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Jean-Marc Lardeaux

Metamorphism and linked deformation in understanding tectonic processes at varied scales

Published online: 24 April 2023

https://doi.org/10.5802/crgeos.204

Part of Special Issue: Geodynamics of Continents and Oceans – A tribute to Jean Aubouin
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Les Comptes Rendus. Géoscience — Sciences de la Planète *sont membres du Centre Mersenne pour l'édition scientifique ouverte*
www.centre-mersenne.org
e-ISSN : 1778-7025

Comptes Rendus
Géoscience — Sciences de la Planète
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Geodynamics of Continents and Oceans – A tribute to Jean Aubouin / *Géodynamique des continents et des océans – Hommage à Jean Aubouin*

Metamorphism and linked deformation in understanding tectonic processes at varied scales

Jean-Marc Lardeaux [a, b]

[a] Géoazur - UMR 7329, Université Côte d'Azur, 250 Rue A. Einstein, Sophia-Antipolis, 06560 Valbonne, France

[b] Center for Lithospheric Research, Czech Geological Survey, Klárov 3, 11821, Prague 1, Czech Republic

E-mail: jean-marc.lardeaux@univ-cotedazur.fr

Abstract. This contribution presents a review exploring some aspects and issues surrounding the links between metamorphism and deformation at different scales. I first discuss the quantification methods of thermodynamics and the parameters able to overcome the kinetic barriers for metamorphic reactions. On the basis of some world's type iconic examples I discuss how metamorphism is likely to portray the thermo-mechanical evolution of lithosphere active zones, thus large-scale tectonic processes. Finally, I present the multiple interactions between metamorphism and deformation at rock and outcrop scales.

Keywords. Metamorphism, Ductile deformation, Tectonic processes, Subduction zones, Collision belts.

Published online: 24 April 2023

1. Introduction

Metamorphic rocks have long held interest for geologists owing to the specificity of their mineral assemblages in relation with the diversity of mountain belts in which they outcrop [e.g. Barrow, 1893, Eskola, 1915, Franchi, 1900, Suess, 1875]. Since the second half of the twentieth century there is a broad consensus that metamorphism is the dominant transformation mechanism in the lithosphere. Thus, the link between type of metamorphism and tectonic environment is widely recognized since the seminal publication of Miyashiro [1961]. Metamorphism generally occurs when a rock is subjected to conditions under which, for thermodynamic reasons, its mineral composition is no longer stable. But the presence of fluids and the mechanisms of inter- or intracrystalline deformation control the velocities of metamorphic reactions. It is therefore important to consider the quality and uncertainties of available methods for quantifying intensive parameters but also the age, the duration and the mechanisms of metamorphic transformations.

The goal of this review is, after a discussion of the methods of quantification of thermodynamic parameters and of the processes that help overcoming kinetic barriers for reactions, to present the state of knowledge on the links between metamorphism and large-scale geodynamic contexts. Finally the interaction between ductile deformation and metamorphism at the scale of the rock or outcrop will be presented.

2. Metamorphic pressure (*P*)–temperature (*T*) estimates and significance

2.1. *Quantification of metamorphic P–T conditions*

One can derive the *P–T* conditions experienced by metamorphic rocks by comparing their mineral associations with experimental and thermodynamic data. During the twentieth century numerous experimental data were produced, among which some have become references for the stability of metamorphic minerals (i.e. glaucophane stability field, aluminium-silicates triple point, ...). Moreover, since the late 1800's and the application of the phase rule in heterogeneous systems [Gibbs, 1875–1876], the conceptual framework of equilibrium thermodynamics has provided significant information on the formation of metamorphic rocks [Powell, 1978]. This concept led first to the topologic analysis of metamorphic reactions, i.e. the number and geometric arrangement in the *P–T* space of the reaction curves and most stables mineral associations [Zen, 1966]. Equilibrium thermodynamics led also, during the second half of the twentieth century, to the development of geo-thermometers and geo-barometers rooted in the thermodynamics of solid solutions and cationic exchanges and/or mutual solubility between coexisting minerals [see Krogh Ravna and Paquin, 2003, Spear, 1993, for reviews]. Applications of metallurgical concepts were at the origin of thermo-barometers based on disorder/order phase transitions [Carpenter, 1981] or discontinuous precipitations [Joanny et al., 1991]. Decisive progress in thermodynamic analysis has been made since the late 1980s with (i) the production of internally consistent thermodynamic databases [Berman, 1988, Holland and Powell, 2004, 2011], (ii) the formulations of mixing properties and activity-composition relationships for mineral solid-solutions and melts [Green et al., 2016, White et al., 2014] and (iii) the development of softwares using these multiple databases to model the mineralogical evolution of a rock from its chemical composition. This led to the development of modelled phase diagrams (often called "pseudosections"), as THERMOCALC [Powell et al., 1998] PERPLE_X [Connolly, 2005], THERIAK-DOMINO [De Capitani and Petrakakis, 2010], BINGO-ANTIDOTE [Duesterhoeft and Lanari, 2020] and GeoPS [Xiang and Connolly, 2022] are currently used. Pseudosections allow the effects of major and minor elements, of the Fe-oxidation state and/or of the amount and nature of fluids on *P–T* stability fields of mineral assemblages to be explored. These models allow also the mode and the composition of minerals to be determined for a given rock composition under specific *P–T* conditions [Lanari and Duesterhoeft, 2019, Yakymchuk, 2017]. Furthermore, since the last two decades, thermometers based on trace elements solubility in minerals are available [Thomas et al., 2010, Tomkins et al., 2007]. Last, using trapped mineral inclusions, spectroscopic thermometers and barometers, along with laser Raman micro-spectroscopy, and called "Thermoba-Raman-try", have been calibrated [Angel et al., 2017, Kohn, 2014].

2.2. *Uncertainties of P–T quantifications*

Experiments produced to calibrate the stability of a given mineral assemblage or the equilibrium curve of a given reaction should be well reversed and not rely on synthesis runs only. Many experiments were obtained at temperatures higher than 800 °C and many were not compositionally reversed under conditions similar to those under which natural rocks are metamorphosed. When undertaken on natural rock compositions a restricted number of mineral phases is generally observed in the produced runs. This discrepancy with respect to thermodynamic rules makes their direct application to natural assemblages always subject to discussion [Johnson et al., 2008].

With the exception of methods based on single element solubility within a single mineral, the basic prerequisite of all kinds of thermodynamic analyses is the achievement of chemical equilibrium in the investigated system. But metamorphic rocks commonly show textural and/or chemical evidences of disequilibrium such as corona-like textures with preservation of relicts, strongly zoned minerals, or preserved metastable phases. These various petrographic observations highlight the role of kinetics on metamorphic reactions [Lasaga, 1998]. Defining the scales from which the chemical equilibrium is reached is thus of crucial importance [Lanari and Engi, 2017]. The definition of the possibly equilibrated volume requires careful petrographic analysis of the textures of metamorphic rocks in thin sections, coupled with detailed chemical analysis of the phases observed before any attempt at thermodynamic quantification. Mineral geothermobarometry imposes the equilibration of several coexisting phases as well as high-resolution data on activity-composition relationships for mineral solid solutions. The accuracy of the obtained results may be also affected by the difficulty of measuring the amount of Fe^{3+} in minerals and by compositional re-equilibration during retrograde evolution. The results extracted from thermodynamic modelling methods are at the first order dependent of the selected chemistry of the considered system. Their accuracy requires thus to determine the effective (or reactive) rock composition which is still challenging in retrogressed or polyphased metamorphic rocks [Lanari and Engi, 2017].

At present the most robust strategy could be to cross the results obtained by thermodynamic modelling (including variations in chemical compositions of minerals, i.e. isopleths) with P–T conditions extracted from trace elements solubility in specific minerals (quartz, zircon, titanite ...) and from geothermobarometry of coexisting phases in textural equilibrium. The rise of petrochronology [Engi et al., 2017] and the recent developments of dating in-situ techniques [e.g. Tual et al., 2022] allow precise time constraints to be obtained. This has led, over the past 20 years, to improve the accuracy of P–T–t paths and thus the quantification of finite metamorphic field gradients.

The evolution of thermodynamic data and methods has led to a significant revision of the P–T fields of the classical metamorphic facies [Spear, 1993] with the definition of ultra high-pressure metamorphism (Figure 1A), thus a specific coesite and/or diamond bearing dry eclogite facies [Ernst and Liou, 2008]. This extension of metamorphic facies in the P–T space is, since the discovery of coesite-bearing assemblages in Alpine and Caledonian belts [Chopin, 1984, Smith, 1984], in conformity with the discoveries of numerous minerals or exsolution textures typical of ultra high-pressure conditions (micro-diamonds, Zr-ellenbergerite, majorite, stishovite, ... see Schertl and O'Brien, 2013 for an extensive review).

2.3. *Geological significance of calculated metamorphic T and P values*

The temperature distribution in the lithosphere depends on possible heat sources and efficiency of heat transfer by conduction or advection. The main heat source is the radioactive elements decay, even if localized, generally minors, mechanical ("shear or frictional heating") or chemical (latent heat of reaction or crystallization) should also be taken into account. This global heat production is dissipated by conduction within the lithosphere. However, in some geological contexts, an active transport of heat by advection is added to the system by magmatic intrusions, hydrothermal fluids or deep mantle diapirs, while subduction zones are largely cooled by downgoing oceanic lithosphere. Thus, understanding the temperature distribution with depth requires a deep geological knowledge of the area of interest. In most of the studies, a conductive geothermal gradient serves as a reference for interpreting metamorphic temperatures.

Pressure increases with depth due to the force exerted by the mass of rocks overlying a given point of interest (i.e. lithostatic pressure). The relationship between depth and pressure is thus given by $P = \rho \cdot g \cdot z$ (with ρ the density, g the acceleration due to gravity, i.e. 9.81 ms^{-2}, and z the depth). In the Earth, pressure is thus considered to be hydrostatic. This classical relationship must be in some cases questioned due to the accumulation of deviatoric, thus nonhydrostatic, stress during deformation ["tectonic overpressure" Mancktelow, 2008, Moulas et al., 2019]. In such a case, the depth can be over-estimated. However both numerical thermo-mechanical modelling on convergent zones and non-equilibrium thermodynamics applied to deformed metamorphic rocks highlight that magnitude of pressure deviations are on the order of 10–20% from the lithostatic values [Hobbs et al., 2010, Li et al., 2010, Marques et al., 2018], thus of the same order of error margins bars of calculated metamorphic pressures. At shallow crustal levels (the first few kilometres) where fluids are abundant, both hydrostatic and lithostatic pressure must be considered as physical components of the "effective pressure" [Jaeger and Cook, 1979, Moulas et al., 2019]. In the first 2~3 kilometres of continental crust, if fluids are H_2O rich, the hydrostatic gradient must be 10 MPa/km and thus, with a density of upper crustal rocks of 2500 kg/m^3, $P_{\text{fluid}} \approx 1/2.5\ P_{\text{lithostatic}}$. In this case, the calculated depth must be corrected by this factor.

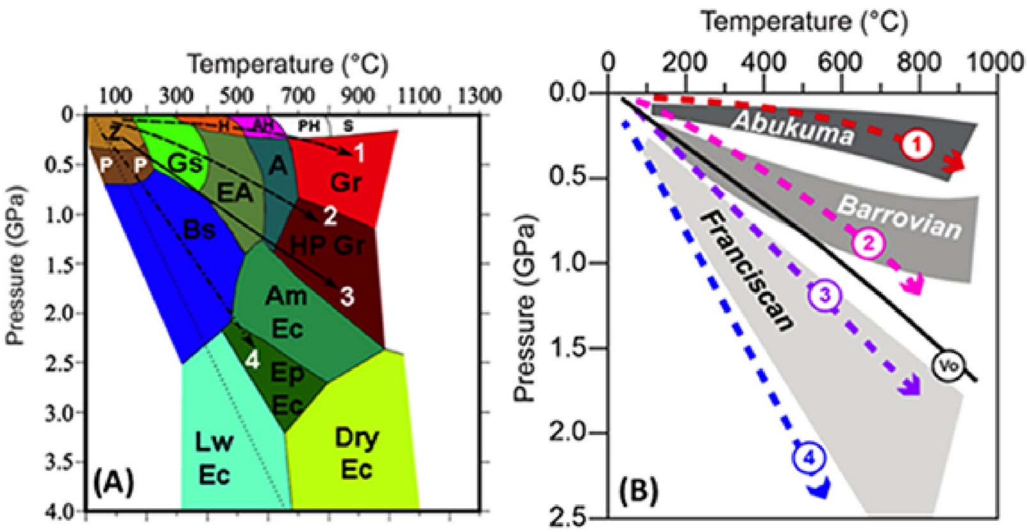

Figure 1. (A) Metamorphic facies and geothermal gradients (modified after Regorda et al., 2021; Z: zeolite; PP: prehnite-pumpellyite; Gs: greenschist; EA: epidote amphibolite; A: amphibolite; Gr: granulite; HPGr: high-pressure granulite; Bs: blueschist; AmEc: amphibole-eclogite; ApEc: epidote-eclogite; LwEc: lawsonite-eclogite; DryEc: dry-eclogite; S: sanidinite; PH: pyroxene-hornfels, AH: amphibole-hornfels; H: epidote-hornfels; 1: arc regions; 2: collision zones; 3: warm subductions; 4: cold subductions). (B) Typical metamorphic field gradients. 1: magmatic arcs and ridges; 2: collision zones; 3: warm subductions; 4: cold subductions [after Cloos, 1993]. Black line: standard geothermal gradient.

3. Metamorphism and large-scale geodynamic contexts

Since Miyashiro [1961] and Ernst [1971a,b], it is widely recognized that specific metamorphic facies series (i.e. observed metamorphic field gradients) portray the thermo-mechanical evolutions of lithosphere active zones, as a function of tectonic environments (Figure 1).

Franciscan, Barrovian and Abukuma type series reflect the observed metamorphic field gradients, and therefore the finite metamorphic architecture of an orogen. But in each area of an observed finite metamorphic zonation, rocks were more or less buried and in all cases exhumed through time, thus their tectonic history can only be understood by the construction of quantitative P–T–t paths [England and Richardson, 1977, Spear and Peacock, 1989, Thompson and England, 1984, Figure 2], or by the production of time-dependant metamorphic maps [Lardeaux, 2014a,b]. These latter approaches allow identification of the progressive metamorphic evolution through time and space of a given metamorphic unit.

3.1. *Subduction zones*

3.1.1. *Metamorphism of the oceanic lower plate*

It is primarily in subduction zones that the link between metamorphism and large-scale geodynamics was established. Along the Californian active margin the occurrence of eclogite pods and garnet-glaucophane-bearing schists led to the recognition of the “iconic” California Mesozoic-Cenozoic HP-LT accretionary complex [Coleman and Lanphere, 1971, Ernst, 1971a]. Eclogites and blueschist-facies rocks are embodied within serpentinites and mud-rich meta-sediments within the so-called Franciscan mélange [Cloos, 1982, Ernst, 2015, Wakabayashi, 1990]. Along the Pacific Ocean, this Franciscan complex is located west of the Great Valley Group, which is a typical forearc basin [Ernst, 2011, 2015, Orme and Surpless, 2019]. Eclogites and blueschists represent fragments of oceanic crust subducted and

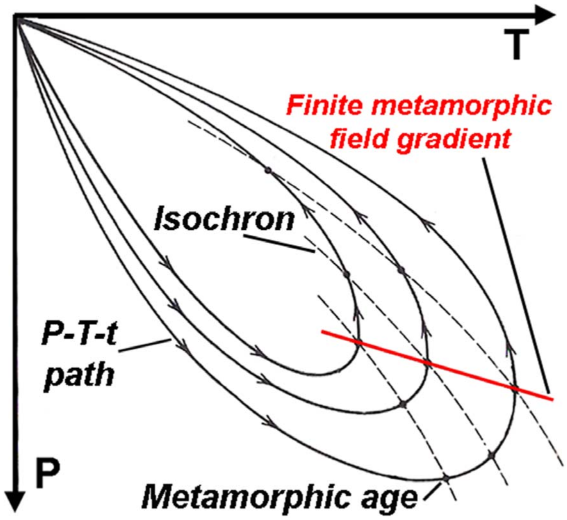

Figure 2. Theoretical relation between finite field gradient and P–T–t paths.

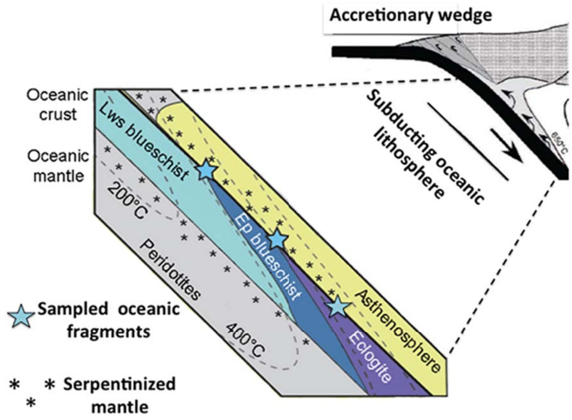

Figure 3. HP-LT metamorphic facies in subducted oceanic plate.

exhumed by return flow within subduction channels, composed of low-density meta-sediments or serpentinites, during long-lasting oceanic subduction [Cloos, 1986, Cloos and Shreve, 1988, Ernst and Liou, 2008, Grigull et al., 2012, Wakabayashi, 1992, Wassmann and Stöckhert, 2012]. A similar HP-LT metamorphic accretionary complex is recognized since several decades in Japan [Ernst, 1971b, Ishiwatari and Tsujimori, 2003, Maruyama et al., 1996, Miyashiro, 1961]. These circumpacific orogens are at the origin of the world's type model of HP-LT metamorphism of the subducted oceanic lower plate (Figure 3).

A remarkable example of the link between formation and exhumation of HP-LT rocks and long-term intra-oceanic subduction is offered by the Caribbean example, with the distribution of eclogites and blueschists along both northern and southern Greater Antilles Arcs (Figure 4). The Caribbean present-day configuration is the result of the eastward progressive Pacific plate moving between North and South America from Late Jurassic until its current position indicated by the active Lesser Antilles arc [Kerr et al., 2003, Pindell and Kennan, 2009]. This displacement was accompanied by a reversal of the subduction polarity, relative to the initial and abandoned trench, at ca. 120 Ma and by regional-scale transpression. In this context, HP/LT metamorphism developed during Cretaceous and eclogites and blueschists were exhumed under low-temperature conditions [García-Casco et al., 2006, Hu et al., 2022, Stöckhert et al., 1995, Tsujimori et al., 2006, West et al., 2014].

Exhumation took place during on-going subduction by mantle corner flow in serpentinized subduction channels [Blanco-Quintero et al., 2011, Guillot et al., 2009, Gorczyk et al., 2007, Maresch and Gerya, 2005]. If quartz-bearing eclogites and blueschists are dominant, UHP conditions are also reported in Guatemala [Martens et al., 2017, Tsujimori et al., 2006, and Figure 5]. The "classical" P–T domain of the "Franciscan" metamorphic gradient must be widened to both high pressures and low temperatures. Thus, the lawsonite-bearing eclogites from Guatemala are close to the famous "forbidden zone" of Liou et al. [2000], i.e. a geotherm of ~5 °C·km^{-1}. The division proposed by Cloos [1993] deserves to be questioned, as in a given subduction context, both hot and cold metamorphic paleo-gradients can develop simultaneously. Thereby, the data obtained in eastern Cuba and Guatemala show that within the same tectonic unit, eclogites outcropping close to each other recorded contrasting P–T conditions.

This dataset is in line with the thermo-mechanical models of subduction channels. Indeed, since Shreve and Cloos [1986] and Cloos and Shreve [1988], numerous models of a specific layer of low viscosity rocks dragged by the subducted plate beneath the upper plate have been developed [Gerya et al.,

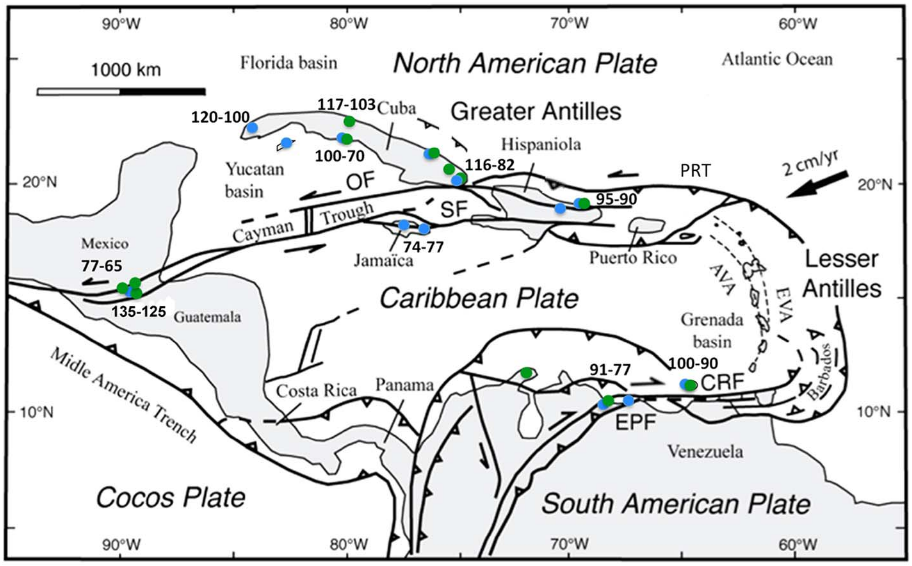

Figure 4. Location and ages of eclogites (green dots) and blueschists (blue dots) around the Caribbean plate. EVA: extinct volcanic arc; AVA: active volcanic arc; PRT: Puerto-Rico trench. EPF, El Pilar fault; CRF, central range fault; OF, oriental fault; SF, septentrional fault.

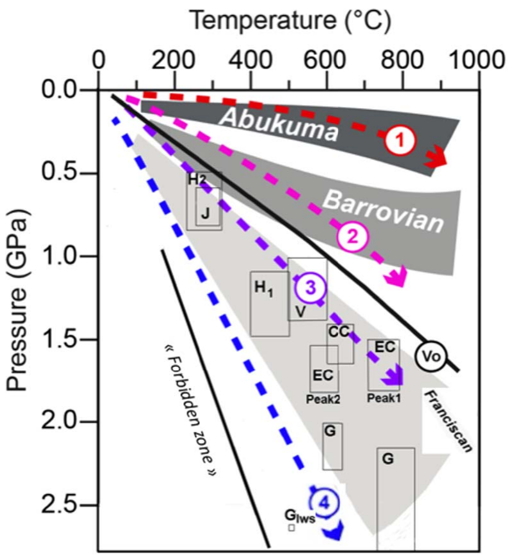

Figure 5. P–T conditions of Caribbean HP-LT metamorphic rocks. Legend same as Figure 1B. G: Guatemala eclogites; Glws: Guatemala lawsonite-eclogites; EC: Eastern Cuba eclogites; CC: Central Cuba eclogites; V: Venezuela eclogites; H1: Hispaniola eclogites; H2: Hispaniola blueschists; J: Jamaïca blueschists.

2002, Marotta and Spalla, 2007, Roda et al., 2012, Van Hunen and Allen, 2011]. These models, combining a linear viscous rheology for the sub-lithospheric mantle and/or accretion prism with a linear viscoplastic rheology for the lithosphere, provide for short wavelength convective flow in the subduction channel (downward and upward displacements of subducted rocks) and thus simultaneously developed contrasted P–T conditions [Angiboust et al., 2013, Hebert et al., 2009, Maresch and Gerya, 2005, Meda et al., 2010, Regorda et al., 2021]. This probably reflects the versatility of subduction zones gradients with respect to a dogmatic vision of “steady-state” systems.

3.1.2. *Metamorphism in the upper plate (magmatic/volcanic arcs)*

Still in subduction zones the concept of paired metamorphic belts was developed [Miyashiro, 1961]. This model, revisited and extended by Brown [2010], predicts the development of regional-scale high heat flow in the overriding plate, coupled with HP-LT conditions in the subducted plate, leading the development of intermediate-pressure granulite facies in the lower crust up to zeolite facies at uppermost crustal levels (Abukuma type metamorphism). Medium to low P/high T series typically develop within the upper plate depending on subduction velocity, age of subducted plate and amount of magmas produced in the magmatic arc.

Extinct and deeply exhumed continental magmatic arcs exhibit regional scale amphibolite to granulite facies conditions and extensive partial melting [Ducea et al., 2015]. The Coast Mountains in British Columbia or the southern Sierra Nevada in California document arc crustal sections exhumed from paleodepths of 5 to 35 km [Chapman et al., 2014, Ducea et al., 2015]. In both cases mafic magmatic underplating is described and arc-related metamorphic conditions evolve from prehnite-pumpellyite or greenschist facies up to medium to high-pressure granulite facies from the shallowest to the deepest exposed levels [Day and Springer, 2005, Girardi et al., 2012]. High-P granulites are also reported from the extinct Arthur River continental arc complex in New Zealand [De Paoli et al., 2009, Flowers et al., 2005]. At shallow levels of active continental magmatic arcs, as exemplified by the Andean Cordillera, low-grade metamorphism (i.e. zeolite and/or prehnite-pumpellyite facies up to greenschist facies) is well documented [Aguirre et al., 2000, Muñoz et al., 2010]. Because this metamorphism affects sediments and interlayered volcanic rocks, it is frequently mentioned as "burial" metamorphism, which requires a temporal evolution from extensional versus compressional tectonic regimes. In any cases, high thermal gradients (i.e. >40 °C/km) and extensive hydrothermal fluids circulation are reported to produce the observed metamorphic mineralogy. All these characteristics must be combined to propose a schematic vertical crustal section showing the typical metamorphic pattern of continental magmatic arcs (Figure 6).

Exhumed fossil oceanic magmatic arcs display similar metamorphic patterns, as for example the fossil (i.e. obducted) Kohistan oceanic magmatic arc in Pakistan where abundant mafic magmatic underplating together with amphibolite and high-P granulite facies are reported [Burg, 2011].

Arc-related metamorphism has been recently discovered at shallow crustal levels of the active volcanic island arc from the Guadeloupe archipelago [Lesser Antilles arc, Favier et al., 2021, Vérati et al., 2018, Figure 4]. The 2 cm/yr, southwest oriented, subduction of the American plate beneath the Caribbean one led to development of this oceanic volcanic arc [López et al., 2006]. The arc is divided in two ridges with an eastern Mid-Eocene ancient arc and a still active, since 5 Ma, western arc [Samper et al., 2007]. The conductive geothermal gradient was measured in between 69.3 ± 1.5 and 98.2 ± 8.8 °C/km around the Guadeloupe archipelago [Manga et al., 2012]. In Guadeloupe, the active arc includes from north to south different volcanic complexes [Ricci et al., 2015, Samper et al., 2007, Figure 7] and arc-related metamorphism, associated with ductile deformation, was identified in the oldest, thus most eroded and exhumed, 4.28 to 2.67 Ma aged Basal Complex [Favier et al., 2019].

The volcanic rocks are affected by young (<3 Ma) greenschist to sub-greenschist (i.e. prehnite-bearing) facies metamorphism (0.6–2 kbar for 250–300 °C), and a re-equilibration under zeolite facies conditions, consistent with the elevated geothermal gradients measured regionally for the arc axis [Favier et al., 2019]. In the Basal Complex, the ductile finite strain pattern is defined by localized, pressure-solution induced, schistose domains surrounding pods of undeformed rocks. A conceptual model for this arc-related hydrothermal tectono-metamorphic pattern is presented in Figure 8.

3.2. *Continental collision zones*

3.2.1. *Continental collision zones with preserved subduction metamorphism pattern*

The Alpine belt is the result of the Tertiary continental collision between the Adriatic promontory of the African plate and the thinned continental margin of the European-Iberian plate [Handy et al., 2010, Schmid et al., 2004]. This collision followed the closure, by subduction, of the Ligure–Piemontese Ocean started during Upper Cretaceous times [Agard, 2021, Agard and Handy, 2021, Dal Piaz et al., 2003, Rosenbaum and Lister, 2005, Rubatto et al., 1998, Spalla et al., 2010].

In this tectonic framework, the western Alps are a remarkable example of collision chain having preserved a subduction-related metamorphic signature. Significant occurrences of low-temperature eclogites and blueschists are reported since the end of the nineteenth century [see Lardeaux, 2014a, for review]. Ernst [1971b] was the first is to identify a typical,

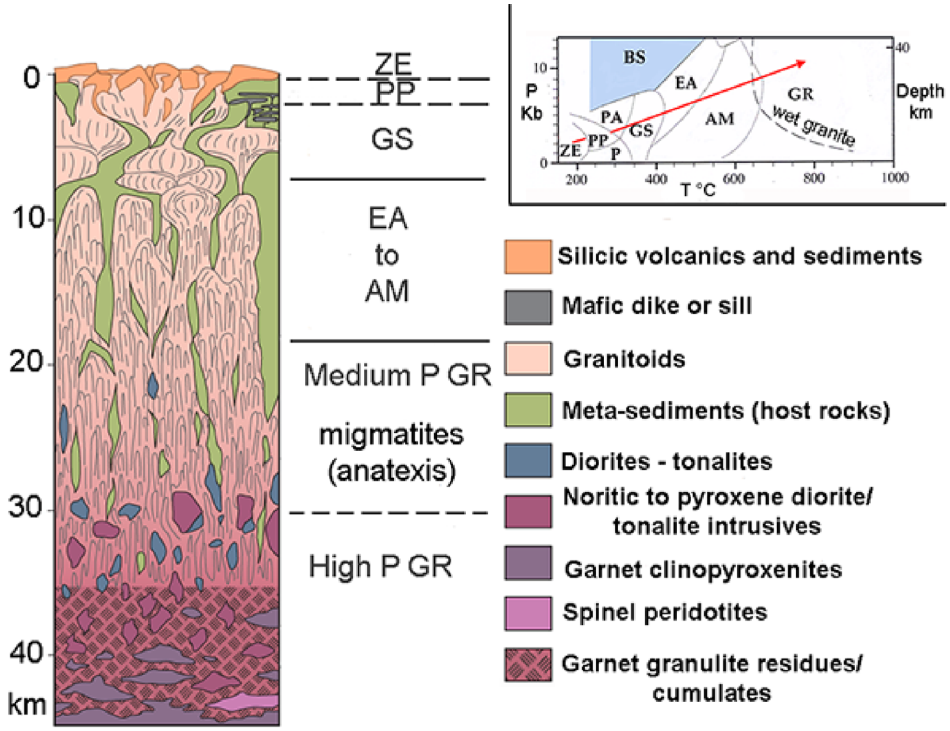

Figure 6. Vertical metamorphic pattern in continental arcs [modified after Ducea et al., 2015]. Inset shows the related metamorphic field gradient (red arrow). Metamorphic facies after Ernst and Liou [2008]. ZE: Zeolite facies; PP: Prehnite-Pumpellyite facies; GS: Greenschist facies; EA: Epidote-Amphibolite facies; AM: Amphibolite facies; GR: Granulite facies; BS: Blueschist facies; P: Prehnite facies; PA: Prehnite-Actinolite facies;

east-oriented, Franciscan metamorphic field gradient. Four decades of detailed petrologic investigations led to the production of synthetic metamorphic maps highlighting this subduction related metamorphic gradient in the internal western Alps [i.e. east of the Penninic front, Bousquet et al., 2008, Goffé et al., 2004, Lardeaux, 2014a, Oberhänsli et al., 2004, Figure 9].

From a geodynamic and/or tectonic point of view, the metamorphic data available today for internal western Alps highlight the following fundamental points:

- The finite metamorphic field gradient is in the range of 5–10 °C/km, thus similar to the previously presented circumpacific ones, compatible with long-lasting oceanic subduction (ca. 55 Ma) between Upper Cretaceous [Handy et al., 2010, Rebay et al., 2018] and subsequent Late-Eocene/Oligocene continental collision [Belhassen et al., 2014].
- The finite metamorphic field gradient portrays the Alpine subduction polarity. However, ages of HP and/or UHP metamorphism vary from top to bottom of the Alpine tectonic pile. Indeed, eclogite facies metamorphism is Late Cretaceous—Paleocene (85–65 Ma) in the Austro-Alpine Sesia-Lanzo Zone, Early to Middle Eocene (60–45 Ma) in the oceanic units and late Eocene (40–35 Ma) in the European plate-derived Dora Maira Massif [see Bousquet et al., 2008, Lardeaux, 2014a, Manzotti et al., 2022, with references therein].
- Significant metamorphic heterogeneities (i.e. *P* and *T* gaps) can be seen even within a single tectono-metamorphic unit. Examples are reported in the Dora Maira unit

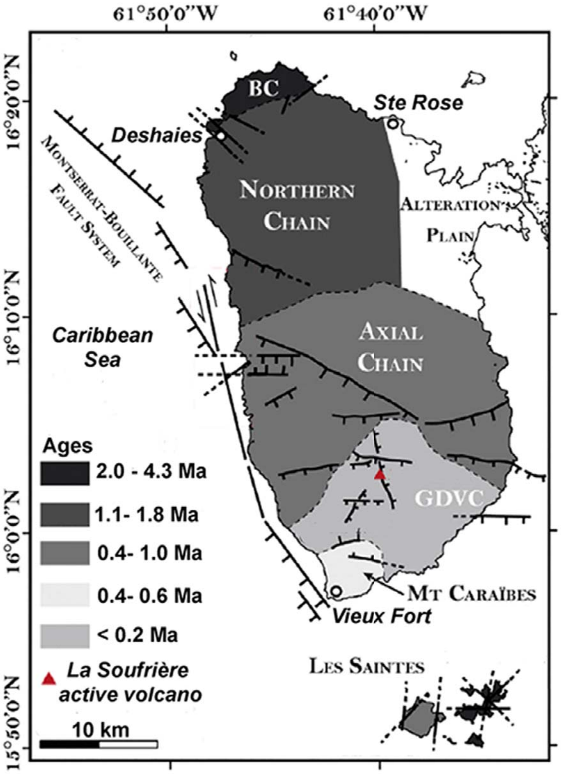

Figure 7. Basse-Terre (Guadeloupe) volcanic complexes and main faults [modified after Samper et al., 2007, Favier et al., 2019]. BC: Basal Complex, GDVC: Grande Découverte Volcanic Complex.

[Groppo et al., 2019, Manzotti et al., 2022], in the "Schistes Lustrés" unit located west of the Gran-Paradiso Massif [Bousquet, 2008], or in the Sesia-Lanzo Zone [Giuntoli et al., 2018, Roda et al., 2020, 2021, Zucali and Spalla, 2011]. In Zermatt zone or Monviso meta-ophiolites these heterogeneities are still a matter of debate. Some authors recognized contrasted *P–T* conditions [Luoni et al., 2019, Rebay et al., 2012, 2018], while Angiboust et al. [2009, 2012] proposed quite homogeneous peak conditions for these units. The size of the units, which have undergone a homogeneous evolution, differ widely according to the authors, resulting in contrasted exhumation models. Some authors consider syn-subduction exhumation of Alpine HP-LT rocks in accretionary wedge and subduction channel [Allemand and Lardeaux, 1997, Bousquet, 2008, Gilio et al., 2019, Guillot et al., 2009, Polino et al., 1990, Roda et al., 2012, Spalla et al., 1996, Stöckhert and Gerya, 2005]. On the other hand, Agard et al. [2009] and Angiboust et al. [2012] consider a synchronous exhumation of coherent slivers along the entire belt.

- Since the discovery of coesite in the Dora-Maira unit [Chopin, 1984], the identification of UHP conditions in the Western Alps is progressively increasing. UHP or nearly UHP conditions are now documented in continental meta-sediments and meta-granitoids [Chopin et al., 1991, Kienast et al., 1991, Groppo et al., 2019, Manzotti et al., 2022, Chen et al., 2023], in oceanic meta-sediments [Reinecke, 1991] in oceanic meta-basalts and meta-gabbros [Angiboust et al., 2012, Bucher et al., 2005, Ghignone et al., 2022, Luoni et al., 2019] as well as in oceanic mantle serpentinites [Rebay et al., 2012, 2018].
- Slices of both oceanic and continental crusts were subducted during Alpine orogeny. It was in the western Alps that the subduction of the continental crust was for the first time depicted since the early 1970s. It is in the Austro-Alpine units that subduction of the upper continental crust [Compagnoni and Maffeo, 1973, Compagnoni et al., 1977, Dal Piaz et al., 1972] and the lower continental crust [Dal Piaz et al., 1983, Lardeaux et al., 1982, Lardeaux and Spalla, 1991] was identified. HP to UHP metamorphic conditions were depicted later in all the Internal Crystalline Massifs. These Internal Crystalline Massifs are attributed to the distal part of the extended Briançonnais palaeo-margin [i.e. European lower plate, Handy et al., 2010, Schmid et al., 2004] and are presently located beneath the oceanic units. On the other hand, the Austro-Alpine units derived from the Adria margin (i.e. promontory of the African upper plate) and are thrust onto the oceanic Piemonte Zone [Polino et al., 1990]. Ablative subduction at the continent-ocean active margin, as predicted by numerous thermo-mechanical models of subduction

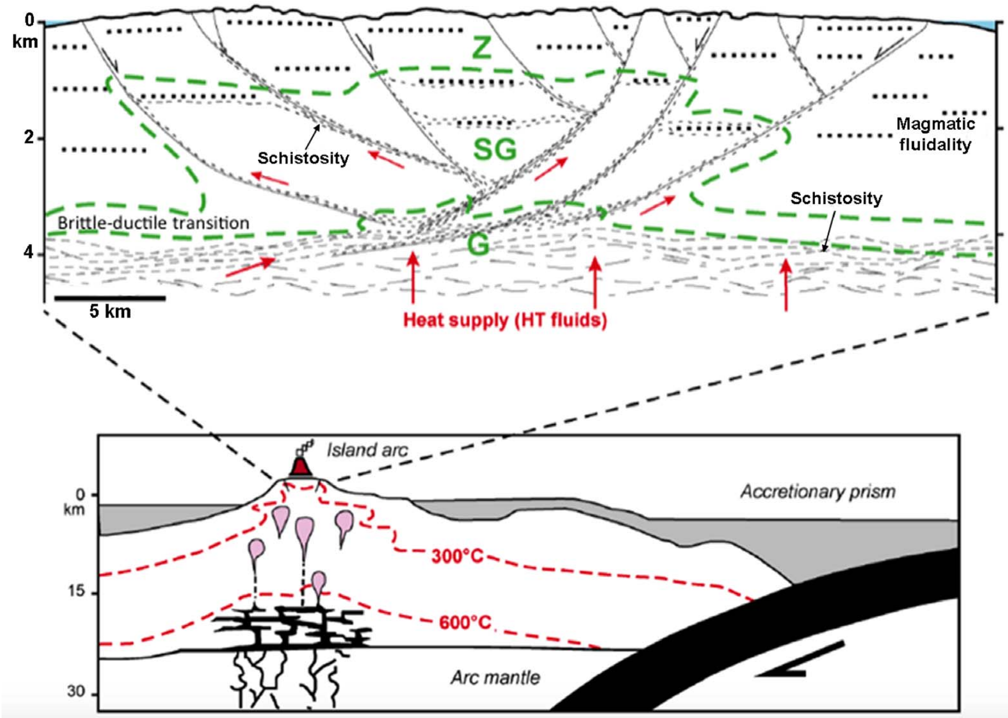

Figure 8. Metamorphic pattern and deformation in the upper crust of the Guadeloupe active volcanic arc [modified after Favier et al., 2019]. Z: zeolite; SG: sub-greenschist; G: greenschist.

zones [Gerya et al., 2002, Gerya and Stöckhert, 2006, Meda et al., 2010, Regorda et al., 2021, Roda et al., 2012], is required to generate eclogite facies metamorphism in the upper plate-derived units. In such a case, the metamorphic pattern depends on oceanic subduction velocity and to a lesser extent on value of shear heating at plates interface [Regorda et al., 2021].

In contrast, continental subduction driven by the down going oceanic lithosphere is responsible for HP to UHP metamorphism in the lower plate-derived units. In the latter case, continental subduction may be considered as the premises of continental collision.

Taking into account the contrasted ages of HP and/or UHP metamorphism (see above), the western Alps offer thus an iconic example of a belt where both upper and lower plate-derived continental slices are subducted (Figure 10).

3.2.2. *Continental collision zones with hidden subduction pattern and diffuse cryptic suture zones*

The Variscan chain is an 8000 km-long belt formed as the consequence of Palaeozoic subduction and collision events [Martínez Catalán et al., 2020, Matte, 2001, Schulmann et al., 2014]. Successive rifting, subduction and collision of different continental microblocs and/or island arcs were identified before the final collision of Laurussia and Gondwana [Franke et al., 2017]. Finally, late orogenic strike-slip faulting driving block rotations, and/or late orogenic extension led to the present-day configuration [Edel et al., 2018, Faure, 1995, Faure et al., 2005].

In the tectonic framework of the Europe Variscan belt, the French Massif Central (FMC) essentially belongs to the Moldanubian Zone, the internal zone of this orogen [Lardeaux et al., 2014, Martínez Catalán et al., 2020, Figure 11]. The architecture of the FMC results from the tectonic superposition of allochthonous tectono-metamorphic units upon para-autochthonous units [see Faure et al., 2009, with references therein].

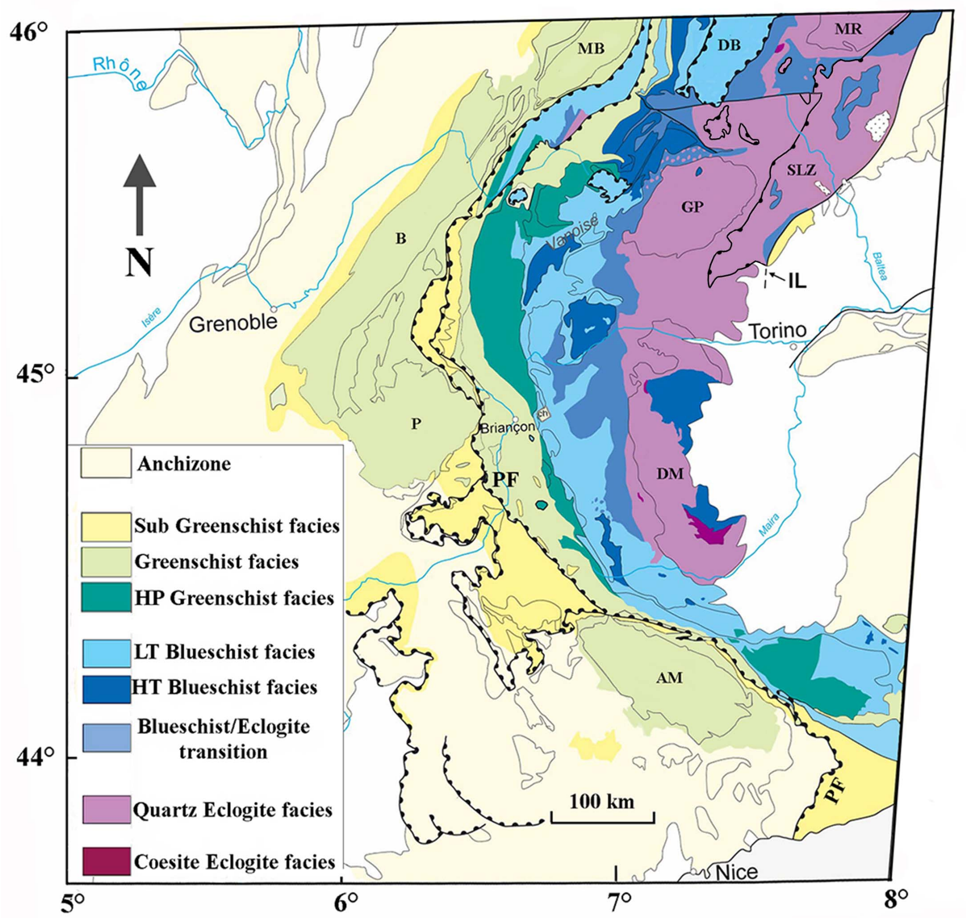

Figure 9. Metamorphic map of the western Alps [modified after Oberhänsli et al., 2004, Lardeaux, 2014a]. PF: Penninic front; IL: Insubric Line; AM: Argentera-Mercantour; P: Pelvoux; B: Belledonne; MB: Mont-Blanc; DM: Dora-Maira; GP: Gran-Paradiso; MR: Monte Rosa; DB and SLZ: Austro-alpine Dent-Blanche and Sesia-Lanzo Zone respectively.

The allochthonous units are characterized by the occurrence of eclogites associated with garnet-bearing peridotites [Lardeaux, 2014b] which are the only visible witnesses of the early subduction prior to the continental collision. Unlike in the Western Alps, blueschists and Low-T eclogites are rare in the Variscan belt [Ile de Groix in the Armorican Massif or Saxothuringian zone of the Bohemian Massif, Ballèvre et al., 2009, Schulmann et al., 2009, with references therein]. In the FMC, the main metamorphic field gradient is related to thickening processes during continental collision. The protoliths of these eclogites range from E and N-MORB tholeiites to ocean-floor tholeiites or supra-subduction zone basalts [Berger et al., 2005, 2006, Briand et al., 1988]. The FMC eclogites are generally severely retrogressed under lower-pressure and HT conditions, resulting in the disappearance of HP peak equilibrium assemblages. However, since the discovery of small-sized relicts of coesite within garnets from the Mont du Lyonnais eclogites [Lardeaux et al., 2001], the application of modern methods of thermodynamic modelling to these rocks demonstrated their formation under UHP to HP conditions, thus under paleo-gradients typical of subduction zones [Benmammar et al., 2020, Berger et al., 2010, De Hoÿm de Marien et al., 2020, Lotout et al., 2018, 2020, Figure 12].

Following these last studies, eclogite facies metamorphism is Devonian (400–365 Ma) and thus coeval

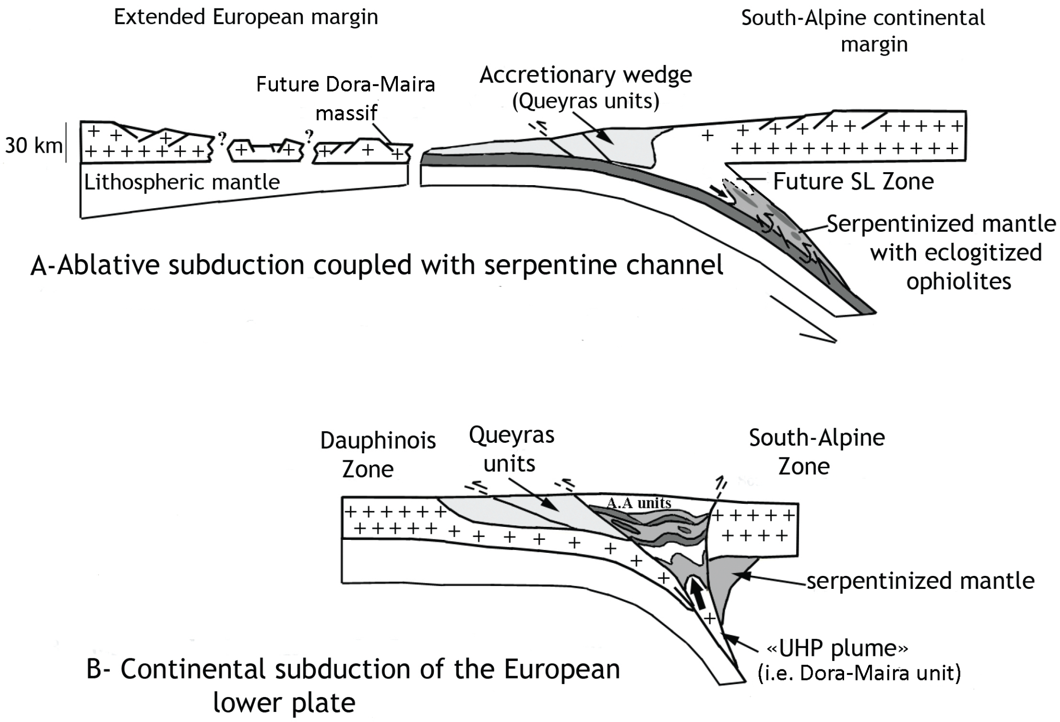

Figure 10. One of the possible tectonic sketche showing two episodes of continental subductions during the evolution of the western Alps [modified after Lardeaux, 2014a].

with the development, at the scale of the entire European Variscan belt, of arc and back-arc magmatic systems drawing a nowadays hidden subduction system [Schulmann et al., 2022]. In this framework, the Montagne Noire eclogites (southern FMC) offer a different scenario, with conditions of higher temperature and an age of 310 Ma [Whitney et al., 2020]. Although this age is widely debated [Faure et al., 2014, Faure, 2020, 2021], they could be witnesses of lower crust fragments exhumed from the root of orogenic thickened crust rather than relics of suture zones.

3.2.3. *Barrovian inverted metamorphism: archetype of collision-related metamorphism*

First defined by Barrow in the meta-pelites in the southeast Highlands of Scotland (Caledonian orogeny, 1893, 1912), Barrovian metamorphism is archetypical for orogenic metamorphism in continental collision belts. It is characterized by a sequence of zones and the typical "index" mineral in each is: Chlorite zone, Biotite zone, Garnet zone, Staurolite zone, Kyanite zone and Sillimanite zone [see Spear, 1993, for a review]. For example, in the FMC, this sequence is temporally associated with progressive under-thrusting of the lowermost units (i.e. Lower Gneissic and Para-autochthonous Units) during continental collision [Burg et al., 1989, Faure et al., 2009]. In these lowermost units, this sequence defines a syn-tectonic prograde evolution from greenschist facies to medium-pressure granulite facies conditions and to crustal anatexis generally during the first stages of decompression along the P–T–t path (Figure 13).

In collision belts, this metamorphism is frequently described as "inverted". First reported in the European Variscan belt [Bohemian Massif and FMC, Jung and Roques, 1936, Suess, 1926], it has become an emblematic example in the Himalaya with the report of an increase in metamorphic grade towards the

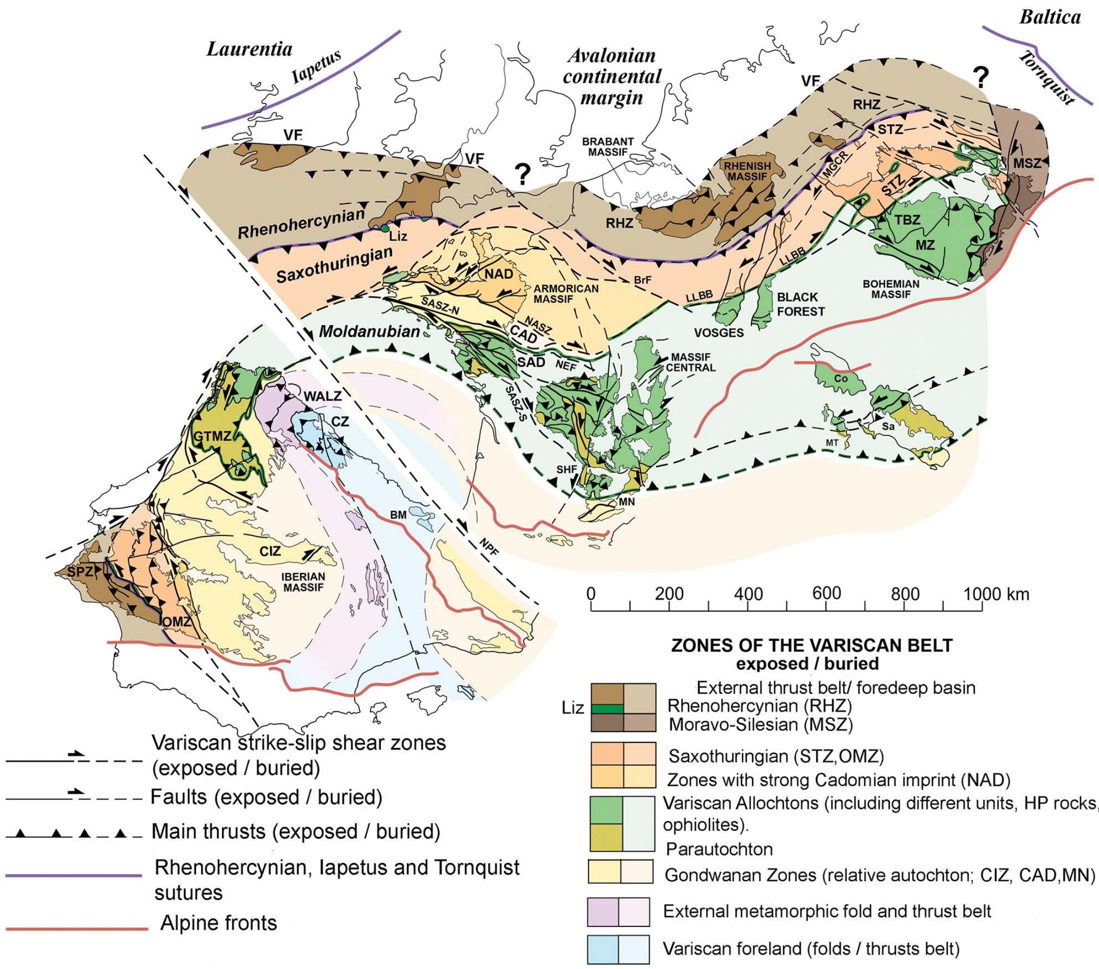

Figure 11. The French Massif Central in the framework of the late Carboniferous pattern of the Variscan belt [modified from Martínez Catalán et al., 2020]. VF: Variscan Front; OMZ: Ossa-Morena Zone; CIZ: Central Iberian Zone; SPZ: South Portuguese Zone; GTMZ: Galicia-Trás-os-Montes Zone; WALZ: West Asturian-Leonese Zone; CZ: Cantabrian Zone; BM: Basques Massifs; NPF: North Pyrenean Fault; Liz: Lizard Complex; NAD: North Armorican Domain; CAD: Central Armorican Domain; SAD: South Armorican Domain; NASZ: North Armorican Shear Zone; SASZ-N: South Armorican Shear Zone (northern part); SASZ-S: South Armorican Shear Zone (southern part); NEF: Nort-sur-Erdre Fault; SHF: Sillon Houiller Fault; MN: Montagne Noire; BrF: Bray Fault; RHZ: Rhenohercynian Zone; LLBB: Lalaye–Lubine–Baden-Baden Fault Zone; MGCR: Mid-German Crystalline Rise; STZ: Saxothuringian Zone; TBZ: Teplá-Barrandian Zone; MZ: Moldanubian Zone; MSZ: Moravo-Silesian Zone; Co:Corsica; Sa: Sardinia.

Main Central Thrust [Johnson, 2005, Le Fort, 1975]. If the link between Barrovian inverted metamorphism and thrust tectonics is undeniable in numerous belts, different models are in competition to explain it: (1) thrust-related isotherms inversion inducing "hot-iron" effect with deep and hot metamorphic units upon colder ones [Molnar and England, 1990], (2) post-metamorphic large-scale folding of isograds [Searle and Rex, 1989], (3) post-metamorphic sequential stacking of contrasted metamorphic zones [Brunel and Kienast, 1986, Jessup et al., 2008], (4) heterogeneously distributed shearing across the tectonic sequences [Jamieson et al., 1996], (5) shear heating [England et al., 1992] and (6) variations in lo-

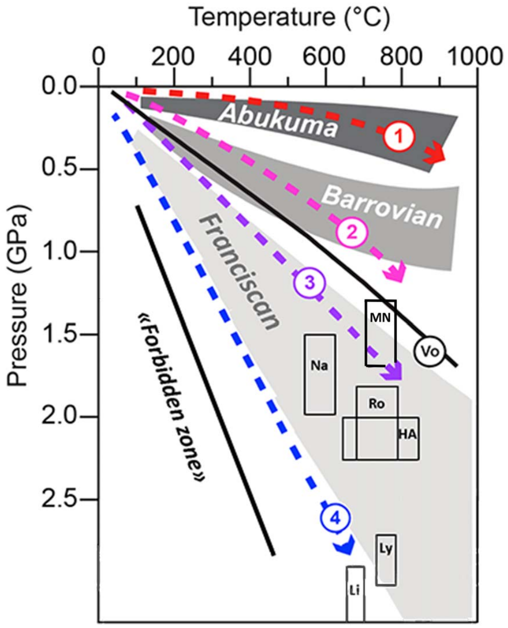

Figure 12. *P–T* conditions of Massif Central eclogites. Legend as Figure 1B. Na: Najac; Ro: Rouergue; HA: Haut-Allier; Ly: Monts du Lyonnais; Li: Limousin; MN: Montagne Noire (see text for references).

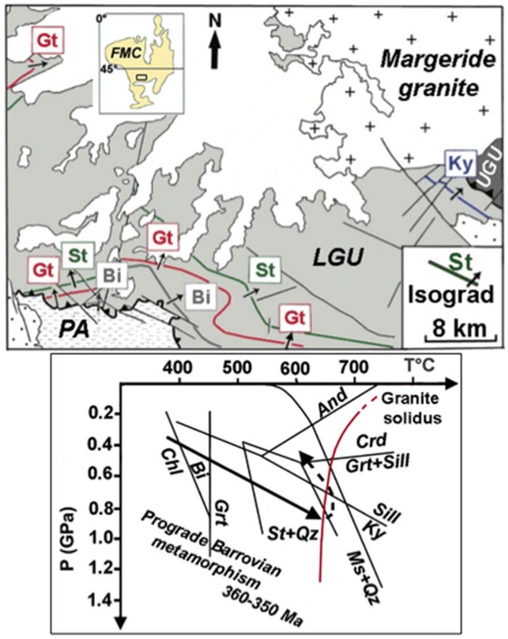

Figure 13. Carboniferous Barrovian metamorphism in the Lot serie [Massif Central, modified after Burg et al., 1989, Lardeaux, 2014b]. UGU, LGU, PA: Upper Gneiss Unit, Lower Gneiss Unit and Para-Aurochton respectively [after Faure et al., 2009]. Chl: Chlorite; Bi: Biotite; Grt: Garnet; St: Staurolite; Qz: Quartz; Ms: Muscovite; Sill: Sillimanite; Crd: Cordierite; And: Andalusite.

calization of deformation along the main thrust zone in association with contrasted thermal budget of the overriding unit [Štípská et al., 2019].

3.2.4. *Continental collision zones with late-orogenic collapse*

In the southern and eastern parts of the Variscan FMC, Barrovian-type metamorphic field gradients are replaced by a new high-temperature/low-pressure, up to significant partial melting, metamorphic pattern during Late Carboniferous [i.e. Pennsylvanian, Gardien et al., 1997, Lardeaux, 2014b]. This late metamorphic evolution is the record of high paleo-gradients, ca. 70 °C/km, associated with post-thickening intracontinental extension. The latter results from collapse of the orogenic crust that also led to the formation of intramontane basins [Faure, 1995, Faure et al., 2009, Gardien et al., 2022]. These high-temperature conditions developed during pressure decrease (i.e. crustal thinning) and are in most cases coeval with intrusion of mantle-derived mafic magmas at the base of the widely molten orogenic root [Ledru et al., 2001]. In domains of continental collision zones affected by these types of late-orogenic events, the early regional-scale metamorphic imprints can be completely erased and replaced by Abukuma-type metamorphic field gradients similar to those identified in magmatic arcs.

4. Ductile deformation and metamorphic rate controls

4.1. *Deformation features and micro- to meso-structures of metamorphic rocks*

Since Zwart [1962], the first approach to the relationship between metamorphism and tectonics was temporal. The chronologic relationships are based on the identification of ante-, syn-, or post-tectonic minerals. This type of analysis is always fundamental, making it possible to identify under which $P–T$ conditions, and therefore at what structural level a given deformation episode has developed. In return, the recognition of superposed generations of tectonic structures is a relative chronological marker that constitutes a robust basis to construct $P–T–t$ paths, as successfully exemplified in the Western Alps [Ballèvre, 1988, Bousquet et al., 2008, Dal Piaz et al., 1983, Gosso et al., 2015, Lanari et al., 2012, Lardeaux et al., 1982, Spalla et al., 2005, Zucali and Spalla, 2011]. However, in naturally deformed terrains, the amount of finite strain is always heterogeneously distributed [Ramsay, 1980] resulting in the common occurrence of un-deformed rock volumes embodied within multiply folded domains and/or ductile shear zones. Thus under constant $P–T$ conditions, metamorphic rocks may be subject to different strain rates giving rise to contrasted metamorphic textures (i.e. coronitic, foliated and mylonitic textures).

4.2. *Ductile deformation and achievement of thermodynamic equilibrium*

Teall [1885] reported the first demonstration of ductile deformation control on kinetics of metamorphic reactions, describing the progressive transformation of undeformed meta-dolerites into hornblende schists within shear zones from NW Scotland. From the early 1980s until quite recently, numerous studies have highlighted the critical role of intra- or inter-crystalline deformation mechanisms in the various stages involved in a metamorphic reaction [i.e. dissolution of reactants, chemical transfer with or without fluids, nucleation and growth, Gratier et al., 2013, Hobbs et al., 2010, Jamtveit and Austrheim, 2010]. High strain rates, grain size reduction, generation and migration of crystal defects and tectonically induced paths for fluids migration decrease the necessary activation energy for mineral reactions and thus increase reaction kinetics. In metamorphic terrains, mylonitic rocks within shear zones are the best candidates for sampling rocks in which thermodynamic equilibrium is achieved for a given metamorphic stage, while undeformed rocks with corona-type textures offer the best chances of finding preserved relic minerals. These concepts lead to a sampling strategy that, if applied, improves the construction of $P–T–t$ paths in metamorphic rocks.

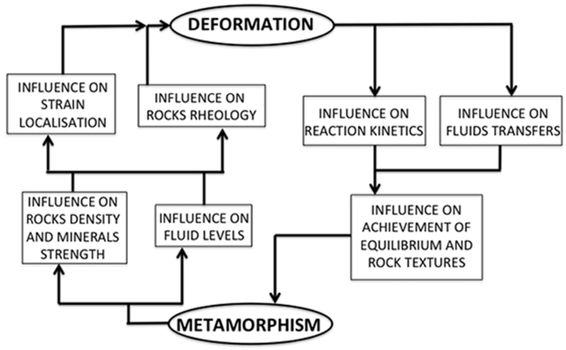

Figure 14. Graphical chart showing the links between metamorphic and tectonic processes [modifed after Hobbs et al., 2010].

4.3. *Metamorphic evolutions and associated crustal rheology*

Deformation and metamorphism interrelate in a reciprocal way. Deformation increases the kinetics of reactions but, in return, phase transitions can induce significant variations in rock density and crustal rheology. A world-renowned example is the transformation of oceanic basalts and gabbros (density ca. 2.9) into eclogites (density ca. 3.5), and then became an important driving force of oceanic subduction. Furthermore, in the upper continental crust, mainly constituted by quartzo-feldspathic lithology, quartz is regarded as the weaker phase whose deformation mechanisms control crustal rheology. Still in the continental crust, lower-crust derived mafic rocks are generally considered as one of the strongest lithology [Ranalli, 1997]. However, rocks metamorphosed under granulite facies conditions reveal rheological inversions for instance for feldspar and quartz, for garnet and feldspar or more generally for mafic and felsic rocks as clearly reported from southern Madagascar Pan-African high-strain zones [Martelat et al., 2012].

Summing up, the multiple interactions between metamorphism and deformation may be illustrated in Figure 14.

5. Conclusions: future perspectives

After this review that explored some links between metamorphism and tectonics, for the future the following tasks seem exciting and relevant:

(1) improving the methods of thermodynamic modelling, particularly the quantification of the real reactive rock volumes to consider for models definition, (2) acquiring high-resolution temporal constraints on P–T–t paths with systematic petrochronologic studies (combined in-situ dating and chemical analyses, comprising trace elements, of metamorphic minerals), (3) understanding better in situ deformation processes using laboratory experiments to adress overcoming strain rate and temperatures issues (4) progress in the application of non-equilibrium thermodynamics to metamorphic and tectonic processes to shed light on the finite rock structures and their potential record in active tectonic processes (5) as most active subduction zones are ablative, better quantify in orogens the volumes of HP/UHP tectonic units derived from the overriding upper plates, (6) identifying the volumes of metamorphic rocks which have been subject to strictly identical P–T conditions and better explain the intriguing metamorphic heterogeneities reported from many metamorphic domains, (7) producing thermo-mechanical models that better reflect the fluxes of material exchanges between subducted oceanic and/or continental crust and mantle as well as the crustal relamination and trans-lithospheric diapirism reported from some emblematic orogens (i.e. Himalayas, Variscan belt, . . .).

Conflicts of interest

The author has no conflict of interest to declare.

Acknowledgements

I sincerely would like to thank the reviews, the comments and the suggestions of Samuel Angiboust, Michel Faure and of Pierre Lanari that significantly improved the manuscript.

References

Agard, P. (2021). Subduction of oceanic lithosphere in the Alps: Selective and archetypal from (slow-spreading) oceans. *Earth Sci. Rev.*, 214, article no. 103517.

Agard, P. and Handy, M. (2021). Ocean subduction dynamics in the Alps. *Elements*, 17, 9–16.

Agard, P., Yamato, P., Jolivet, L., and Burov, E. (2009). Exhumation of ocean blueschists and eclogites in subduction zones: Timing and mechanisms. *Earth Sci. Rev.*, 92, 53–79.

Aguirre, L., Robinson, D., Bevins, R. E., Morata, D., Vergara, M., Fonseca, E., and Carrasco, J. (2000). A low-grade metamorphic model for the Miocene volcanic sequences in the Andes of central Chile, New Zealand. *J. Geol. Geophys.*, 43(1), 83–93.

Allemand, P. and Lardeaux, J.-M. (1997). Strain partitioning and metamorphism in a deformable orogenic wedge: Application to the Alpine belt. *Tectonophysics*, 280, 157–169.

Angel, R. J., Mazzucchelli, M. L., Alvaro, M., and Nestola, F. (2017). EosFit-Pinc: A simple GUI for host-inclusion elastic thermobarometry. *Am. Mineral.*, 102, 1957–1960.

Angiboust, S., Agard, P., de Hoog, J. C. M., Omrani, J., and Plunder, A. (2013). Insights on deep, accretionary subduction processes from the Sistan ophiolitic "mélange" (Eastern Iran). *Lithos*, 156, 139–158.

Angiboust, S., Agard, P., Jolivet, L., and Beyssac, O. (2009). The Zermatt-Saas ophiolite: the largest (60 km wide) and deepest (c. 70–80 km) continuous slice of oceanic lithosphere detached from a subduction zone? *Terra Nova*, 21, 171–180.

Angiboust, S., Laangdon, R., Agard, P., Waters, D., and Chopin, C. (2012). Eclogitization of the Monviso ophiolite (W. Alps) and implications on subduction dynamics. *J. Metamorph. Geol.*, 30, 37–61.

Ballèvre, M. (1988). *Collision continentale et chemins P–T: L'unité pennique du Grand Paradis (Alpes occidentales)*, volume 19 of *Mém. Doc. Centre Armor. Et. Struct. Socles.*

Ballèvre, M., Bosse, V., Ducassou, C., and Pitra, P. (2009). Palaeozoic history of the Armorican Massif: models for the tectonic evolution of the suture zones. *C. R. Geosci.*, 341, 174–201.

Barrow, G. (1893). On an intrusion of muscovite-biotite gneiss in the southeastern Highlands of Scotland and its accompanying metamorphism. *Q. J. Geol. Soc. London*, 49, 330–358.

Barrow, G. (1912). On the geology of lower Deeside and the southern Highland border. *Proc. Geol. Assoc.*, 23, 268–284.

Belhassen, N., Mouthereau, F., Boutoux, A., Bellanger, M., Lacombe, O., Jolivet, L., and Rolland, Y. (2014). Collision kinematics in the western external Alps.

Tectonics, 33, 1055–1088.

Benmammar, A., Berger, J., Triantafyllou, A., Duchêne, S., Bendaoud, A., Baele, J. M., Bruguier, O., and Diot, H. (2020). Pressure-temperature conditions and significance of upper Devonian eclogite and amphibolite facies metamorphisms in southern French Massif central. *BSGF Earth Sci. Bull.*, 191, article no. 28.

Berger, J., Féménias, O., Mercier, J. C., and Demaiffe, D. (2005). Ocean-floor hydrothermal metamorphism in the Limousin ophiolites (Western French Massif Central): evidence of a rare preserved Variscan oceanic marker. *J. Metamoroh. Geol.*, 23, 795–812.

Berger, J., Féménias, O., Mercier, J. C., and Demaiffe, D. (2006). A Variscan slow-spreading ridge (MOR-LHOT) in Limousin (French Massif Central): magmatic evolution and tectonic setting inferred from mineral chemistry. *Mineral. Mag.*, 70, 175–185.

Berger, J., Féménias, O., Ohnenstetter, D., Bruguier, O., Plissart, G., Mercier, J. C., and Demaiffe, D. (2010). New occurrence of UHP eclogites in Limousin (French Massif Central): Age, tectonic setting and fluid–rock interactions. *Lithos*, 118, 365–382.

Berman, R. G. (1988). Internally-consistent thermodynamic data for minerals in the system Na_2O–K_2O–CaO–MgO–FeO–Fe_2O_3–Al_2O_3–SiO_2–TiO_2–H_2O–CO_2. *J. Petrol.*, 29, 445–522.

Blanco-Quintero, I. F., Garcia-Casco, A., and Gerya, T. V. (2011). Tectonic blocks in serpentinite mélange (eastern Cuba) reveal large-scale convective flow of the subduction channel. *Geology*, 39, 79–82.

Bousquet, R. (2008). Metamorphic heterogeneities within a single HP unit: overprint effect or metamorphic mix? *Lithos*, 103, 46–69.

Bousquet, R., Oberhänsli, R., Goffé, B., Wiederkehr, M., Koller, F., Schmid, S. M., Schuster, R., Engi, M., Berger, A., and Martinotti, G. (2008). Metamorphism of metasediments in the scale of an orogen: A key to the Tertiary geodynamic evolution of the Alps. In Siegesmund, S., Fügenschuh, B., and Froitzheim, N., editors, *Tectonic Aspects of the Alpine-Dinaride-Carpathian System*, Geological Society, London, Special Publications, 298, pages 393–412. Geological Society of London.

Briand, B., Piboule, M., and Bouchardon, J.-L. (1988). Diversité géochimique des métabasites des groupes leptyno-amphiboliques du Rouergue et de Marvejols (Massif central). Origine et implications. *Bull. Soc. Géol. Fr.*, 8(IV), 489–498.

Brown, M. (2010). Paired metamorphic belts revisited. *Gondwana Res.*, 18, 46–59.

Brunel, M. and Kienast, J. R. (1986). Etude pétro-structurale des chevauchements ductiles himalayens sur la transversale de l'Everest-Makalu (Népal oriental). *Can. J. Earth Sci.*, 23, 1117–1137.

Bucher, K., Fazis, Y., De Capitani, C., and Grapes, R. (2005). Blueschists, eclogites, and decompression assemblages of the Zermatt-Saas ophiolite: high-pressure metamorphism of subducted Tethys lithosphere. *Am. Mineral.*, 90, 821–835.

Burg, J. P. (2011). The Asia–Kohistan–India collision: Review and discussion. In Brown, D. and Ryan, P. D., editors, *Arc-Continent Collision*, Frontiers in Earth Sciences, pages 279–309. Springer-Verlag, Berlin, Heidelberg.

Burg, J. P., Delor, C. P., Leyreloup, A. F., and Romney, F. (1989). Inverted metamorphic zonation and Variscan thrust tectonics in the Rouergue area (Massif Central, France): *P–T–t* record from mineral to regional scale. In Daly, J. S., Cliff, R. A., and Yardley, B. W. D., editors, *Evolution of Metamorphic Belts*, Geological Society, London, Special Publications, 43, pages 423–439. Geological Society of London.

Carpenter, M. A. (1981). Omphacite microstructures as time-temperature indicators of blueschist and eclogite facies metamorphism. *Contrib. Mineral. Petrol.*, 78, 411–451.

Chapman, A. D., Ducea, M. N., Kidder, S., and Petrescu, L. (2014). Geochemical constraints on the petrogenesis of the Salinian arc, central California: implications for the origin of intermediate magmas. *Lithos*, 200(1), 126–141.

Chen, Y. X., Zhou, K., He, Q., Zheng, Y.-F., Schertl, H.-P., and Chen, K. (2023). First finding of continental deep subduction in the Sesia Zone of Western Alps and implications for subduction dynamics. *Natl. Sci. Rev.*, 10, article no. nwad023.

Chopin, C. (1984). Coesite and pure pyrope in high-grade blueschists of the Western Alps: A first record and some consequences. *Contrib. Mineral. Petrol.*, 86, 107–118.

Chopin, C., Henry, C., and Michard, A. (1991). Geology and petrology of the coesite bearing terrain, Dora Maira massif, Western Alps. *Eur. J. Mineral.*, 3, 263–291.

Cloos, M. (1982). Flow melanges: Numerical modelling and geologic constraints on their origin in the Franciscan subduction complex, California. *Geol. Soc. Am. Bull.*, 93, 330–345.

Cloos, M. (1986). Blueschists in the Franciscan Complex of California: Petrotectonic constraints on uplift mechanisms. *Geol. Soc. Am. Mem.*, 164, 77–93.

Cloos, M. (1993). Lithospheric buoyancy and collisional orogenesis: subduction of oceanic plateaus, continental margins, island arcs, spreading ridges, and seamounts. *Geol. Soc. Am. Bull.*, 105, 715–737.

Cloos, M. and Shreve, R. L. (1988). Subduction-channel model of prism accretion, melange formation, sediment subduction, and subduction erosion at convergent plate margins, 1. Background and description. *Pure Appl. Geophys.*, 128, 455–500.

Coleman, R. G. and Lanphere, M. A. (1971). Distribution and age of high-grade blueschists, eclogites, and amphibolites from Oregon and California. *Geol. Soc. Am. Bull.*, 82, 2397–2412.

Compagnoni, R., Dal Piaz, G. V., Hunziker, J. C., Gosso, G., Lombardo, B., and Williams, P. F. (1977). The Sesia-Lanzo zone, a slice of continental crust with Alpine high pressure–low temperature assemblages in the Western Italian Alps. *Rend. Soc. It. Miner. Petrol.*, 33, 281–334.

Compagnoni, R. and Maffeo, B. (1973). Jadeite-bearing metagranites l.s. and related rocks in the Mount Mucrone area (Sesia-Lanzo zone, Western Italian Alps). *Schweiz. Mineral. Petrogr. Mitt.*, 53, 355–378.

Connolly, J. A. D. (2005). Computation of phase equilibria by linear programming: a tool for geodynamic modelling and its application to subduction zone decarbonation. *Earth Planet. Sci. Lett.*, 236, 524–541.

Dal Piaz, G. V., Bistacchi, A., and Massironi, M. (2003). Geological outline of the Alps. *Episodes*, 26, 175–180.

Dal Piaz, G. V., Hunziker, J. C., and Martinotti, G. (1972). La zona Sesia-Lanzo e l'evoluzione tettonico metamorfica delle Alpi nordoccidentali interne. *Mem. Soc. Geol. It.*, 11, 433–460.

Dal Piaz, G. V., Lombardo, B., and Gosso, G. (1983). Metamorphic evolution of the Mt. Emilius klippe, Dent Blanche nappe, Western Alps. *Am. J. Sci.*, 283A, 438–458.

Day, H. W. and Springer, R. K. (2005). The first appearance of actinolite in the prehnite-pumpellyite facie, Sierra Nevada, California. *Can. Mineral.*, 43, 89–104.

De Capitani, C. and Petrakakis, K. (2010). The computation of equilibrium assemblage diagrams with Theriak/Domino software. *Am. Mineral.*, 95, 1006–1016.

De Hoÿm de Marien, L., Pitra, P., Cagnard, F., and Le Bayon, B. (2020). Prograde and retrograde *P–T* evolution of a Variscan high-temperature eclogite, French Massif Central, Haut-Allier. *BSGF Earth Sci. Bull.*, 191, article no. 14.

De Paoli, M. C., Clarke, G. L., Klepeis, K. A., Allibone, A. H., and Turnbull, I. M. (2009). The eclogite-granulite transition: mafic and intermediate assemblages at Breaksea Sound, New Zealand. *J. Petrol.*, 50, 2307–2343.

Ducea, M. N., Saleeby, J. B., and Bergantz, B. (2015). The architecture, chemistry, and evolution of continental magmatic arcs. *Annu. Rev. Earth Planet. Sci.*, 43, 10.1–10.33.

Duesterhoeft, E. and Lanari, P. (2020). Iterative thermodynamic modelling—Part 1: A theoretical scoring technique and a computer program (Bingo-Antidote). *J. Metamorph. Geol.*, 38(5), 527–551.

Edel, J. B., Schulmann, K., Lexa, O., and Lardeaux, J. M. (2018). Late Palaeozoic palaeomagnetic and tectonic constraints for amalgamation of Pangea supercontinent in the European Variscan belt. *Earth Sci. Rev.*, 177, 589–612.

Engi, M., Lanari, P., and Kohn, M. J. (2017). Significant ages—An introduction to petrochronology. *Rev. Mineral. Geochem.*, 83, 1–12.

England, P., Le Fort, P., Molnar, P., and Pecher, A. (1992). Heat sources for tertiary metamorphism and anatexis in the Annapurna-Manaslu region central Nepal. *J. Geophys. Res. Solid Earth*, 97, 2107–2128.

England, P. C. and Richardson, S. W. (1977). The influence of erosion upon the mineral facies of rocks from different metamorphic environments. *J. Geol. Soc.*, 134, 201–213.

Ernst, W. G. (1971a). Tectonic contact between the Franciscan mélange and the Great Valley sequence, crustal expression of a late Mesozoic Benioff zone. *J. Geophys. Res.*, 75, 886–901.

Ernst, W. G. (1971b). Metamorphic zonations on presumably subducted lithospheric plates from Japan, California, and the Alps. *Contrib. Mineral. Petrol.*, 34, 43–59.

Ernst, W. G. (2011). Accretion of the Franciscan Complex attending Jura-Cretaceous geotectonic development of northern and central California. *Geol. Soc. Am. Bull.*, 123, 1667–1678.

Ernst, W. G. (2015). Franciscan geologic history constrained by tectonic/olistostromal high-grade metamafic blocks in the iconic California Mesozoic-Cenozoic accretionary complex. *Am. Mineral.*, 100, 6–13.

Ernst, W. G. and Liou, J. (2008). High and ultrahigh-pressure metamorphism: Past results and future prospects. *Am. Mineral.*, 93, 1771–1786.

Eskola, P. (1915). On the relation between the chemical and mineralogical composition in the metamorphic rocks of the Orijarvi region. *Bull. Comm. Geol. Finland*, 44, 109–145.

Faure, M. (1995). Late orogenic Carboniferous extensions in the Variscan French Massif Central. *Tectonics*, 14, 132–153.

Faure, M. (2020). Structure et évolution pré-permienne du Massif central français. Partie 1. Site Planet-Terre, ENS Lyon. Ressources scientifiques pour l'enseignement des sciences de la Terre et de l'Univers. ISSN 2552-9250. https://planet-terre.ens-lyon.fr/article/MCF-pre-Permien-structuration.xml.

Faure, M. (2021). La chaine varisque en France. Site Planet-Terre, ENS Lyon. Ressources scientifiques pour l'enseignement des sciences de la Terre et de l'Univers. ISSN 2552-9250. https://planet-terre.ens-lyon.fr/article/chaine-varisque-France-1.xml.

Faure, M., Bé Mézème, E., Duguet, M., Cartier, C., and Talbot, J. Y. (2005). Paleozoic tectonic evolution of medio-Europa from the example of the French Massif Central and Massif Armoricain. *J. Virtual Explor.*, 19(5), 1–26.

Faure, M., Cocherie, A., Gaché, J., Esnault, C., Guerrot, C., Rossi, P., Wei, L., and Qiuli, L. (2014). Middle Carboniferous intracontinental subduction in the Outer Zone of the Variscan Belt (Montagne Noire Axial Zone, French Massif Central): multi-method geochronological approach of polyphase metamorphism. In *Geological Society, London, Special Publications*, volume 405, pages 289–311. Geological Society of London.

Faure, M., Lardeaux, J. M., and Ledru, P. (2009). A review of the pre-Permian geology of the Variscan French Massif Central. *C. R. Geosci.*, 341, 202–213.

Favier, A., Lardeaux, J. M., Corsini, M., Verati, C., Navelot, V., Géraud, Y., Diraison, M., Ventalon, S., and Voitus, E. (2021). Characterization of an exhumed high-temperature hydrothermal system and its application for deep geothermal exploration: an example from Terre-de-Haut Island (Guadeloupe archipelago, Lesser Antilles volcanic arc). *J. Volcanol. Geotherm. Res.*, 418, article no. 107256.

Favier, A., Lardeaux, J.-M., Legendre, L., Verati, C., Philippon, M., Corsini, M., Münch, P., and Ventalon, S. (2019). Tectono-metamorphic evolution of shallow crustal levels within active volcanic arcs. Insights from the exhumed Basal Complex of Basse-Terre (Guadeloupe, FrenchWest Indies). *BSGF Earth Sci. Bull.*, 190, article no. 10.

Flowers, R. M., Bowring, S. A., Tulloch, A. J., and Klepeis, K. A. (2005). Tempo of burial and exhumation within the deep roots of a magmatic arc, Fiordland, New Zealand. *Geology*, 33(1), 17–20.

Franchi, S. (1900). Sopra alcuni giacimenti di rocce giadeitiche nelle Alpi Occidentali e nell' Appennino ligure. *Boll. R. Com. Geol. It.*, 31, 119–158.

Franke, W., Cocks, L. R. M., and Torsvik, T. H. (2017). The Palaeozoic Variscan oceans revisited. *Gondwana Res.*, 48, 257–284.

García-Casco, A., Torres-Roldán, R. L., Iturralde-Vinent, M. A., Millán, G., Núñez Cambra, K., Lázaro, C., and Rodríguez Vega, A. (2006). High pressure metamorphism of ophiolites in Cuba. *Geol. Acta*, 4, 63–88.

Gardien, V., Lardeaux, J. M., Ledru, P., Allemand, P., and Guillot, S. (1997). Metamorphism during late orogenic extension: insights from the French variscan belt. *Bull. Soc. Géol. Fr.*, 168(3), 271–286.

Gardien, V., Martelat, J. E., Leloup, P. H., Mahéo, G., Bevillard, B., Allemand, P., Monié, P., Paquette, J. L., Grosjean, A. S., Faure, M., Chelle-Michou, C., and Fellah, C. (2022). Fast exhumation rate during late orogenic extension: the new timing of the Pilat detachment fault (French Massif Central, Variscan belt). *Gondwana Res.*, 103, 260–275.

Gerya, T. and Stöckhert, B. (2006). Two-dimensional numerical modeling of tectonic and metamorphic histories at active continental margins. *Int. J. Earth Sci.*, 95, 250–274.

Gerya, T., Stöckhert, B., and Perchuk, A. L. (2002).

Exhumation of high-pressure metamorphic rocks in a subduction channel-a numerical simulation. *Tectonics*, 21(6), article no. 1056.

Ghignone, S., Scaramuzzo, E., Gilio, M., Bruno, M., Livio, F., and Alvaro, M. (2022). First evidence of UHP in the Lago Superiore Unit (Monviso, Western Alps). In *15th Emile Argand Conference on Alpine Geological Studies, alpshop2022*, page 47.

Gibbs, J. W. (1875–1876). On the equilibrium of heterogeneous substances. *Trans. Connecticut Acad. Arts Sci.*, 3, 108–248.

Gilio, M., Scambelluri, M., Agostini, S., Godard, M., Peters, D., and Pettke, T. (2019). Petrology and geochemistry of serpentinites associated with the ultra-high pressure Lago di Cignana Unit (Italian Western Alps). *J. Petrol.*, 60, 1229–1262.

Girardi, J. D., Patchett, P. J., Ducea, M. N., Gehrels, G. E., Cecil, M. R., Rusmore, M. E., Woodsworth, G. J., Pearson, D. M., Manthei, C., and Wetmore, P. (2012). Elemental and isotopic evidence for granitoid genesis from deep-seated sources in the Coast Mountains Batholith, British Columbia. *J. Petrol.*, 53, 1505–1536.

Giuntoli, F., Lanari, P., Burn, M., Kunz, B. E., and Engi, M. (2018). Deeply subducted continental fragments Part 2: Insight from petrochronology in the central Sesia Zone (Western Italian Alps). *Solid Earth*, 9(1), 191–222.

Goffé, B., Schwartz, S., Lardeaux, J. M., and Bousquet, R. (2004). Explanatory note to the map: Metamorphic structure of the Western and Ligurian Alps. *Mitt. Österr. Mineral Gesell.*, 149, 125–144.

Gorczyk, W., Guillot, S., Gerya, T. V., and Hattori, K. (2007). Asthenospheric upwelling, oceanic slab retreat and exhumation of UHP mantle rocks: Insights from Greater Antilles. *Geophys. Res. Lett.*, 34, article no. L211309.

Gosso, G., Rebay, G., Roda, M., Spalla, M. I., Tarallo, M., Zanoni, D., and Zucali, M. (2015). Taking advantage of petrostructural heterogeneities in subduction-collisional orogens, and effect on the scale of analysis. *Period. Mineral.*, 84(3B), 779–825.

Gratier, J.-P., Dysthe, D. K., and Renard, F. (2013). The role of pressure solution creep in the ductility of the Earth's upper crust. *Adv. Geophys.*, 54, 47–179.

Green, E. C. R., White, R. W., Diener, J. F. A., Powell, R., Holland, T. J. B., and Palin, R. M. (2016). Activity–composition relations for the calculation of partial melting equilibria in metabasic rocks. *J. Metamorph. Geol.*, 34(9), 845–869.

Grigull, S., Krohe, A., Moos, C., Wassmann, S., and Stöckhert, B. (2012). "Order from chaos": A field-based estimate on bulk rheology of tectonic mélanges formed in subduction zones. *Tectonophysics*, 568–569, 86–101.

Groppo, C., Ferrando, S., Gilio, M., Botta, S., Nosenzo, F., Balestro, G., Festa, A., and Rolfo, F. (2019). What's in the sandwich? New *P–T* constraints for the (U)HP nappe stack of southern Dora-Maira Massif (Western Alps). *Eur. J. Mineral.*, 31, 665–683.

Guillot, S., Hattori, K., Agard, P., Schwartz, S., and Vidal, O. (2009). Exhumation processes in oceanic and continental subduction contexts: a review. In Lallemand, S. and Funiciello, F., editors, *Subduction Zone Dynamics*, pages 175–204. Springer-Verlag, Berlin, Heidelberg.

Handy, M. R., Schmid, S. M., Bousquet, R., Kissling, E., and Bernoulli, D. (2010). Reconciling plate tectonic reconstructions of Alpine Tethys with the geological-geophysical record of spreading and subduction in the Alps. *Earth Sci. Rev.*, 102, 121–158.

Hebert, L. B., Antoshechkina, P., Asimow, P., and Gurnis, M. (2009). Emergence of a low-viscosity channel in subduction zones through the coupling of mantle flow and thermodynamics. *Earth Planet. Sci. Lett.*, 278(3–4), 243–256.

Hobbs, B. E., Ord, A., Spalla, M. I., Gosso, G., and Zucali, M. (2010). The interaction of deformation and metamorphic reactions. In Spalla, M. I., Marotta, A. M., and Gosso, G., editors, *Advances in Interpretation of Geological Processes: Refinement of Multi-scale Data and Integration in Numerical Modelling*, Geological Society, London, Special Publications, 332, pages 189–223. Geological Society of London.

Holland, T. J. B. and Powell, R. (2004). An internally consistent thermodynamic data set for phases of petrological interest. *J. Metamorph. Geol.*, 16, 309–343.

Holland, T. J. B. and Powell, R. (2011). An improved and extended internally consistent thermodynamic dataset for phases of petrological interest, involving a new equation of state for solids. *J. Metamorph. Geol.*, 29(3), 333–383.

Hu, H. Y., Stern, R. J., Rojas-Agramonte, Y., and Garcia-Casco, A. (2022). Review of geochronologic and geochemical data of the Greater Antilles volcanic arc and implications for the evolution of oceanic arcs. *Geochem. Geophys. Geosyst.*, 23, article no. e2021GC010148.

Ishiwatari, A. and Tsujimori, T. (2003). Paleozoic ophiolites and blueschists in Japan and Russian Primorye in the tectonic framework of East Asia: A synthesis. *Island Arc*, 12, 190–206.

Jaeger, J. C. and Cook, N. G. W. (1979). *Fundamental of Rock Mechanics*. Chapman and Hall, London, 3rd edition.

Jamieson, R. A., Beaumont, C., Hamilton, J., and Fullsack, P. (1996). Tectonic assembly of inverted metamorphic sequences. *Geology*, 24, 839–842.

Jamtveit, B. and Austrheim, H. (2010). Metamorphism: The role of fluids. *Elements*, 6, 153–158.

Jessup, M. J., Cottle, J. M., Searle, M. P., Law, R. D., Newell, D. L., Tracy, R. J., and Waters, D. J. (2008). *P–T–t–D* paths of Everest Series schist, Nepal. *J. Metam. Geol.*, 26, 717–739.

Joanny, V., van Roermund, H., and Lardeaux, J. M. (1991). The clinopyroxene/plagioclase symplectite in retrograde eclogites: a potential geothermometer. *Geol. Runds.*, 80, 303–320.

Johnson, M. R. W. (2005). Structural settings for the contrary metamorphic zonal sequences in the internal and external zones of the Himalaya. *J. Asian Earth Sci.*, 25, 695–706.

Johnson, T. E., White, R. W., and Powell, R. (2008). Partial melting of metagreywacke: a calculated mineral equilibria study. *J. Metamorph. Geol.*, 26, 837–853.

Jung, J. and Roques, M. (1936). Les zones d'isométamorphisme dans les terrains cristallophylliens du Massif Central français. *Rev. Sc. Nat. Auvergne.*, I(4), 38–85.

Kerr, A. C., White, R. V., Thompson, P. M. E., Tarney, J., and Saunders, A. D. (2003). No oceanic plateau—no Caribbean plate? The seminal role of an oceanic plateau in Caribbean plate evolution. In Bartolini, C., Buffler, R. T., and Blickwede, J., editors, *The Circum—Gulf of Mexico and Caribbean: Hydrocarbon Habitats, Basin Formation, and Plate Tectonics*, American Association of Petroleum Geologists Memoir, 79, pages 126–268. Boulder, Tusla (USA).

Kienast, J. R., Lombardo, B., Biino, G., and Pinardon, J. L. (1991). Petrology of very-high-pressure eclogitic rocks from the Brossasco-Isasca complex, Dora-Maira massif, Italian Western Alps. *J. Metamorph. Geol.*, 9, 19–34.

Kohn, M. J. (2014). "Thermoba-Raman-try": Calibration of spectroscopic barometers and thermometers for mineral inclusions. *Earth Planet. Sci. Lett.*, 388, 187–196.

Krogh Ravna, E. and Paquin, J. (2003). Thermobarometric methodologies applicable to eclogites and garnet ultrabasites. In Carswell, D. A. and Compagnoni, R., editors, *Ultrahigh Pressure Metamorphism: European Union Notes in Mineralogy*, volume 5, pages 229–259. European Union, Budapest.

Lanari, P. and Duesterhoeft, E. (2019). Modeling metamorphic rocks using equilibrium thermodynamics and internally consistent databases: Past achievements, problems and perspectives. *J. Petrol.*, 60(1), 19–56.

Lanari, P. and Engi, M. (2017). Local bulk composition effects on metamorphic mineral assemblages. *Rev. Mineral. Geochem.*, 83(1), 55–102.

Lanari, P., Guillot, S., Schwartz, S., Vidal, O., Tricart, P., Riel, N., and Beyssac, O. (2012). Diachronous evolution of the alpine continental subduction wedge: Evidence from *P–T* estimates in the Briançonnais zone houillère (France-Western Alps). *J. Geodyn.*, 56, 39–54.

Lardeaux, J. M. (2014a). Deciphering orogeny: A metamorphic perspective. Examples from European Alpine and Variscan belts. Part I: Alpine metamorphism in the Western Alps. A review. *Bull. Soc. Géol. Fr.*, 185(2), 93–114.

Lardeaux, J. M. (2014b). Deciphering orogeny: a metamorphic perspective. Examples from European Alpine and Variscan belts. Part II: Variscan metamorphism in the French Massif Central. A review. *Bull. Soc. Géol. Fr.*, 185, 281–310.

Lardeaux, J. M., Gosso, G., Kienast, J. R., and Lombardo, B. (1982). Relations entre le métamorphisme et la déformation dans la zone Sésia-Lanzo (Alpes Occidentales) et le problème de l'éclogitisation de la croûte continentale. *Bull. Soc. Géol. Fr.*, 7(XXIV), 793–800.

Lardeaux, J. M., Ledru, P., Daniel, I., and Duchêne, S. (2001). The Variscan French Massif Central—a new addition to the ultrahigh pressure metamorphic "club": exhumation processes and geodynamic consequences. *Tectonophysics*, 332(1–2), 143–167.

Lardeaux, J. M., Schulmann, K., Faure, M., Janoušek, V., Lexa, O., Skrzypek, E., Edel, J. B., and Štípská, P.

(2014). The Moldanubian Zone in the French Massif Central, Vosges/Schwarzwald and Bohemian Massif revisited: differences and similarities. In Schulmann, K., Martínez Catalán, J. R., Lardeaux, J. M., Janoušek, V., and Oggiano, G., editors, *The Variscan Orogeny: Extent Timescale and the Formation of the European Crust*, Geological Society, London, Special Publications, 405, pages 7–44. Geological Society of London.

Lardeaux, J. M. and Spalla, M. I. (1991). From granulites to eclogites in the Sesia Zone (ItalianWestern Alps): A record of the opening and closure of the Piemont Ocean. *J. Metamorph. Geol.*, 9, 35–59.

Lasaga, A. C. (1998). *Kinetic Theory in the Earth Sciences*. Princeton University Press, Princeton, NJ.

Le Fort, P. (1975). Himalayas: the collided range, present knowledge of the continental arc. *Am. J. Sci.*, 275A, 1–44.

Ledru, P., Courrioux, G., Dallain, C., Lardeaux, J. M., Montel, J. M., Vanderhaeghe, O., and Vitel, G. (2001). The Velay dome (French Massif Central): melt generation and granite emplacement during orogenic evolution. *Tectonophysics*, 342, 207–237.

Li, Z. H., Gerya, T., and Burg, J. P. (2010). Influence of tectonic overpressure on *P–T* paths of HP-UHP rocks in continental collision zones: thermomechanical modelling. *J. Metamorph. Geol.*, 28, 227–247.

Liou, J. G., Hacker, B. R., and Zhang, R. Y. (2000). Into the forbidden zone. *Science*, 287, 1215–1216.

López, A. M., Stein, S., Dixon, T., Sella, G., Calais, E., Jansma, P., Weber, J., and Lafemina, P. (2006). Is there a northern Lesser Antilles forearc block? *Geophys. Res. Lett.*, 33, 2–5.

Lotout, C., Pitra, P., Poujol, M., Anczkiewicz, R., and Van Den Driessche, J. (2018). Timing and duration of Variscan high-pressure metamorphism in the French Massif central: a multimethod geochronological study from the Najac Massif. *Lithos*, 308–309, 381–394.

Lotout, C., Poujol, M., Pitra, P., Anczkiewicz, R., and Van Den Driessche, J. (2020). From burial to exhumation: Emplacement and metamorphism of mafic eclogitic terranes constrained through multimethod petrochronology, case study from the Lévézou Massif (French Massif Central, Variscan Belt). *J. Petrol.*, 61(4), 1–27.

Luoni, P., Zanoni, D., Rebay, G., and Spalla, M. I. (2019). Deformation history of ultra high-pressure ophiolitic serpentinites in the Zermatt-Saas Zone, Créton, Upper Valtournanche (Aosta Valley, Western Alps). *Ofioliti*, 44, 111–123.

Mancktelow, N. S. (2008). Tectonic pressure: theoretical concepts and modelled examples. *Lithos*, 103, 149–177.

Manga, M., Hornbach, M. J., Le Friant, A., Ishizuka, O., Stroncik, N., Adachi, T., Aljahdali, M., Boudon, G., Breitkreuz, C., Fraass, A., Fujinawa, A., Hatfield, R., Jutzeler, M., Kataoka, K., Lafuerza, S., Maeno, F., Martinez-Colon, M., Mccanta, M., Morgan, S., Palmer, M. R., Saito, T., Slagle, A., Stinton, A. J., Subramanyam, K. S. V., Tamura, Y., Talling, P. J., Villemant, B., Wall-Palmer, D., and Wang, F. (2012). Heat flow in the Lesser Antilles island arc and adjacent back arc Grenada basin. *Geochem. Geophys. Geosyst.*, 13, 1–19.

Manzotti, P., Schiavi, F., Nosenzo, F., Pitra, P., and Ballèvre, M. (2022). A journey towards the forbidden zone: a new, cold, UHP unit in the Dora-Maira Massif (Western Alps). *Contrib. Mineral. Petrol.*, 177, article no. 59.

Maresch, W. V. and Gerya, T. (2005). Blueschists and blue amphiboles: How much subduction do they need? *Int. Geol. Rev.*, 47, 688–702.

Marotta, A. M. and Spalla, M. I. (2007). Permian-Triassic high thermal regime in the Alps: Result of late Variscan collapse or continental rifting? Validation by numerical modeling. *Tectonics*, 26, 1–27.

Marques, F. O., Mandal, N., Ghosh, S., Ranalli, G., and Bose, S. (2018). Channel flow, tectonic overpressure, and exhumation of high-pressure rocks in the Greater Himalayas. *Solid Earth*, 9, 1061–1078.

Martelat, J. E., Malamoud, K., Cordier, P., Randrianasolo, B., Schulmann, K., and Lardeaux, J. M. (2012). Garnet crystal plasticity in the continental crust, new example from south Madagascar. *J. Metamorph. Geol.*, 30, 435–452.

Martens, U., Tsujimori, T., and Liou, J. G. (2017). Eclogite varieties and petrotectonic evolution of the northern Guatemala Suture Complex. *Int. Geol. Rev.*, 59(5–6), 721–740.

Martínez Catalán, J. R., Collett, S., Schulmann, K., Aleksandrowski, P., and Mazur, S. (2020). Correlation of allochthonous terranes and major tectonostratigraphic domains between NW Iberia and the Bohemian Massif, European Variscan belt. *Int. J. Earth Sci.*, 109, 1105–1131.

Maruyama, S., Liou, J. G., and Terabayashi, M. (1996). Blueschists and eclogites of the world and their exhumation. *Int. Geol. Rev.*, 38, 490–596.

Matte, P. (2001). The Variscan collage and orogeny (480–290 Ma) and the tectonic definition of the Armorica microplate: a review. *Terra Nova*, 13, 122–128.

Meda, M., Marotta, A. M., and Spalla, M. I. (2010). The role of mantle hydration into the continental crust recycling in the wedge region. In *Geological Society, London, Special Publications*, volume 332, pages 149–172. Geological Society of London.

Miyashiro, A. (1961). Evolution of metamorphic belts. *J. Petrol.*, 2, 277–311.

Molnar, P. and England, P. (1990). Temperatures, heat flux, and frictional stress near major thrust faults. *J. Geophys. Res. Solid Earth*, 95, 4833–4856.

Moulas, E., Schmalholz, S. M., Podladchikov, Y., Tajčmanová, L., Kostopoulos, D., and Baumgartner, L. (2019). Relation between mean stress, thermodynamic, and lithostatic pressure. *J. Metamorph. Geol.*, 37, 1–14.

Muñoz, M., Aguirre, L., Vergara, M., Demant, A., Fuentes, F., and Fock, A. (2010). Prehnite-pumpellyite facies metamorphism in the Cenozoic Abanico Formation, Andes of central Chile (33°50′S): chemical and scale controls on mineral assemblages, reaction progress and the equilibrium state. *Andean Geol.*, 37(1), 54–77.

Oberhänsli, R., Bousquet, R., Engi, M., Goffé, B., Gosso, G., Handy, M., Höck, V., Koller, F., Lardeaux, J.-M., Polino, R., Rossi, P., Schuster, R., Schwartz, S., and Spalla, M. I. (2004). *Metamorphic Structure of the Alps.* Commission for the Geological Map of the World, Paris.

Orme, D. A. and Surpless, K. D. (2019). The birth of a forearc: The basal Great Valley Group, California, USA. *Geology*, 47(8), 757–761.

Pindell, J. L. and Kennan, L. (2009). Tectonic evolution of the Gulf of Mexico, Caribbean and northern South America in the mantle reference frame: An update. In James, K. H., Lorente, M. A., and Pindell, J. L., editors, *The Origin and Evolution of the Caribbean Plate*, Geological Society, London, Special Publications, 328, pages 1–55. Geological Society of London.

Polino, R., Gosso, G., and Dal Piaz, G. V. (1990). Un modello attualistico sulla genesi delle Alpi. *Mem. Soc. Geol. It.*, 1990(45), 71–75.

Powell, R. (1978). *Equilibrium Thermodynamics in Petrology: An Introduction.* Harper and Row Publishers, New York.

Powell, R., Holland, T., and Worley, B. (1998). Calculating phase diagrams involving solid solutions via non-linear equations, with examples using THERMOCALC. *J. Metamorph. Geol.*, 16, 577–588.

Ramsay, J. G. (1980). Shear zone geometry: a review. *J. Struct. Geol.*, 2, 83–99.

Ranalli, G. (1997). Rheology of the lithosphere in space and time. In Burg, J.-P. and Ford, M., editors, *Orogen Through Time*, Geological Society, London, Special Publications, 121, pages 19–37. Geological Society of London.

Rebay, G., Spalla, M. I., and Zanoni, D. (2012). Interaction of deformation and metamorphism during subduction and exhumation of hydrated oceanic mantle: Insights from the Western Alps. *J. Metamorph. Geol.*, 30(7), 687–702.

Rebay, G., Zanoni, D., Langone, A., Luoni, P., Tiepolo, M., and Spalla, M. I. (2018). Dating of ultramafic rocks from the Western Alps ophiolites discloses Late Cretaceous subduction ages in the Zermatt–Saas Zone. *Geol. Mag.*, 155, 298–315.

Regorda, A., Spalla, M. I., Roda, M., Lardeaux, J. M., and Marotta, A. M. (2021). Metamorphic facies and deformation fabrics diagnostic of subduction: Insights from 2D numerical models. *Geochem. Geophys. Geosyst.*, 22, article no. e2021GC009899.

Reinecke, T. (1991). Very high-pressure metamorphism and uplift of coesite-bearing metasediments from the Zermatt-Saas zone, Western Alps. *Eur. J. Mineral.*, 10, 7–17.

Ricci, J., Quidelleur, X., and Lahitte, P. (2015). Volcanic evolution of Central Basse-Terre Island revisited on the basis of new geochronology and geomorphology data. *Bull. Volcanol.*, 77, article no. 84.

Roda, M., Spalla, M. I., and Marotta, A. M. (2012). Integration of natural data within a numerical model of ablative subduction: A possible interpretation for the Alpine dynamics of the Austroalpine crust. *J. Metamorph. Geol.*, 30, 973–996.

Roda, M., Zucali, M., Corti, L., Visalli, R., Ortolano, G., and Spalla, M. I. (2021). Blueschist mylonitic zones accommodating syn-subduction exhumation of deeply buried continental crust: The example of the Rocca Canavese Thrust Sheets Unit (Sesia–Lanzo Zone, Italian Western Alps). *Swiss J. Geosci.*, 114(6), 1–33.

Roda, M., Zucali, M., Regorda, A., and Spalla, M. I. (2020). Formation and evolution of a subduction-related melange: The example of the Rocca Canavese Thrust Sheets (Western Alps). *Bull. Geol. Soc. Am.*, 132(3–4), 884–896.

Rosenbaum, G. and Lister, G. S. (2005). The Western Alps from the Jurassic to Oligocene: spatio-temporal constraints and evolutionary reconstructions. *Earth Sci. Rev.*, 69, 281–306.

Rubatto, D., Gebauer, D., and Fanning, M. (1998). Jurassic formation and Eocene subduction of the Zermatt-Saas-Fee ophiolites: implications for the geodynamic evolution of the central and Western Alps. *Contrib. Mineral. Petrol.*, 132, 269–287.

Samper, A., Quidelleur, X., Lahitte, P., and Mollex, D. (2007). Timing of effusive volcanism and collapse events within an oceanic arc island: Basse-Terre, Guadeloupe archipelago (Lesser Antilles Arc). *Earth Planet. Sci. Lett.*, 258, 175–191.

Schertl, H. P. and O'Brien, P. J. (2013). Continental crust at mantle depths: Key minerals and microstructures. *Elements*, 9, 261–266.

Schmid, S. M., Fügenschuh, B., Kissling, E., and Schuster, R. (2004). Tectonic map and overall architecture of the Alpine orogen. *Eclogae Geol. Helv.*, 97, 93–117.

Schulmann, K., Edel, J. B., Martínez Catalán, J. R., Mazur, S., Guy, A., Lardeaux, J. M., Ayarza, P., and Palomeras, I. (2022). Tectonic evolution and global crustal architecture of the European Variscan belt constrained by geophysical data. *Earth Sci. Rev.*, 234, article no. 104195.

Schulmann, K., Konopásek, K., Janousek, V., Lexa, O., Lardeaux, J.-M., Edel, J.-B., Štípská, P., and Ulrich, S. (2009). An andean type Palaeozoic convergence in the Bohemian Massif. *C. R. Geosci.*, 341, 266–286.

Schulmann, K., Lexa, O., Janoušek, V., Lardeaux, J. M., and Edel, J. B. (2014). Anatomy of a diffuse cryptic suture zone: an example from the Bohemian Massif, European Variscides. *Geology*, 42, 275–278.

Searle, M. P. and Rex, A. J. (1989). Thermal model for the Zanskar Himalaya. *J. Metamorph. Geol.*, 7, 127–134.

Shreve, R. L. and Cloos, M. (1986). Dynamics of sediment subduction, melange formation, and prism accretion. *J. Geophys. Res.*, 91(B10), 10229–10245.

Smith, D. C. (1984). Coesite in clinopyroxene in the Caledonides and its implications for geodynamics. *Nature*, 310, 641–644.

Spalla, M. I., Gosso, G., Marotta, A. M., Zucali, M., and Salvi, F. (2010). Analysis of natural tectonic systems coupled with numerical modelling of the polycyclic continental lithosphere of the Alps. *Int. Geol. Rev.*, 52(10–12), 1268–1302.

Spalla, M. I., Lardeaux, J. M., Dal Piaz, G. V., Gosso, G., and Messiga, B. (1996). Tectonic significance of Alpine eclogites. *J. Geodyn.*, 21(3), 257–285.

Spalla, M. I., Zucali, M., Di Paola, S., and Gosso, G. (2005). A critical assessment of the tectono-thermal memory of rocks and definition of tectono-metamorphic units: Evidence from fabric and degree of metamorphic transformations. In *Geological Society, London, Special Publications*, volume 243, pages 227–247. Geological Society of London.

Spear, F. S. (1993). *Metamorphic Phase Equilibria and Pressure–Temperature–Time Paths*. Monograph Serie 1. Mineralogical Society of America, Washington, DC (USA).

Spear, F. S. and Peacock, S. M. (1989). *Metamorphic Pressure–Temperature–Time Paths*. Short Course in Geology, 7. American Geophysical Union, Washington, DC (USA).

Štípská, P., Schulmann, K., Racek, M., Lardeaux, J. M., Hacker, B. R., Kylander-Clark, A. R. C., Holder, R., and Košuličová, M. (2019). Finite pattern of Barrovian metamorphic zones: interplay between thermal reequilibration and post-peak deformation during continental collision—insights from the Svratka dome (Bohemian Massif). *Int. J. Earth Sci.*, 109, 1161–1187.

Stöckhert, B. and Gerya, T. (2005). Pre-collisional high-pressure metamorphism and nappe tectonics at active continental margins: a numerical simulation. *Terra Nova*, 17, 102–110.

Stöckhert, B., Maresch, W. V., Brix, M., Kaiser, C., Toetz, A., Kluge, R., and Krückhans-Lueder, G. (1995). Crustal history of Margarita Island (Venezuela) in detail: Constraint on the Caribbean plate-tectonic scenario. *Geology*, 23, 787–790.

Suess, F. E. (1875). *Die entstehung der Alpen*. Wilhelm Braumuller, Vienna.

Suess, F. E. (1926). *Intrusionstektonik und Wandertektonik im variszischen Grundgebirge*. Verlag von Gebrüder Borntraeger, Berlin.

Teall, J. J. H. (1885). The metamorphosis of dolerite into hornblende schist. *Q. J. Geol. Soc. London*, 41, 133–145.

Thomas, J. B., Watson, E. B., Spear, F. S., Shemella, P. T., Nayak, S. K., and Lanzirotti, A. (2010). TitaniQ under pressure: the effect of pressure and temperature on the solubility of Ti in Quartz. *Contrib. Mineral. Petrol.*, 160, 743–759.

Thompson, A. B. and England, P. C. (1984). Pressure–temperature–time paths of regional metamorphism. Part II: their influence and interpretation using mineral assemblages in metamorphic rocks. *J. Petrol.*, 25, 929–955.

Tomkins, H. S., Powell, R., and Ellis, D. J. (2007). The pressure dependance of the zirconium-in-rutile thermometer. *J. Metamorph. Geol.*, 25, 703–713.

Tsujimori, T., Sisson, V. B., Liou, J. G., Harlow, G. E., and Sorensen, S. S. (2006). Very-low-temperature record of the subduction process: A review of worldwide lawsonite eclogites. *Lithos*, 92, 609–624.

Tual, L., Smit, M., Cutts, J., Kooijman, E., Kielman-Schmitt, M., and Foulds, I. (2022). Rapid, paced garnet growth in blueschists from Lu-Hf dating of laser-cut domains combined with trace-element mapping. *Chem. Geol.*, 607, 1–14.

Van Hunen, J. and Allen, M. B. (2011). Continental collision and slab break-off: A comparison of 3-D numerical models with observations. *Earth Planet. Sci. Lett.*, 302(1–2), 27–37.

Vérati, C., Lardeaux, J.-M., Favier, A., Corsini, M., Philippon, M., and Legendre, L. (2018). Arc related metamorphism in the Guadeloupe archipelago (Lesser Antilles active island arc): first report and consequences. *Lithos*, 320–321, 592–598.

Wakabayashi, J. (1990). Counterclockwise P–T–t paths from amphibolites, Franciscan Complex, California: Relics from the early stages of subduction zone metamorphism. *J. Geol.*, 98, 657–680.

Wakabayashi, J. (1992). Nappes, tectonics of oblique plate convergence, and metamorphic evolution related to 140 million years of continuous subduction, Franciscan Complex, California. *J. Geol.*, 100, 19–40.

Wassmann, S. and Stöckhert, B. (2012). Matrix deformation mechanisms in HP–LT tectonic mélanges—microstructural record of jadeite blueschist from the Franciscan. *Tectonophysics*, 568–569, 135–153.

West, D. P., Abbott Jr, R. N., Bandy, B. R., and Kunk, M. J. (2014). Protolith provenance and thermotectonic history of metamorphic rocks in eastern Jamaica: Evolution of a transform plate boundary. *GSA Bull.*, 126(3/4), 600–614.

White, R. W., Powell, R., Holland, T. J. B., Johnson, T. E., and Green, E. C. R. (2014). New mineral activity-composition relations for thermodynamic calculations in metapelitic systems. *J. Metamorph. Geol.*, 32, 261–286.

Whitney, D. L., Hamelin, C., Teyssier, C., Raia, N. H., Korchinski, M. S., Seaton, N. C. A., Bagley, B. C., von der Handt, A., Roger, F., and Rey, P. F. (2020). Deep crustal source of gneiss dome revealed by eclogite in migmatite (Montagne Noire, French Massif Central). *J. Metam. Geol.*, 38(3), 297–327.

Xiang, H. and Connolly, J. A. D. (2022). GeoPS: An interactive visual computing tool for thermodynamic modelling of phase equilibria. *J. Metamorph. Geol.*, 40(2), 243–255.

Yakymchuk, C. (2017). Applying phase equilibria modelling to metamorphic and geological processes: Recent developments and future potential. *Geosci. Canada*, 44, 27–46.

Zen, E. A. (1966). *Construction of Pressure-Temperature Diagrams for Multicomponent Systems after the Method of Schreinemakers: A Geometric Approach.* US Geological Survey Bulletin, 1225. United States Government Printing Office, Washington.

Zucali, M. and Spalla, M. I. (2011). Prograde lawsonite during the flow of continental crust in the Alpine subduction: strain vs. Metamorphism partitioning, a field-analysis approach to infer tectonometamorphic evolutions (Sesia-Lanzo zone, Western Italian Alps). *J. Struct. Geol.*, 33, 381–398.

Zwart, H. J. (1962). On the determination of polymetamorphic mineral associations and its application to the Bosost area (Central Pyrenees). *Geol. Runds.*, 52, 38–65.