2 Deciphering processes of open-system fluid-present mechanical mixing leading to the formation of amphibole-chlorite schists shear zones

The changes in mineralogy and chemistry involved by the fluid-assisted transformation coupled to localized deformation of the Marine de Giottani metagabbros into amphibole-chlorite schists is summarized in Figure 11. Schists are the products of



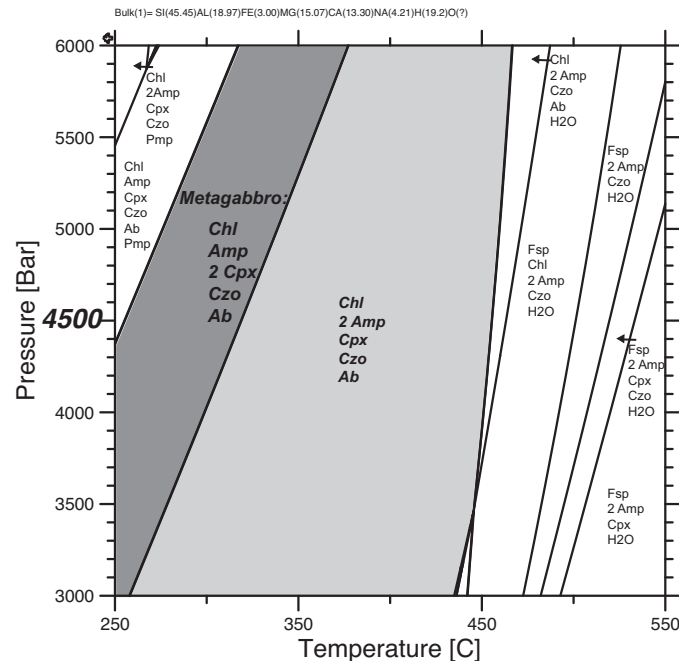


Fig. 8. Pressure-Temperature (P-T) equilibrium assemblage diagram showing the stability field of the observed mineral paragenesis in metagabbros. Abbreviations are after [Whitney and Evans \(2010\)](#) as follows Ab (albite), Amp (amphibole), Chl (chlorite), Cpx (clinopyroxene), Czo (clinozoisite), Fsp (feldspar), Pmp (pumpellyite).

a fluid-assisted mechanical mixing and metasomatism between metagabbros, metamorphic fluids and the serpentinite clasts present locally. Firstly, this is shown by the bulk chemical data ([Fig. 6](#)) that indicate that the chemistry of schist results from a fluid-assisted mixing and metasomatism of two components (metagabbros and serpentinite). This mechanism is able to create the chemical variations observed in the schists. The variability in schists' compositions reflects whether the transformation is principally controlled by the metagabbros under open-system conditions or if it is associated with the participation of the serpentinite clast component. With increasing deformation and fluid-rock ratios through time, sodium is progressively lost reflecting the destabilization of plagioclase into epidote and white micas. On the contrary, magnesium, silicon, water and iron significantly increase in the system via precipitation after serpentinite clasts alteration, certainly enhanced by deformation and dissolution processes. This is probably controlled by the thermodynamic stability of hydrated (Fe-) Mg-rich minerals like tremolite and chlorite whose modal abundance drastically increases in the schists. From a petrological and thermodynamic point of view, this process is characterized by the appearance of amphibole and chlorite at the expense of magmatic minerals (clinopyroxene and plagioclase). From a geochemical point of view, this dissolution-precipitation process is accompanied by gains in MgO, SiO₂, H₂O and FeO (originating from the serpentinite clasts) and a loss in Na₂O. From a mechanical point of view, unstable ultramafic clasts reacted and serve as metasomatic shear zones nuclei. Indeed, the clasts are heterogeneities that favour the chlorite-amphibole-forming softening reactions, promoting localized deformation. These mechanical and chemical heterogeneities are thus essential in the processes

of hydraulic weakening and strain localization and there is a positive feedback loop between chemistry and mechanics to form schists from metagabbros with a serpentinite component.

To summarize, fluid-assisted mechanical mixing and metasomatism allow the complete transformation of a metagabbro into a weak rock. The rheological consequences will be discussed in §6.4. This process occurs within a deformation and temperature continuum (350–450 °C and 3–6 kbars) between metagabbros and serpentinite clasts under Alpine retrograde conditions.

6.3 Comparison with amphibole-chlorite schists within metagabbros worldwide

Pioneer work on thermodynamic modelling of fluid-assisted deformed and metasomatized rocks has shed some light on thermo-chemical processes controlling shear zone formation in a metagranodioritic system ([Goncalves *et al.*, 2012](#)) and *P-T-X* diagrams can successfully describe the effects of mass transfer on phase relations in open systems ([Oliot *et al.*, 2010](#); [Goncalves *et al.*, 2013](#); this study). We have followed the same methodology to decipher thermochemical changes in a different chemical system (*i.e.* the mafic oceanic crust).

Both in felsic or mafic rocks, the opening of the chemical system is often associated with a gain in Mg which is often interpreted in terms of metasomatism. In the Alpine realm, some authors consider that chemical transfer between greenschist facies Alpine shear zones in the Mont Blanc granitoids in the external Alps ([Rossi *et al.*, 2005](#)) and surrounding rocks (episyenite and granite) do not necessitate external source fluids. However, many authors show evidence

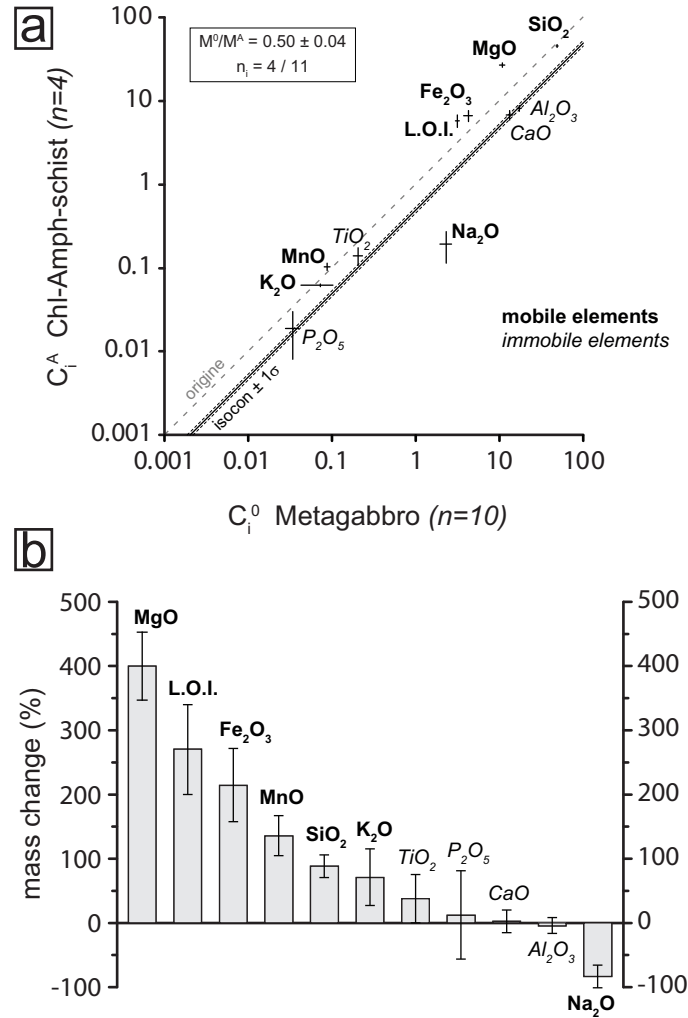
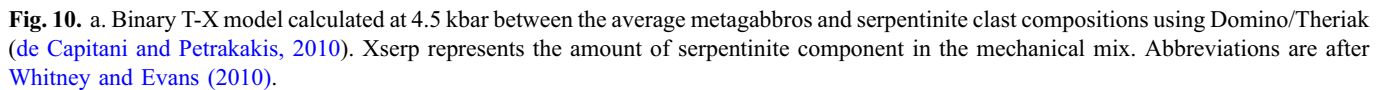


Fig. 9. Results of mass balance calculations. a. Log-Log Isocon diagrams (after Baumgartner and Olsen, 1995) illustrating the results of mass transfers between the "altered" schists and "host" metagabbros; b. Histogram showing the relative mass changes of each oxide during the low-grade shear zone development.

of open system Mg – metasomatism, for example in shear zones in metagranitoids from the internal domains (e.g., Ferrando, 2012; Goncalves *et al.*, 2012 and references therein). The Mg-rich fluids circulating in faults and shear zones originate from a diachronous interaction between underlying ultramafic rocks and seawater. Similar conclusions were drawn for the origin of white schists from Austroalpine units (Demeny *et al.*, 1997) in which D and O isotope data indicate that metasomatic fluids take their origin in hydrothermally altered oceanic crust. In oceanic environments as well, Mg-metasomatism is also recognized and related to the interaction between the hydration of ultramafic rocks and gabbros in the presence of fluids (Scambelluri and Rampone, 1999). In the Eastern Alps, Barnes *et al.* (2004) have shown that the effect of fluids generated by serpentinite devolatilization on the metasomatized protolith is similar whether the interaction is close to the source serpentinite (*i.e.* formation of blackwalls around the serpentinite clast itself) or further away (crystallization of blackwall-like schists) along the fluid pathways. In this study, serpentinite is present in the same structural unit as

the studied metagabbros, and serpentinite clasts as well (Figs. 1, 2 and 3). Therefore the latter may be the source of the external Fe and Mg that are added to metamorphic fluids. Finally, the formation of late-stage albite-rich veins associated with the greenschist retrogression (Miller and Cartwright, 2006) is a possible sink in the same geological unit for the released Na.

Metasomatism in orogenic systems is classically accompanied by Na- and Ca- losses which are often linked to the breakdown of plagioclase (e.g., Condie and Sinha, 1996, Streit and Cox, 1998, Ague, 2011, Goncalves *et al.*, 2012) whether the protolith is granitic or gabbroic. In our study, Na is lost while Ca does not appear to leave the system during the low-grade shear zone formation. In addition, we propose that Al is as well immobile, being often not affected by water-rock interactions (Carmichael, 1969; Ragnarsdottir and Walther, 1985). This is consistent with the fact that Al is regularly considered immobile in mass-transfer calculations (Grant, 1986; Streit and Cox, 1998; Barnes *et al.*, 2004; Rossi *et al.*, 2005). In mafic protoliths, the formation of mylonitized



Part of the processes leading to the formation of amphibole-chlorite schists occurred due to mass transfers

Page 18 of 22

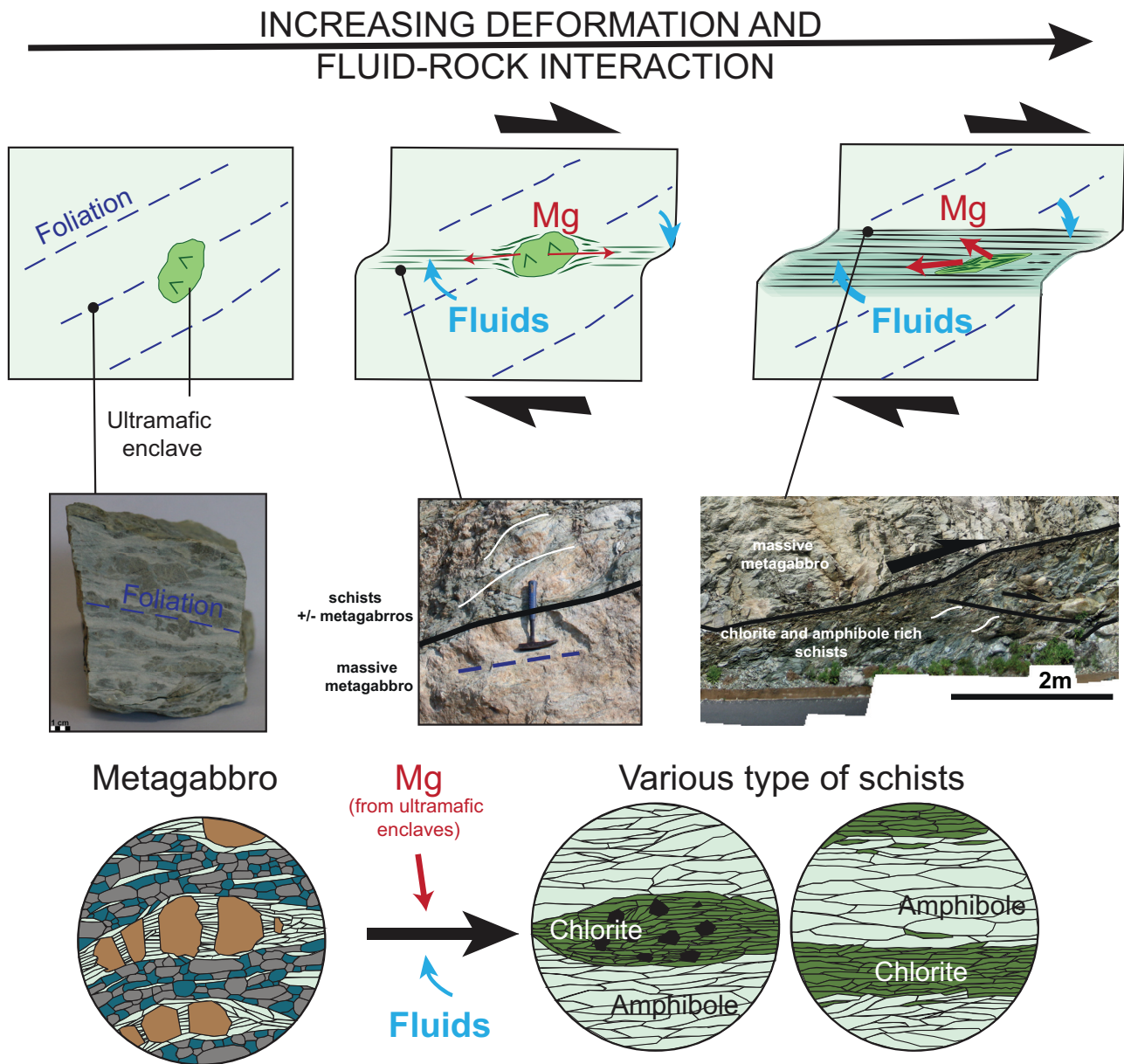


Fig. 11. Schematic structural and petrologic sketch summarizing the formation mechanisms of amphibole-chlorite schists in shear zones in the Marine de Giottani metagabbros. The deformation in metagabbros that initially localizes around serpentinite clasts is enhanced by metamorphic reactions implied by fluid-assisted mechanical mixing and metasomatism between those two end-members. Deformation, fluids and metamorphism create and maintain a positive feedback loop that allows rock weakening within the newly formed amphibole-bearing shear zones.

mixing and fluid infiltration in a subduction mélange zone over a continuum of a large range of P-T conditions leading to hybrid chemical compositions of melts derived from this heterogeneous system. According to [Essaifi *et al.* \(2004\)](#), amphibole-dominated and chlorite-dominated mylonites and shear zones occur in the layered mafic-ultramafic Kettara intrusion in Morocco due to large-scale fluid flow associated with regional MT-LP metamorphism. Similarly, the La Melada metagabbro in Argentina records an entire retrograde P-T path from granulite to sub-greenschist facies conditions ([Cruciani *et al.*, 2011](#)). Both during the crustal thickening-related metamorphism under amphibolite facies and the later stage

associated with post-orogenic extensional shear deformation, actinolite – chlorite – quartz rocks form at the expense of magmatic and metamorphic minerals (pyroxene, amphibole and plagioclase). Mylonitic bands and fault gouges filled with tremolite-chlorite schists within metagabbros are reported in the Voltri Massif of the Ligurian ophiolites as well ([Giacomini *et al.*, 2010](#)). They represent the products of fluid-assisted, dynamic recrystallization of gabbroic rocks under greenschist facies conditions during the Alpine orogeny. Finally, another recent study ([Oyanagi *et al.*, 2023](#)) of mass transfer and fluid flow within the subduction interface shows that the interaction between metasediments and serpentinites leads to the

formation of tremolite-chlorite schists which are considered to influence slab–mantle decoupling and seismicity.

6.4 Rheological implications

This study highlights that, in subduction zones under water-saturated open-system conditions, metagabbros containing serpentinized peridotite clasts can be transformed into amphibole-chlorite-bearing schists during strain localization. Metagabbros is mostly formed of relict magmatic pyroxene, metamorphic plagioclase, epidote and amphibole, while schists are mostly composed of metamorphic amphiboles and chlorite. During low- to mid-temperature deformation, metagabbros are thus stronger than schists, mostly because of the high amount of strong porphyroclastic pyroxene in metagabbros compared to weaker phyllosilicates-rich schists (see rheological parameters in Bürgmann and Dresen, 2008). Fluid-enhanced metamorphic transformation, mass transfers due to synchronous mechanical mixing and metasomatism, and the presence of reacting ultramafic materials induces therefore a major weakening that is responsible for strain localization and the formation of amphibole-chlorite-bearing shear zones. On these bases, we propose that the pyroxene to tremolite transformation acts as a major weakening mechanism in subducting oceanic crust at greenschist facies conditions. In exhumed oceanic mélange, like in the Franciscan complex (see Wakabayashi 2015 for a synthesis), the juxtaposition of metagabbros and serpentinite rocks is common and can trigger such transformation and the formation of very weak amphibole-bearing schists in highly deformed zones. This may provide a potential mechanical explanation for considerable variations in strength along the San Andreas faults, with some creeping sections that may be related to such transformation and the presence of amphibole-bearing schists. This is furthermore consistent with the suggestion that talc-bearing serpentinites can explain the creeping section of the San Andreas Fault (Moore and Rymer, 2007). Note that the metastability of mélanges in subduction settings at higher temperature (500–700 °C) leads to a progressive replacement of weak phyllosilicates (talc, serpentine and chlorite) into stronger minerals (amphibole, olivine and pyroxene and hence induce the strengthening of the mélange during deformation (Penniston-Dorland *et al.*, 2018). The inferred weakening process in our present study is therefore limited inside the subduction zone: the mechanical mixing, fluid-rock interaction and metasomatism implies major weakening at low temperature (greenschist facies conditions) and strengthening at higher temperature (amphibolite facies conditions).

7 Conclusions

The detailed structural, petrological, thermodynamical and geochemical study of the formation of amphibole-chlorite schists within greenschist facies metagabbros in Alpine Corsica shows that i) schists have formed within shear zones associated with the Alpine exhumation of the meta-ophiolites of the Upper Oceanic unit; ii) the transformation of metagabbros into schists occurs under water-saturated open-system conditions in the presence of serpentinite clasts and

Mg-rich metasomatic fluids; iii) this metamorphic transformation induces a major weakening that may be responsible for creeping sections of faults within the subducted oceanic crust. Finally, this study opens new avenues for the understanding of the rheology of the oceanic crust during the subduction-exhumation cycle.

Acknowledgments

We thank the financial support of the INSU/SYSTER program of the CNRS. The authors gratefully acknowledge Christophe Nevado and Doriane Delmas for thin section preparation, Bernard Boyer for his involvement in EPMA at Service Microsonde Sud, Montpellier University and Mélody Philippon for assistance during an early field campaign. J.A.P.N. acknowledges a Ramón y Cajal fellowship RYC2018-024363-I funded by MICIN/AEI/10.13039/501100011033 and the FSE program “FSE invierte en tu futuro”. We thank F. Piccoli, P. Boulvais and three anonymous reviewers for commenting on an earlier version of the manuscript. We thank D. Chardon and L. Jolivet for editorial handling.

References

- Ague JJ. 2011. Extreme channelization of fluid and the problem of element mobility during Barrovian metamorphism. *American Mineralogist* 96: 333–352.
- Allard M, Ildefonse B, Oliot E, Barou F. 2021. Plastic Deformation of Plagioclase in Oceanic Gabbro Accreted at a Slow-Spreading Ridge (Hole U1473A, Atlantis Bank, Southwest Indian Ridge). *J Geophys Res Solid Earth*. <https://doi.org/10.1029/2021JB021964>.
- Baldwin JA, Powell R, Brown M, Moraes R, Fuck RA. 2005. Modelling of mineral equilibria in ultrahigh-temperature metamorphic rocks from the Anapolis-Itaucu Complex, central Brazil. *J Metamorph Geol* 23: 511–531.
- Barnes JD, Selverstone J, Sharp ZD. 2004. Interactions between serpentinite devolatilization, metasomatism and strike-slip strain localization during deep-crustal shearing in the Eastern Alps. *J Metamorph Geol* 22: 283–300.
- Baumgartner LP, Olsen SN. 1995. A least-squares approach to mass transport calculations using the isocon method. *Economic Geol* 90: 1261–1270.
- Bürgmann, R., & Dresen, G. (2008). Rheology of the lower crust and upper mantle: Evidence from rock mechanics, geodesy, and field observations. *Annu. Rev. Earth Planet. Sci.*, 36: 531–567.
- Carmichael DM. 1969. On the mechanism of prograde metamorphic reactions in quartz bearing pelitic rocks. *Contrib Mineral Petrol* 20: 244–267.
- Caron JM, Kiénast JR, Triboulet C. 1981. High-pressure – low-temperature metamorphism and polyphase alpine deformation at Sant’Andrea-di-Cotone (Eastern Corsica, France). *Tectonophysics* 78: 419–451.
- Condie KC, Sinha AK. 1996. Rare earth and other trace element mobility during mylonitization: a comparison of the Brevard and Hope Valley shear zones in the Appalachian Mountains, USA. *J Metamorph Geol* 14: 213–226.
- Cruciani G, Franceschelli M, Brogioni N. 2011. Mineral re-equilibration and P-T path of metagabbros, Sierra de San Luis, Argentina: insights into the exhumation of mafic-ultramafic belt. *Eur J Mineral* 23: 591–608.

- Demeny A., Sharp Z.D., Pfeifer H.R., 1997. Mg-metasomatism and formation conditions of Mg-chlorite-muscovite-quartz-phylrites (leucophyllites) of the Eastern Alps (W. Hungary) and their relations to Alpine whiteschists. *Contributions to Mineralogy and Petrology* 128: 247–260.
- de Capitani C., Petrakakis K. 2010. The computation of equilibrium assemblage diagrams with Theriak/Domino software. *Am Mineralog* 95: 1006–1016.
- Diener JFA, Powell R, White RW, Holland TJB. 2007. A new thermodynamic model for clino- and orthoamphiboles in the system Na₂O-CaO-FeO-MgO-Al₂O₃-SiO₂-H₂O-O. *J Metamorph Geol* 25: 631–656.
- Dipple GM, Ferry JM. 1992. Metasomatism and fluid-flow in ductile fault zones. *Contrib Mineral Petrolog* 112: 149–164.
- Durand C, Oliot E, Marquer D, Sizun JP. 2015. Comparison of three mass-balance approaches applied to mass transfer in a shear zone and a metacarbonate xenolith. *Eur J Mineral.* <https://doi.org/10.1127/ejm/2015/0027-2475>.
- Essaifi A, Capdevila R, Fourcade S, Lagarde JL, Ballèvre M, Marignac CH. 2004. Hydrothermal alteration, fluid flow and volume change in shear zones: the layered mafic-ultramafic Kettara intrusion (Jebilet Massif, variscan belt, Morocco). *J Metamorph Geol* 22: 25–43.
- Ferrando S. 2012. Mg-metasomatism of granitoids from the Alps : genesis and possible tectonic scenarios. *Terra Nova* 24: 423–436.
- Fournier M, Jolivet L, Goffé B, Dubois R. 1991. Alpine Corsica metamorphic core complex. *Tectonics* 10: 1173–1186.
- Giacomini F, Boerio V, Polattini S, Tiepolo M, Tribuzio R, Zanetti A. 2010. Evaluating asbestos fibre concentration in metaophiolites: a case study from the Voltri Massif and Sestri-Voltaggio Zone (Liguria, NW Italy). *Environ Earth Sci* 61: 1621–1639.
- Goncalves P, Oliot E, Marquer D, Connolly JAD. 2012. Role of chemical processes on shear zone formation: an example from the Grimsel metagranodiorite (Aar massif, Central Alps). *J Metamorphic Geol* 30: 703–722.
- Goncalves P, Marquer D, Oliot E, Durand C. 2013. Thermodynamic modelling and thermobarometry of metasomatized rocks. In Harlov, D.E. and Austrheim, H., *Metasomatism and the chemical transformation of rock*, Lecture Notes in Earth System Sciences, Springer-Verlag Berlin Heidelberg.
- Goncalves P, Poilvet JC, Oliot E, Trap P, Marquer D. 2016. How does shear zone nucleate? An example from the *Suretta nappe* (Swiss Eastern Alps). *J Struct Geol* 86: 166–180.
- Guillot S, Schwartz S, Reynard B, Agard P, Prigent C. 2015. Tectonic significance of serpentinites. *Tectonophysics* 646: 1–19.
- Grant JA. 1986. The isocon diagram—a simple solution the Gresens' equation for metasomatic alteration. *Econ Geol* 8: 1976–1982.
- Green E, Holland TJB, Powell R. 2007. An order-disorder model for omphacitic pyroxenes in the system jadeite-diopside-hedenbergite-acmite, with applications to eclogitic rocks. *Am Mineralog* 92: 1181–1189.
- Gueydan F, Leroy YM, Jolivet L, Agard, P. 2003. Analysis of continental midcrustal strain localization induced by microfracturing and reaction-softening. *J Geophys Res* 108: ETG1.1–ETG1.17.
- Gueydan F, Précigout J, Montési LGJ. 2014. Strain weakening enables continental plate tectonics. *Tectonophysics* 631: <https://doi.org/10.1016/j.tecto.2014.02.005>.
- Gueydan F, Brun JP, Phillippon M, Noury M. 2017. Sequential extension as a record of Corsica Rotation during Apennines slab roll-back. *Tectonophysics* 710–711: 149–161.
- Gyomlai T, Agard P, Marschall HR, Jolivet L, Gerdes A. 2021. Metasomatism and deformation of block-in-matrix structures in Syros: The role of inheritance and fluid-rock interactions along the subduction interface. *Lithos* 386–387: 105996.
- Harigane Y, Okamoto A, Morishita T, Snow JE, Tamura A, Yamashita H, Michibayashi K, Ohara Y, Arai S. 2019. Melt-fluid infiltration along detachment shear zones in oceanic core complexes: Insights from amphiboles in gabbro mylonites from the Godzilla Megamullion, Parece Vela Basin, the Philippine Sea. *Lithos* 344–345: 217–231.
- Holland TJB, Powell R. 1998. An internally consistent thermodynamic dataset for phases of petrological interest. *J Metamorph Geol* 16: 309–343.
- Jolivet L, Dubois R, Fournier M, Goffé B, Michard A, Jourdan C. 1990. Ductile extension in Alpine Corsica. *Geology* 18: 1007–1010.
- Kelsey DE, White RW, Powell R. 2005. Calculated phase equilibria in K₂O-FeO-MgO-Al₂O₃-SiO₂-H₂O for silica-undersaturated sapphirine-bearing mineral assemblages. *J Metamorphic Geol* 23: 217–239.
- Klein F, Goldsby DL, Lin J, Andreani M. 2022. Carbonation of serpentinite in creeping faults of California. *Geophys Res Lett* 49: e2022GL099185.
- Lahondère JC, Lahondère D, Lluch D, Ohenstetter M, Dominici R, Vautrelle C. 1992. Notice explicative de la feuille LURI à 1/50000. Éditions du BRGM – BP 6009 – Orléans Cedex 2-France.
- Leake BE, Woolley AR, Arps CES, Birch WD, Gilbert MC, Grice JD, Hawthorne FC, Kato A, Kisch HJ, Krivovichev VG, Linthouk K. 1997. Report. nomenclature of amphiboles: report of the subcommittee on amphiboles of the International Mineralogical Association Commission on new minerals and mineral names. *Mineralog Mag* 61: 295–321.
- Leydier T, Goncalves P, Lanari P, Oliot E. 2019. On the petrology of brittle precursors of shear zones – an expression of concomitant brittle deformation and fluid-rock interactions in the “ductile” continental crust? *J Metamorph Geol* 37: 1129–1149.
- Mancktelow N, Pennacchioni G. 2020. Intermittent fracturing in the middle continental crust as evidence for transient switching of principal stress axes associated with the subduction zone earthquake cycle. *Geology* 48: 1072–1076.
- Miller JA, Cartwright I. 2006. Albite vein formation during exhumation of high-pressure terranes: a case study from alpine Corsica. *J Metamorph Geol* 24: 409–428.
- Molli G. 2008. Northern Apennine-Corsica orogenic system: an updated overview. From: Siegesmund, S., Fügenschuh, B. & Froitzheim, N. (eds) *Tectonic Aspects of the Alpine-Dinaride-Carpathian System*. Geological Society, London, Special Publications 298: 413–442.
- Moore DE, Rymer MJ. 2007. Talc-bearing serpentinite and the creeping section of the San Andreas fault. *Nature* 448. <https://doi.org/10.1038/nature06064>
- Oliot E, Goncalves P, Marquer D. 2010. Role of plagioclase and reaction softening in a metagranite shear zone at mid-crustal conditions (Gotthard Massif, Swiss Central Alps). *J Metamorph Geol* 28: 849–871.
- Oliot E, Goncalves P, Schulmann K, Marquer D, Lexa O. 2014. Mid-crustal shear zone formation in granitic rocks : Constraints from quantitative textural and crystallographic preferred orientations analyses. *Tectonophysics* 612–613: 63–80.
- Oyanagi R, Uno M, Okamoto A. 2023. Metasomatism at a metapelite-ultramafic rock contact at the subduction interface: Insights into mass transfer and fluid flow at the mantle wedge corner. *Contrib Mineral Petrol* 178: 27.

- Penniniston-Dorland SC, Gorman JK, Bebout GE, Piccoli PM, Walker RJ. 2014. Reaction rind formation in the Catalina Schist: Deciphering a history of mechanical mixing and metasomatic alteration. *Chem Geol* 384: 47–61.
- Penniniston-Dorland SC, Kohn MJ, Piccoli PM. 2018. A mélange of subduction temperatures: evidence from Zr-in-rutile thermometry for strengthening of the subduction interface. *Earth Planet Sci Lett* 482: 525–535.
- Picazo S, Cannat M, Delacour A, Escartin J, Rouméjon S, Silantyev S. 2012. Deformation associated with the denudation of mantle-derived rocks at the Mid-Atlantic Ridge 13°-15°N: The role of magmatic injections and hydrothermal alteration. *Geochem Geophys Geosyst* 13: Q04G09.
- Putnis A, Austrheim H. 2010. Fluid-induced processes: metasomatism and metamorphism. *Geofluids* 10: 254–269.
- Ragnarsdottir KV, Walther JV. 1985. Experimental determination of corundum solubilities in pure water between 400-700 °C and 1–3 kbars. *Geochim Cosmochim Acta* 49: 2109–2115.
- Rossi M, Rolland Y, Vidal O, Cox SF. 2005. Geochemical variations and element transfer during shear-zone development and related episyenites at middle crust depths: Insights from the Mont Blanc granite (French-Italian Alps) Geological Society, London, Special Publications 245: 373–396.
- Scambelluri M, Rampone E. 1999. Mg-metasomatism of oceanic gabbros and its control on Ti-clinohumite formation during eclogitization. *Contrib Mineral Petrol* 135: 1–17.
- Schroeder T, John BE. 2004. Strain localization on an oceanic detachment fault system, Atlantis Massif, 30°N, Mid-Atlantic Ridge. *Geochemistry, Geophysics, Geosystems*. <https://doi.org/10.1029/2004GC000728>.
- Streit JE, Cox SF. 1998. Fluid infiltration and volume change during mid-crustal mylonitization of Proterozoic granite, King Island, Tasmania. *J Metamorph Geol* 16 (2): 197–212.
- Vitale Brovarone A, Beyssac O, Malavieille J, Molli G, Beltrando M, Compagnoni R. 2013. Stacking and metamorphism of continuous segments of subducted lithosphere in a high-pressure wedge: the example of Alpine Corsica (France). *Earth Sci Rev* 116: 35–56.
- Wakabayashi J. 2015. Anatomy of a subduction complex: Architecture of the Franciscan Complex, California, at multiple length and time scales multiple length and time scales. *Int Geol Rev* 57: 669–746.
- White RW, Powell R, Clarke GL. 2002. The Interpretation of reaction textures in Fe-rich metapelitic granulites of the Musgrave Block, central Australia: Constraints from mineral equilibria calculations in the system K₂O-FeO-MgO-Al₂O₃-SiO₂-H₂O-TiO₂-Fe₂ O₃. *J Metamorph Geol* 20: 41–55.
- White RW, Powell R, Holland TJB. 2007. Progress relating to calculation of partial melting equilibria for metapelites. *J Metamorph Geol* 25: 511.
- Whitney DL, Evans BW. 2010. Abbreviations for names of rock-forming minerals. *Am Mineralog* 95: 185–187.
- Zihlmann B, Müller S, Coggon RM, Koepke J, Garbe-Schönberg D, Teagle DAH. 2018. Hydrothermal fault zones in the lower oceanic crust: An example from Wadi Gideah, Samail ophiolite, Oman. *Lithos* 323: 103–124.

Cite this article as: Cenki B, Oliot E, Gueydan F, Nègre L, Padrón-Navarta JA. 2025. Strain localization via mechanical mixing and metasomatism: an example from the metagabbros of Marine de Giottani, Alpine Corsica, France *BSGF - Earth Sciences Bulletin* 196: 10. <https://doi.org/10.1051/bsgf/2025003>