

THE GRISCHUN-MALENCO FOSSIL OCEAN-CONTINENT-TRANSITION: THE FATE OF THE SUBCONTINENTAL MANTLE IN A WILSON CYCLE AND ITS SIGNIFICANCE FOR H₂ EXPLORATION

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ABSTRACT

The call for an “energy transition” is undeniably linked to the finding of low-emission energies, among which serpentinization-sourced native hydrogen (H₂) is one of them. However, the knowledge needed to successfully explore for this new energy, i.e., to understand how, when and where during the Wilson cycle native H₂ forms is yet incomplete. Answering these questions is challenging and requires not only much further understanding of serpentinization processes, but first of all a comprehensive understanding of the geological systems in which serpentinization occurs. In this paper, we investigate the characteristics and evolution of the geological system that hosted and/or hosts serpentinization and potential H₂ production. More specifically, we discuss the evolution of mantle rocks during rifting and their emplacement in an ocean-continent transition (OCT) prior to their reactivation and emplacement in a rift-inversion orogen. We illustrate our point by reviewing the evolution of the Grischun-Malenco OCT-derived ophiolites, one of the best documented and exposed examples of an OCT-derived ophiolite worldwide, located in the eastern Central Alps.

We first review the characteristics of OCTs and their H₂ potential based on the well calibrated example of the Iberian margin. Second, we synthesize the state-of-the art knowledge on the Grischun-Malenco OCT-derived ophiolites. Third, we describe the emplacement mechanisms of mantle rocks in orogens, distinguishing between thin-bodied allochthonous mantle and thick-bodied mantle wedges. Finally, we review the mantle-melt and mantle-fluid interactions and discuss their importance for understanding serpentinization-sourced H₂ systems. Our review shows that the Grischun-Malenco fossil OCT may not only serve as a natural laboratory to understand OCT formation and inversion, but also to investigate the potential of serpentinization-sourced H₂ in rift-inversion orogens.

INTRODUCTION

The life cycle of tectonic plates, named the Wilson Cycle, encompasses a range of geodynamic settings that govern the chemical-physical evolution of mantle rocks (Wilson, 1966; Burke, 2011; Heron, 2018; Wilson et al., 2019). Understanding the fate of mantle rocks throughout a Wilson Cycle, in particular when, where and how they interact with fluids, is crucial to explore for the invaluable mantle-related resources, including serpentinization-sourced native hydrogen (H₂) (Neal and Stanger, 1983; Jackson et al., 2024). This requires understanding the evolution of mantle rocks across scales, from regional tectonics to mineral-scale processes. It also requires re-examining sites that record either individual stages of the Wilson Cycle, or their succession. The mantle rocks exposed in the Grischun-Malenco area in SE-Switzerland and N-Italy, discussed in this study, are exceptionally well-preserved and record the evolution from post-orogenic collapse, to rifting and (proto)-oceanization, to (Ampferer-type) subduction and continental collision/orogeny (McCarthy et al., 2020).

Substantial work carried out over the last decades on mid-ocean ridges (MOR) (Klein et al., 2009; Andreani et al., 2013), subduction zones (Deschamps et al., 2010; Merdith et al., 2023), and ophiolites derived from these settings (Dilek and Furnes, 2011) enabled to develop a fair understanding of serpentinization systems. In contrast, ocean-continent transitions (OCTs) and ophiolites derived from such settings, have been much less explored (Manatschal and Müntener, 2009; Albers et al., 2021; Hochscheid et al., 2024). And yet, compared to OCT-derived ophiolites, ophiolites derived from Mid Ocean Ridges (MOR) or Supra-Subduction Zones (SSZ)

are distinctly different in terms of mantle rock composition, mantle-fluid and mantle-magma interactions, and mechanisms of emplacement into a collisional orogen (Rampone et al., 1995; Piccardo et al., 2004; Müntener et al., 2004; Patten et al. 2022).

One reason why the scientific community paid little attention to OCTs and OCT-derived ophiolites may be historical. Indeed, despite Gustav Steinmann, as early as the beginning of the last century, recognized mantle rocks associated with dolerites and deep-water sediments along the Alpine belt in Western Europe, and suggested they were derived from what he considered as an ocean (Steinmann, 1927), the comparison of seismic reflection sections from modern oceans with observations from the Samail Ophiolite in Oman and the Troodos Ophiolite in Cyprus (Boudier and Coleman, 1981; Varga and Moores, 1985) led the community to conclude that oceans are made of a three-layered magmatic crust, referred to as Penrose-type oceanic crust (Anonymous, 1972), rather than of exhumed serpentinized mantle. Hence, in the following from the 1970s to the late 1990s, the Alpine ophiolites were reinterpreted as mélanges, namely incomplete sequences of former Penrose-type oceanic crust that were dismembered during their emplacement in the orogen (Hsü and Bregel, 1991).

Mantle rocks from present-day OCTs have been sampled at only few margins worldwide, among which the Iberia-Newfoundland conjugated magma-poor rifted margins (ODP Legs 103; 149, 173; 210; Müntener and Manatschal, 2006), the SW Australia and the Antarctica margins (McCarthy et al., 2020; Ballay et al., 2025) and the Central Red Sea at Zabargad island (Bonatti et al., 1981; Khudeir et al., 2024) (Fig. 2a). In contrast, fossil OCTs exposed in orogenic

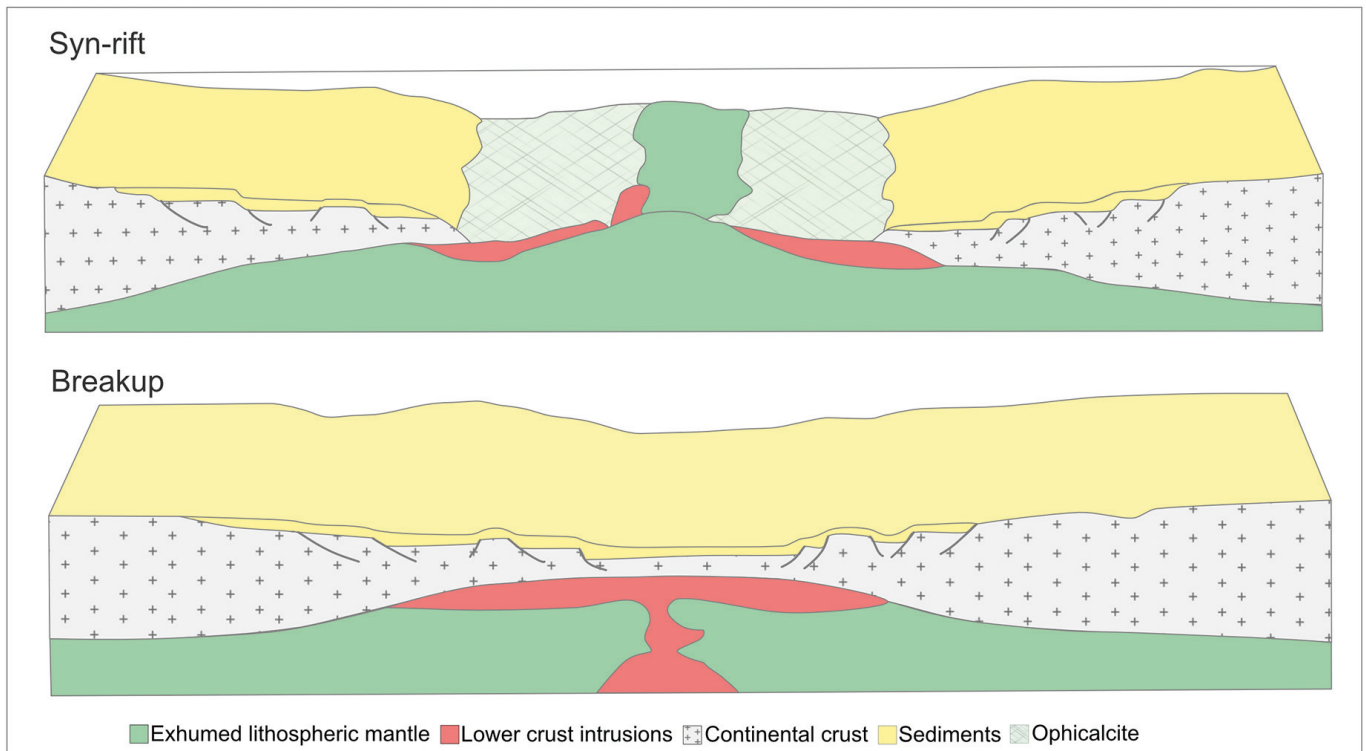


Fig. 1 - Elter's model of an Ocean Continent Transition (modified from Decandia and Elter, 1972). Elter's model shows the evolution from a thinned, continental crust, underplated by gabbros (lower block: breakup) that precedes the exhumation of the subcontinental mantle (upper block: syn-rift).

belts such as the Pyrenees, the Apennines and the Alps of Western Europe, provide direct access and almost unlimited sampling of exhumed mantle rocks, facilitating the study of their geological evolution (Picazo et al., 2016 and references therein). Among them, the Grischun-Malenco fossil OCT forms, together with its modern analogue, the Iberia OCT (Fig. 2b), the type locality of a magma-poor OCT (Whitmarsh et al., 2001). In fact, the characterization and definition of magma-poor OCTs were only possible through the integration of geophysical and drill hole observations conducted along the Iberia OCT (Boillot et al., 1980, 1987; Reston et al., 1995; Sutra et al., 2013) with field observations from the Grischun-Malenco fossil OCT (Florineth and Froitzheim, 1994; Manatschal and Nievergelt, 1997; Epin et al., 2019).

In this study, we first provide a general overview of magma-poor OCTs and their H_2 potential production before focusing on the Grischun-Malenco fossil OCT. Then, we investigate the fate of the subcontinental mantle throughout a Wilson Cycle, from rifting to inversion, using the Grischun-Malenco fossil OCT as an example. This approach allows us to discuss when, where, and how mantle interacts with siliceous and aqueous fluids, thereby triggering major chemical-physical processes (i.e., serpentinization and potential H_2 production). In a final part, we highlight the strong link between the evolution of the subcontinental mantle and production of H_2 , developing a perspective for H_2 exploration in fossil OCTs preserved in rift-inversion orogens. Rather than attempting to draw preliminary conclusions from first encouraging H_2 discoveries, we aim to identify the key questions that drive ongoing and future research in fossil OCTs in general, and the Grischun-Malenco OCT in particular.

OCEAN-CONTINENT TRANSITIONS: A GLOBAL PERSPECTIVE

Definition

We define OCT the domain of rifted margins delimited inboard by the end of undisputable continental crust, and outboard by the onset of undisputable (Penrose-type) oceanic crust. OCTs may display markedly distinct architectures depending on the magma budget during rifting (Fig. 2a). In so-called magma-rich margins, OCTs typically display seaward-dipping reflections (SDRs) presumably formed of magmatic extrusives (Planke and Eldholm, 1994; ODP Leg104; Saunders et al., 1998; ODP Leg152). In such settings mantle rocks are not exhumed and their nature is unknown. In contrast, in the OCT of so-called magma-poor margins, mantle rocks are exhumed to the seafloor over up to several tens of kilometres along dip and several hundreds of kilometres along strike.

Observations from the OCTs of the magma-poor Iberia-Newfoundland conjugate margins

The OCTs of magma-poor rifted margins exhibit distinctive features, well described from the drilled and seismically imaged Iberia-Newfoundland OCTs (Whitmarsh et al., 2001) (Fig. 2b). Drill hole data from both margins show that the exhumed mantle has a subcontinental origin (Müntener and Manatschal, 2006). Besides, the occurrence of a ca. 20 km wide and up to 2 km thick block of continental crust over exhumed mantle offshore Iberia (c.f., ODP Site 1069; Whitmarsh et al., 2001; Wilson et al., 2001; Fig. 2b) excludes a formation of the OCT by seafloor spreading. Hence, this

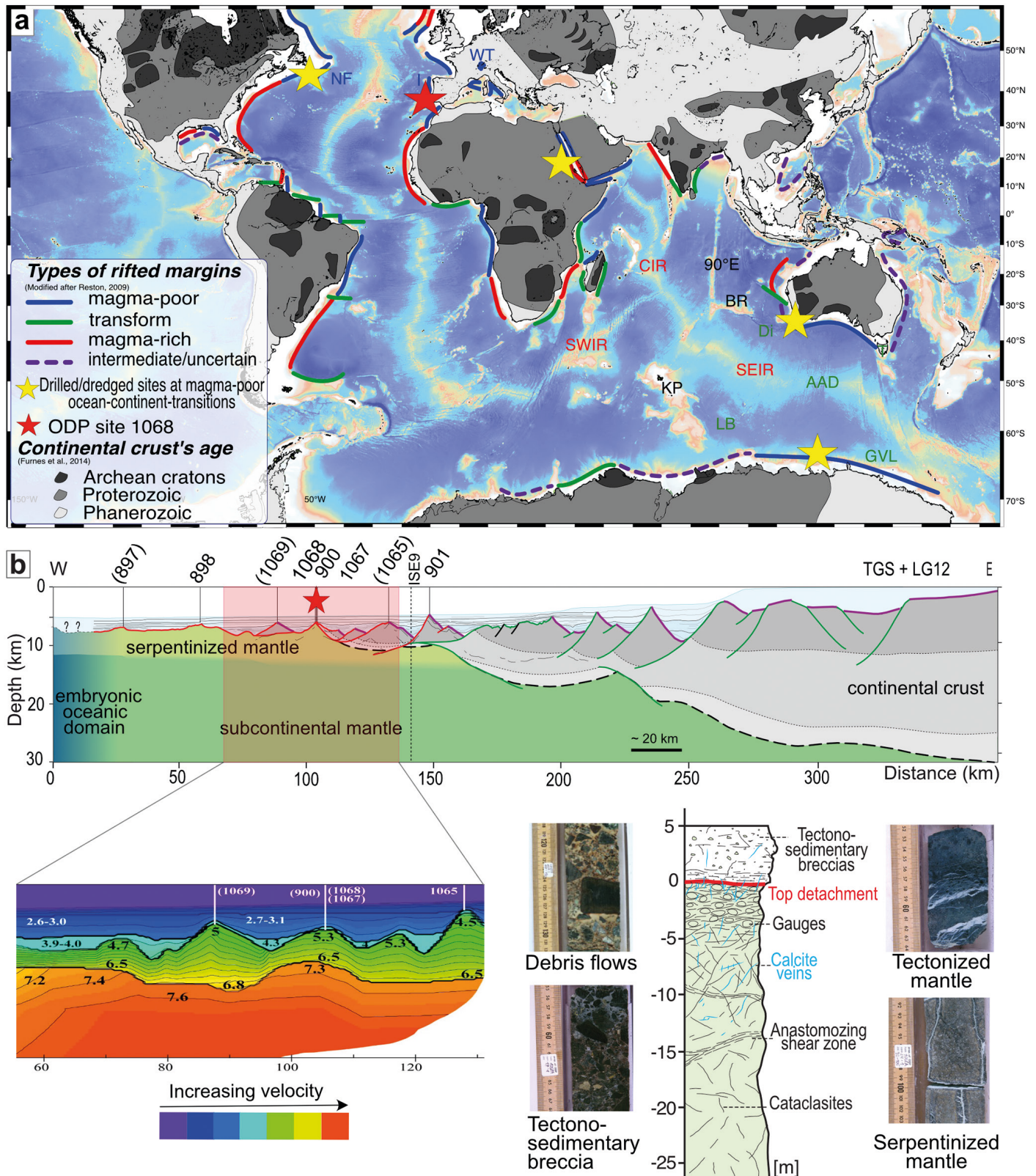


Fig. 2 - a) Map showing the global distribution of the three main types of rifted margins (modified after Ballay et al., 2025). Sites where exhumed mantle rocks have been drilled/dredged at ocean continent transitions along magma-poor rifted margins are shown. b) The upper section shows the crustal architecture across the Western Iberia margin offshore Porto (section based on the interpretation of the TGS/LG12 seismic lines by Sutra et al. 2013). Numbers refer to ODP drill sites from ODP Legs 149 and 173. The lower section shows an excerpt from the seismic refraction image of the ocean continent transition from Chian et al. (1999). The contour interval of velocity is 0.2 km/s. The lower right corner panel shows images of exhumed mantle type-lithologies recovered at the ODP Site 1068. The drilled section shows a transition from debris flows to tectono-sedimentary breccias overlying a tectonized mantle with veins that grade down-section into massive, veined serpentinites.

continental block was interpreted as an extensional allochthon and mantle was assumed to have been exhumed to the seafloor via detachment faults (Boillot et al. 1987; Whitmarsh et al., 2001; Gillard et al., 2019). The mantle rocks in the footwall of these detachment faults are serpentinized cataclasites and gouges that show a decrease in strain and serpentinization with depth (Manatschal et al., 2001; Fig. 2b). They are overlain by deep-water sediments including debris flows reworking the exhumed mantle (Wilson et al., 2001; Robertson, 2002).

Reflection and refraction seismic data show that the exhumed mantle in the Iberian and Newfoundland OCTs forms highs and lows and is serpentinized down to about 6 km (Fig. 2b), indicating that exhumation is associated with severe hydrothermal alteration (Schuba et al., 2018; Lymer et al., 2019). When and where mantle serpentinization occurs during exhumation is not well constrained for OCTs. However, observations from present slow-spreading MORs suggest that it occurs prior to exposure at the seafloor (Cannat et al., 2010). This is in line with the recovery of already serpentinized clasts in debris flows overlying the exhumed mantle (Robertson; ODP Site 1277), calcite veins with a marine O-isotope signature truncating foliated serpentinites (Picazo et al., 2020; ODP Site 1277), and enrichment in mantle-derived elements along intracontinental detachment faults drilled at ODP Site 1067 (Pinto et al., 2023).

Syn-exhumation magmatic activity, whether intrusive (gabbros) or extrusive (basalts), was only encountered in ODP drill holes from the ultra-distal parts of the Iberian and Newfoundland OCTs (Müntener and Manatschal, 2006). Evidence of magmatic activity outlasting exhumation has been found in ODP Site 1276, as indicated by sills in post-rift sediments and imaged in seismic sections (Peron-Pinvidic et al., 2010). The magmas are either alkaline or tholeiitic (Jagoutz et al., 2007). Trace element and isotopic studies of upper mantle rocks in the Iberia-Newfoundland OCTs typically show chemical heterogeneities with isotopic compositions predominantly not in equilibrium with overlying magmatic rocks, which are isotopically more homogeneous (Rampone et al., 1998; Warren et al., 2009; Rampone and Hofmann, 2012; Secchiari et al., 2025).

The main learning from the drilling and seismic imaging of the Iberia-Newfoundland OCTs is that their structure and lithologies show distinct characteristics to that of MORs. For instance, the occurrence of continent-derived extensional allochthons is restricted to OCTs; the mantle of OCTs is generally more fertile than the oceanic mantle beneath MORs (Müntener et al., 2010; Rampone and Sanfilippo, 2021; Albers et al., 2021); and magmatic rocks in OCTs are alkaline to T-MORB whereas MOR are associated with N-MORB (Jagoutz et al., 2007; Amann et al., 2020). Although relatively few samples have been recovered from present magma-poor OCTs worldwide, all show similar geochemical and petrological characteristics like those from the Iberia OCT (Ballay et al., 2025). Moreover, the seismic characteristics of worldwide OCTs (for a review see Gillard et al., 2019) enable us to assign about half of them as belonging to magma-poor margins (Fig. 2a).

The comparison between modern and fossil OCTs was mainly based on the petrological and geochemical characteristics of their mantle rocks (Picazo et al., 2016). In contrast, it is more difficult to compare the geophysical characteristics of modern OCTs with those of fossil OCT. One exception is the Grischun-Malenco fossil OCT (Figs. 3 and 4), where sites such as Tasna or Falotta/Platta enable to compare well

preserved, kilometre-scale outcrops, with seismically imaged OCTs (Hölker et al., 2002; 2003; Betlem et al., 2023). These OCT-derived ophiolites mainly expose serpentinized peridotite, made of spinel lherzolites and harzburgites, flooring detachment faults and overlain by continent-derived allochthons, magmatic extrusives and/or deep-water sediments (Fig. 5). Thus, they compare well with the seismically imaged and drilled modern examples of the Iberia-Newfoundland OCTs (Fig. 2b).

The reactivation of OCTs and their fate in collisional orogens

Understanding the reactivation of OCTs and their emplacement in collisional orogens (Manatschal et al., 2022) is key to comprehend the fate of exhumed mantle during orogeny. This is a prerequisite for reconstructing post-rift serpentinization systems, as well as for identifying source rocks for serpentinization-sourced H_2 production in such orogens. A privileged place to study the reactivation of OCTs is the Biscay-Pyrenean system in SW-Europe (Fig. 2a). Along this system, a complete transition from a magma-poor OCT preserved in the western Bay of Biscay, through its incipient reactivation in the eastern Bay of Biscay, to its incorporation/integration into a rift-inversion orogen in the central Pyrenees (the Lherz massif) can be observed.

Studies in the Pyrenean-Biscay domain (Lescoutre and Manatschal, 2020; Miro et al., 2023) showed that the occurrence of serpentinized mantle plays a key role in localizing the deformation and controlling the exhumation of mantle rocks in rift-inversion orogens. These studies revealed that two situations can be distinguished during inversion of a rift system segmented by transform faults. The first one, mainly observed at rift segment centres, is that basement highs made of exhumed mantle are scalped during convergence and accreted in the orogen. This process can account for the sampling of small bodies, so-called allochthonous mantle bodies, commonly thinner than 500 m, with a top basement capped by a detachment and floored by a thrust. Examples in the Grischun-Malenco OCT in the Alps are the Totalp or the Tasna units (Manatschal and Müntener, 2009) (Fig. 5).

The second situation is linked to the reactivation of overlapping en-echelon rift segments. During the reactivation of adjacent rift segments, thrust shortcuts connecting the two rift segments may result in the incorporation of segment terminations in the hanging wall of the down-going plate. As a consequence, these segment terminations, containing exhumed mantle and hyperextended crust, are accreted in the orogen (for a documented example of this process see Fig. 4, section C in Lescoutre and Manatschal, 2020). This process can explain the occurrence of much larger, up to several km long and several km thick, ultramafic bodies within rift-inversion orogens, also referred to as rooted mantle bodies, or, in this study mantle wedges. Examples are the Bilbao, Mauléon, and Saint Gaudens mantle bodies in the Cantabrian-Pyrenean system, and the Ivrea and likely the Malenco mantle wedge (see below) in the Alps of Western Europe.

Serpentinization-sourced H_2 and its link to OCT and rift-inversion orogens

Although research on native hydrogen is booming in both academic and industrial circles, our understanding of natural H_2 production remains fragmentary and a major breakthrough

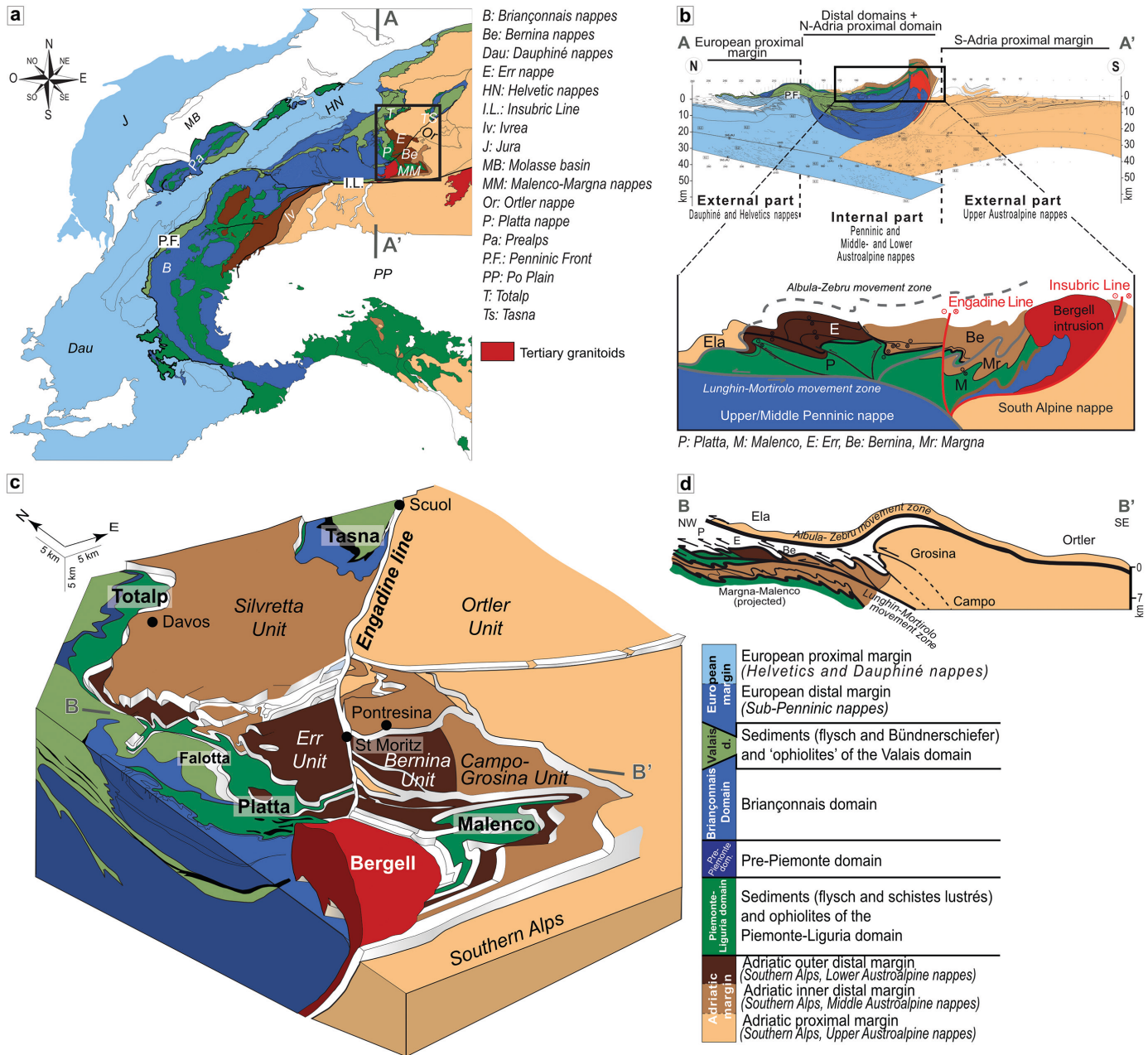


Fig. 3 - a) Tectonic map of the Western and Central Alps (modified after Schmid et al., 1996). b) N-S directed crustal scale cross section across the eastern Central Alps corresponding to the interpretation of the NFP 20 seismic data (modified after Schmid et al., 1996) and a zoom across the study area (modified after Mohn et al., 2012). For location of the section see trace A-A' in the map in (a). c) 3D block of the Grischun-Malenco area (modified after Froitzheim et al., 1994). d) SE-NW directed cross section across the southern Grischun-Malenco area (modified after Mohn et al., 2012; for location see trace B-B' in (c)).

– namely, the discovery of an economically viable source of hydrogen – has yet to be achieved. So far, most studies have focused, with considerable success, on the detection of native H_2 through surface measurements (e.g., Truche, 2018; Moretti, 2021; Lefeuvre, 2022; Levy, 2023; Azor de Freitas et al., 2025; Diehl et al., 2026), or on estimating serpentinization-sourced H_2 potential based on geochemical and/or geodynamic investigations of mantle rocks evolution (e.g., Andreani et al., 2013; Albers et al., 2021; Liu et al., 2023; Zwann et al., 2025). Other studies have instead emphasized the evaluation of different production mechanisms (e.g., radiolysis vs serpentinization), potential accumulation sites (reservoir) or water-supply and H_2 -migration pathways (Truche et al. 2018; Ballentine et al., 2025; Diehl et al., 2026). To

date, few studies focused on the serpentinization-sourced H_2 systems at OCT and rift-inversion orogens, but revealing important learnings. In this context, we refer to three main achievements obtained in the last years.

A first important step was achieved with the studies of Albers et al. (2021) and Liu et al. (2023). Both studies applied complementary approaches to estimate H_2 potential production at magma-poor rifted margins. The study by Albers et al. (2021) was based on drill-cores of serpentinized subcontinental mantle rocks from the West Iberia Margin, whereas the study by Liu et al. (2023) was developed based on the tectonic structures of the conjugate Newfoundland and West Iberia margin. Albers et al. (2021) estimated, by mass balance and thermodynamic calculations, production values of

about 120 to >300 mmol H₂ per kg of serpentinized rock at OCTs, similar to values of about 200 to 350 mmol obtained for slow-spreading MORs. Liu et al., 2023 estimated, through their 2D thermomechanical model, a rate of $(7.5 \pm 2.5) \times 10^7$ mol/(year $\times$ km) of H₂ release, during mantle exhumation, and an accumulation of approximately 4.3×10^{18} mol (about 8.6×10^{12} metric tons) prior to the opening of the North Atlantic Ocean, at a rate of about 1.4×10^{17} mol/million years. These estimates are based on the measurement of the area of exhumed mantle in OCTs, which is derived from wide-angle seismic profiles. Both studies show considerable potential for H₂ production in OCT geological settings, potentially representing up to one quarter of the total predicted global H₂ flux generated at mid-ocean ridges (Liu et al., 2023). In particular, H₂ production associated with seawater-lherzolite interac-

tions at OCTs were inferred to be up to two times higher than those produced during hydration of harzburgites at ultraslow-spreading MORs (Albers et al., 2021).

A second important step was the systematic and worldwide detection of H₂ outgassing linked to ophiolites that has skyrocketed over the last few years (Boulart et al., 2013; Zgonnik et al., 2019; Lefeuvre et al., 2022; Levy et al., 2023; Diehl et al., 2026). While for most H₂ occurrences the origin of the ophiolite (OCT, MOR or SSZ) remains to be evaluated, the Pyrenean ophiolites are undeniably linked to OCTs (Lagabrielle and Bodinier, 2008). Over the last few years, the Pyrenees, and more particularly in the Mauléon Basin became the type example of a rift inversion orogen (Lescoutre and Manatschal, 2020) with an active H₂ system (Lefeuvre et al., 2022). Due to Maupasacq dense seismic network in the Mauleon Basin/

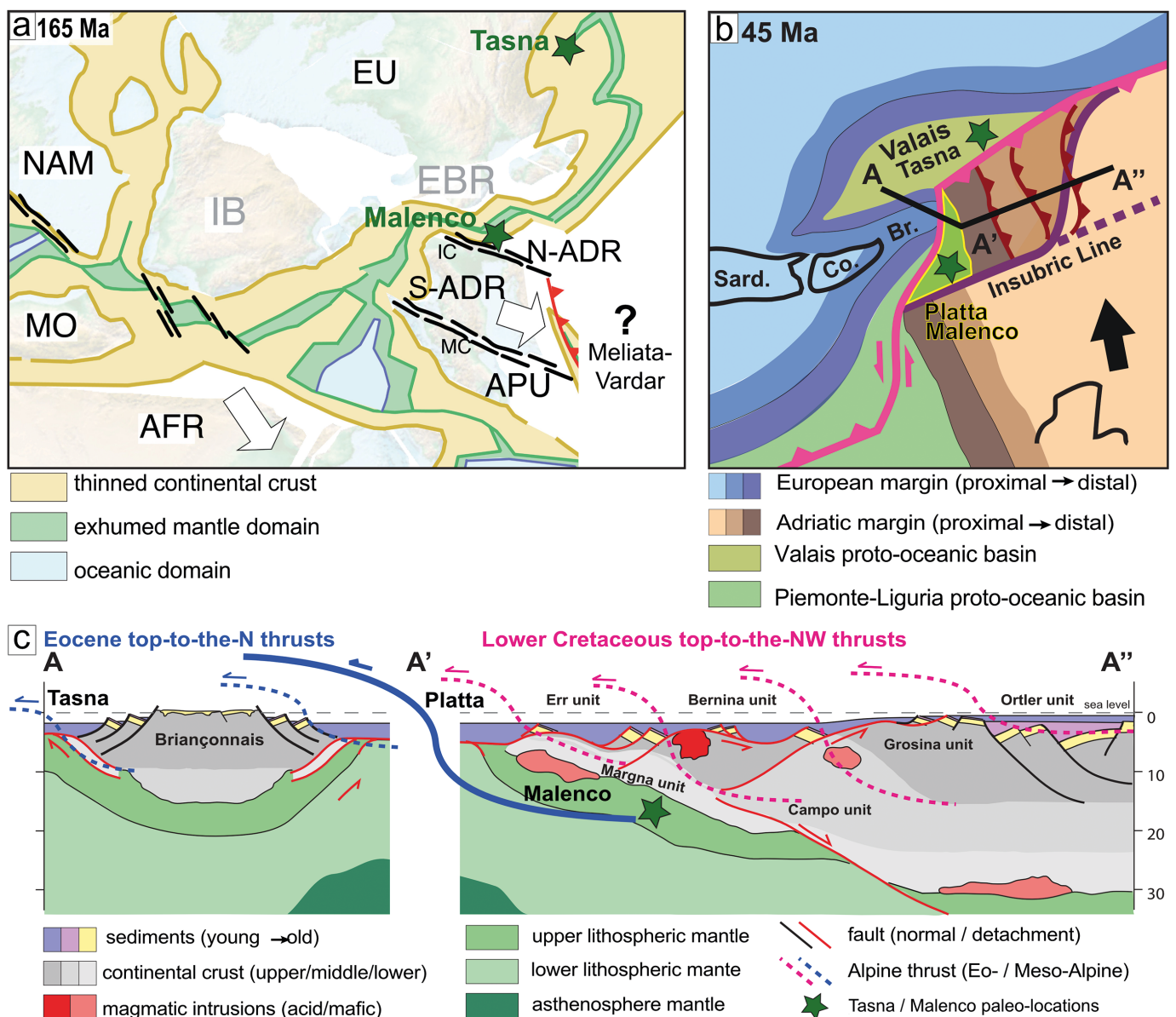


Fig. 4 - a) Snapshot of the kinematic reconstruction at 165 Ma of the Alpine Tethys Jurassic rift (modified after Frasca et al., 2024) (AFR: African plate; EU: European plate; APU: Apulia; S-ADR: southern Adria; N-ADR: northern Adria; IL: Insubric Line). b) Paleogeographic reconstruction at 45 Ma, showing onset of collision between Adria and the European margin (modified after Manatschal et al., 2022) (Co: Corsica; Br: Briançonnais). c) Cross section across the Adriatic-European margin (modified after Mohn et al., 2012), showing the location of the main future thrust faults of Eo-Alpine age (red faults in the Adriatic margin) and main Meso-Alpine thrusts (blue faults). Traces of section (A-A'-A'') are shown in map (b).

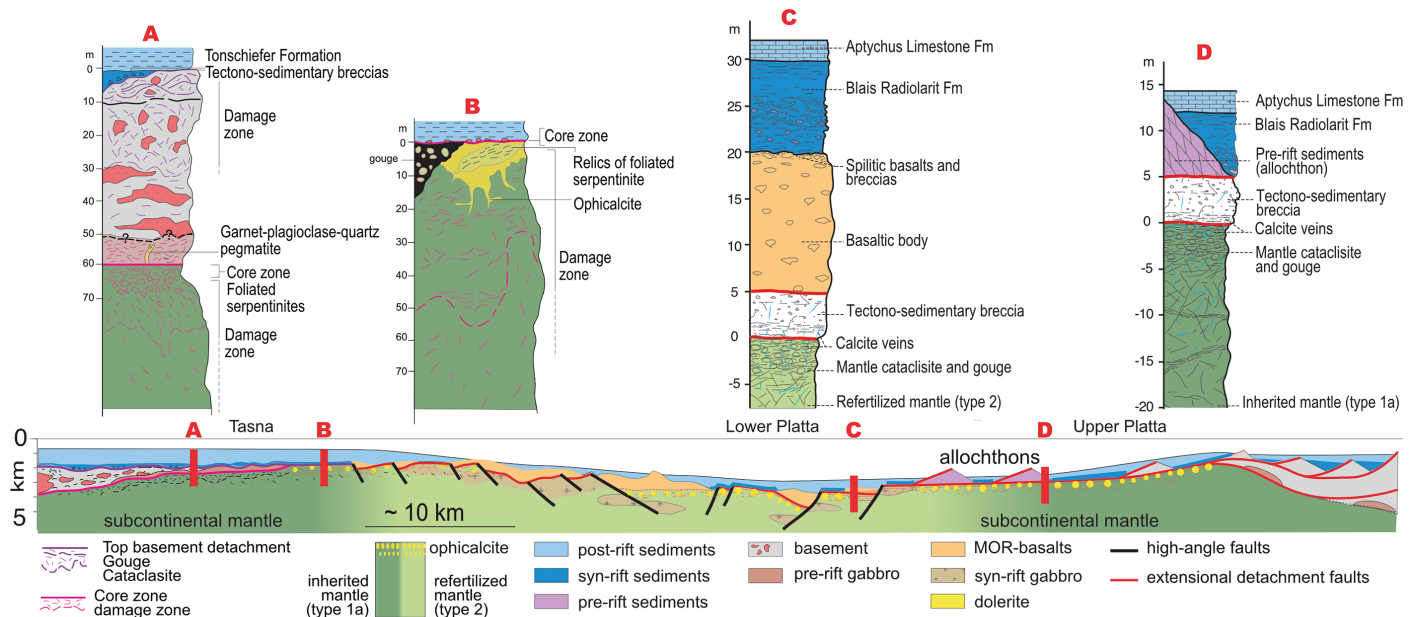


Fig. 5 - Palinspastic reconstruction of the Grischun-Malenco OCT based on field observations. Note that Tasna has been projected into the section and does not correspond to the direct conjugate of the Platta (OCT). Lithological sections across the Grischun-Malenco OCT: A, B (Tasna), C (Lower Platta) and D (Upper Platta) (modified after Manatschal et al. 2006 and Manatschal and Müntener, 2009).

Western Pyrenees (Lehujour et al. 2021) combined with systematic H_2 measurements, it was possible to link H_2 migration along faults with the existence of an ultramafic body flooring the Mauléon Basin (Lefeuvre et al. 2022). These studies showed that mantle bodies, exhumed during rift-related hyperextension and trapped in the orogen during subsequent convergence, can still produce H_2 . In the last years, numerous studies have further investigated and analysed the H_2 system in the Mauléon Basin, which has become a natural laboratory to study a serpentinization-source native H_2 systems in rift-inversion orogens. While studies in the Mauléon Basin took advantage of decades of hydrocarbon exploration, allowing access to seismic reflection images and drill hole data, neither the production site nor the plumbing system of this H_2 production system is exposed in 3D, conversely to the Grischun-Malenco area investigated in this study.

A third important step in linking serpentinization-sourced H_2 systems with OCTs and rift-inversion orogens is the study of Zwaan et al. (2025), which shows that rift-inversion orogens are hot spots for onshore H_2 exploration. Their model shows the fate of mantle rocks during a Wilson cycle using a dynamic model, and predicts the volume of produced H_2 as a function of the geodynamic stage. Quantification of H_2 fluxes and volumes using numerical modelling (Zwaan et al., 2025) is surely an important step towards prediction and exploration of H_2 systems, however, such models require testing and calibration. Therefore, natural laboratories, such as the Mauléon Basin or the Grischun-Malenco fossil OCTs are important. Most important for these models is that they need to incorporate site-specific parameters.

THE GRISCHUN-MALENCO FOSSIL OCT

Geological setting

The Grischun-Malenco fossil OCT is part of the eastern Central Alps, located between southeast Switzerland and the

Valtellina valley in northern Italy (Figs. 3a and 3c). It is part of an Austroalpine and Penninic thrust-sheet system sampling remnants of the Alpine Tethys and the adjacent European and Adriatic margins (Figs. 4a, 4b and 4c). It contains four major ultramafic bodies, Tasna north of Scuol, Totalp north of Davos, Platta in the Surses valley to the west, and Malenco north of Sondrio (Fig. 3c). The present study focuses on these four ultramafic bodies and their link to the surrounding continent-derived units forming together the Grischun-Malenco fossil OCT (Figs. 3a and 3c).

The Grischun-Malenco OCT was part of the Tethyan system, which developed over Variscan post-orogenic lithosphere. Following the end of Variscan convergence, the resulting large orogen collapsed during Permian time. This event brought back crustal thickness to ca. 30 km thickness over entire Western Europe and was associated with widespread mantle-derived magmatic activity (see section 4.2). Subsequent rifting in the future Alpine realm generated two (proto-) oceanic domains, namely the Triassic Vardar-Meliata system east of Adria, and the Jurassic Alpine Tethys system between the European and Adria-African plates (Fig. 4a). Note that the Alpine Tethys rift system, from which the Grischun-Malenco fossil OCT derives, was segmented: on the Adriatic side, the “Insubric system”, a major transform zone, delimited Northern Adria and the Piemonte segment of the Alpine Tethys from Southern Adria and the Ligurian segment of the Alpine Tethys (Fig. 4a; Frasca et al., 2024); and on the European side, the Valais V-shaped basin was separated from the Alpine Tethys by the Briançonnais continental ribbon (Figs. 4a and 4c; Manatschal et al., 2022). As a result, both margins of the Alpine Tethys were markedly uneven.

If the Alpine Tethys basin evolved into a steady-state spreading oceanic basin is at present debated, as are the size and duration of its subduction. However, the lack of unambiguous oceanic crust, the absence of depleted oceanic mantle showing a genetic link to MOR-basalts, as well as the non-existence of arcs in the Alpine domain question the existence

of a mature MOR and large subduction system (for a discussion see McCarthy et al., 2020).

The nappes including the Grischun-Malenco OCT have been emplaced during two collisional events, referred to as the Eo- and Meso-Alpine events (Froitzheim et al., 1994). The Eo-Alpine event was linked to the closure of the Vardar-Meliata proto-oceanic domain and the inversion of the eastern Adriatic margin during Late Jurassic to Late Cretaceous (Schmid et al., 2008). It is noteworthy that closure of the Meliata-Vardar system occurred contemporaneously to rifting of the present-day North Atlantic (Fig. 4a). The Eo-Alpine orogeny resulted in a top-to-the-west-directed nappe transport responsible for the stacking of the Austroalpine and South Pennine units containing the Grischun-Malenco OCT (Froitzheim et al., 1994).

During the Late Cretaceous (about 84 Ma), the opening of the South Atlantic induced a counterclockwise rotation of the African plate, triggering N-S convergence between Europe, Adria and Africa. This initiated the relocation of the main subduction within the Alpine Tethys, with the subduction of this proto-oceanic basin beneath Adria, which culminated in continental collision between Europe and Adria (Fig. 4b). This reorganization occurred simultaneously with the transition of northern Adria from a footwall position, during the Eo-Alpine shortening, to a hanging-wall position, relative to the main subduction zone, during the Meso-Alpine shortening, as well as with a change in the kinematic transport direction from a top-to-the-west, to a top-to-the-north direction.

During the north-directed Meso-Alpine event, the Eo-Alpine nappe stack, including the Grischun-Malenco OCT, formed a largely undeformed orogenic lid (Fig. 3b). Its hanging-wall position relative to the subducting Alpine Tethys explains the lack of a high-pressure Meso-Alpine metamorphic overprint. The collision of the previously formed Eo-Alpine nappe stack with the European margin (Froitzheim et al., 1994) occurred during the late Eocene (Fig. 4b). During early collision, parts of the distal European margin, including the Tasna OCT, were accreted within the Meso-Alpine nappe stack. During the final Oligocene collision (Fig. 3b), the whole nappe stack was uplifted. To the south, Malenco was back-thrust over central Adria along the Insubric system, the former rift segment boundary acting as a backstop. To the north, Totalp and Tasna were thrust northward over the European necking zone (i.e., domain of rifted margins where major crustal thinning is achieved), which was in turn thrust onto the European proximal margin. Hence, rift inversion of the Grischun-Malenco OCT was polyphase and juxtaposed remnants derived from the former Adriatic OCT (Totalp, Platta, and Malenco) with remnants from the European OCT (Tasna) (for details see Manatschal and Müntener, 2009; Fig. 4b).

The units of the Grischun-Malenco fossil OCT show different P-T histories and Alpine metamorphic overprints, depending on their position during the Eo- and Meso-Alpine convergent events. Whereas the Eo-Alpine stage resulted in a minor metamorphic overprint in the units forming the Grischun-Malenco fossil OCT, the Meso-Alpine event resulted in an increase of the Alpine P-T conditions from north to south. For instance, neither the Eo- nor the Meso-Alpine metamorphic overprints wiped out the pre-Alpine thermal record in Totalp, and hence this unit displays a well-preserved pre-Alpine serpentinized mantle section. In contrast, the Malenco unit experienced a lower amphibolite facies Meso-Alpine metamorphic overprint, with important consequences on the record of its serpentinization history.

Apart from the Alpine inversion, two prominent features

are important for the understanding of the present Grischun-Malenco fossil OCT. The first one is the intrusion of the younger Tertiary Bregaglia pluton (32–28 Ma, Oligocene) into the Meso-Alpine Pennine nappe stack (Fig. 3a; von Blanckenburg et al., 1995). It is associated with a very local contact metamorphic overprint within the Malenco unit (Trommsdorff and Evans, 1977; Hermann et al., 1997). Von Blanckenburg et al. (1995) interpreted this event as resulting from slab breakoff, dating the final stage of convergence in the Central Alps.

The second prominent local structure is the Engadin Fault (Figs. 3a and 3c), a major >100 km SW-NE striking structure which, although little investigated, bears important consequences for the onshore exploration of H₂ potential production, as discussed in the final part of this contribution. The Engadin Fault resulted from post-collisional oblique strike-slip movements during Oligocene-Miocene time, which created a tectonic window in the area of Scuol (Schmid and Froitzheim, 1993; Fig. 3c). The Engadin Fault transects along its entire strike both the Eo- and Meso-Alpine Austroalpine and Pennine nappe stacks containing the ultramafic rocks of the Grischun-Malenco OCT.

An historical review

Numerous pioneering and fundamental studies have been conducted in the Grischun-Malenco region over the last century, trying to decipher the relationships between the Pennine and Austroalpine units (Trumphy, 1975; Dietrich, 1970; Froitzheim et al. 1994, Manatschal and Nievergelt 1997, Mohn et al., 2010). First attempts date back to the beginning of the last century and include the mapping of the area. Among the numerous studies, the most important were those of Cornelius (1932; 1935; 1950), and Decandia and Elter (1972), Dietrich (1970) (Platta/Err), Staub (1946) and, more locally, Trommsdorff et al. (2005) (Bernina/Malenco), Peters (1963) (Totalp) and Cadisch (1928), Florineth and Froitzheim (1994) (Tasna). While these studies enabled to define and understand the local geology, it was Gustav Steinmann who brought to light the genetic link between mantle rocks, dolerites and radiolarian cherts, the so-called Steinmann trinity, a first attempt to describe oceanic sequences (Bernoulli et al., 2003). The first researchers to consciously describe an OCT based on field observations from the Bracco-Levanto area in the Apennines were Decandia and Elter (1972). They proposed a first OCT model, which we refer to as the “Elter model”, suggesting exhumed mantle along extended crust (Fig. 1). After the advent of Plate tectonics in the 70ties to 90ties, and the general rejection of Elter’s OCT model (see section 1; Fig. 1), the primary contacts between continent-derived crustal rocks and mafic- to ultramafic rocks sealed by sediments accurately documented by Cornelius (1935, 1950) and Dietrich (1970) (e.g., Platta nappe) were reinterpreted and described as dismembered oceanic sequences or mélanges (Hsü and Briegel, 1991). Consequently, the interest in mantle rocks from the Grischun-Malenco OCT waned, with the exception of petrological studies investigating the Alpine prograde metamorphic evolution of the ultramafic rocks and overlying sediments in N-S sections from Totalp, through Platta to Malenco (Trommsdorff and Evans, 1974; Ferreiro-Mähmann, 1995). These studies not only enabled to constrain pressure-temperature (P-T) paths linked to burial and exhumation during Alpine orogenesis, but also allowed to calibrate thermometers and define the effect of magmatic intrusions thanks to the Tertiary Bregaglia pluton (Trommsdorff and Evans, 1972; Lafay et al. 2022).

It was only in the late 80ties and early 90ties that two major discoveries revived Elter's OCT model (Fig. 1) and boosted research in the Grischun-Malenco region. The contemporaneous discovery of exhumed mantle along the Iberia margin during ODP Leg 103 (Boillot et al., 1987), and the description of detachment faults in the Basin and Range province in the SW USA (Wernicke, 1981). It was Niko Froitzheim who first described the Jurassic Err detachment system in the lower Austroalpine Err nappe (Froitzheim and Eberli, 1991). This study triggered the remapping of the Bernina-Err-Platta units, (Manatschal and Nievergelt, 1997; Desmurs et al., 2002; Masini et al., 2012; Mohn et al., 2012; Epin et al., 2018), the Tasna unit (Florineth and Froitzheim, 1994), the Totalp ophiolite (Picazo et al., 2013), and Malenco (Müntener and Hermann 1997). At the same time, Trommsdorff proposed a subcontinental origin for the mantle rocks exposed in the Malenco area and Herrmann et al. (1997) suggested that the contact between mantle rocks (Malenco) and continental rocks from the Margna nappe represent a fossil Permian Moho. Using Ar-Ar geochronology on amphibole and biotite, and U-Pb zircon dating, Froitzheim and Rubatto (2002), Schaltegger et al. (2002), and Petri et al. (2017) dated the metamorphic and exhumation stages of the rocks in the Grischun-Malenco area. These, together with stratigraphic constraints (Weissert and Bernoulli, 1985; Ribes et al., 2019a), allowed to establish a robust temporal framework for the formation and inversion of the OCT in the Grischun-Malenco area (Mohn et al., 2012).

The studies from the Grischun-Malenco OCT, combined with the results from academic and industrial seismic reflection and drill hole data from global OCTs (Boillot et al., 1980, 1987; Reston et al., 1995; Sutra et al. 2013; Osmundsen and Peron-Pinvidic, 2018), provided the foundation to establish a global model for magma-poor OCTs. Numerous studies progressively refined the description of OCTs, addressing the nature of rocks, structures and processes. The main highlights from the studies on the Grischun-Malenco fossil OCT included the description of detachment systems in the Bernina-Err-Platta and Tasna units (Manatschal, 2004; Epin et al., 2019; Florineth and Froitzheim, 1994; Ribes et al., 2019b; Betlem et al., 2023), the characterisation of the OCT syn-rift tectono-sedimentary evolution (Masini et al., 2013; Ribes et al., 2019c), the description of fluid transfers associated with mantle exhumation (Pinto et al., 2015; Incerpi et al., 2020; Coltat et al., 2019; Hochscheid et al., 2022), and the description of various types of mantle rocks (Müntener et al., 2010; Picazo et al., 2016). This multidisciplinary integration enabled a holistic description of the Grischun-Malenco fossil OCT, which makes it, at present, the best calibrated OCTs worldwide. Last, but not least, the well-preserved OCT structures exposed in Tasna, Err-Platta and Totalp have been visited by many researchers working on global present-day margins, which made the Grischun-Malenco region a very popular laboratory to study OCTs (see field guide; Manatschal and Chenin, 2023).

The architecture of the Grischun-Malenco fossil OCT

In this section, we synthesize the main observations made on the Grischun-Malenco fossil OCT, which includes the Tasna, Totalp, Platta and Malenco mantle bodies. We summarize the main observations made at the four sites and propose a conceptual section across this former OCT (Fig. 5).

The Tasna OCT, exposed in the Engadin window north of Scuol (Figs. 3a and 6a) preserves, over about 6 km, a con-

tinuously exposed transition from a wedge of continental crust to an exhumed mantle domain (Fig. 6b) (Florineth and Froitzheim, 1994; Manatschal et al., 2006). The mantle is of subcontinental origin (Mantle Type 1a in Picazo et al., 2016). The top of the exhumed mantle as well as the top and base of the crustal wedge are made by Jurassic extensional detachment faults (Figs. 6c, 6d, and 6f). The top of the exhumed mantle and the top of the continental wedge are covered by upper Jurassic and Cretaceous deep water post-rift and pre-orogenic sediments (Figs. 6c, 6e and 6g; Ribes et al., 2019b). In the south, mantle rocks are separated from the continental crust by an extensional detachment corresponding to a petrological Moho (Fig. 6f). Further north, the mantle is directly exposed at the seafloor and sealed by shales containing re-worked clasts of continental crust and mantle (Figs. 6c and 6d). The mantle is foliated and completely serpentized and its top is carbonatized. Carbonation occurred under low temperature and through reaction with seawater (Coltat et al., 2022). Remnants of pyroxenites contain phlogopites. $^{40}\text{Ar}/^{39}\text{Ar}$ dating of these phlogopites extracted from a spinel websterite yielded ages of 169.1–170.5 $\pm$ 0.4 Ma (for analytical data see Manatschal et al., 2006). These Jurassic ages are interpreted as cooling ages dating the exhumation of the mantle towards the seafloor (Manatschal et al., 2006). The sedimentary sequence overlying the exhumed mantle (Figs. 6e, 6g and 6h) contains debris flows with clasts derived from the Briançonnais/European domain (Ribes et al., 2019b). It also shows a transition into Eocene syn-convergent turbidites (e.g., Flysch type sediments). Both indicate a European position for the Tasna OCT (Figs. 4b and 4c).

The Totalp ophiolite is exposed north of Davos (Fig. 3a). It is nested within the north-directed Meso-Alpine Pennine nappe stack, sandwiched between European/Briançonnais- and Austroalpine-derived units (Fig. 3a). The Totalp ophiolite is exposed over ca. 6 km in E-W direction and is formed by two thrust sheets (Fig. 7a) mainly made of mantle rocks of subcontinental origin (Mantle Type 1a in Picazo et al., 2016). Intrusive magmatic rocks are limited to one outcrop containing feldspar gabbros within the lower unit. Extrusive magmatic rocks are not observed. The mantle in Totalp is capped by a very well exposed seafloor sequence (see section in Fig. 7e; Weissert and Bernoulli, 1985). The sequence is floored by exhumed mantle, topped by a tectonized mantle made of foliated serpentinite, cataclasites and gouges (Fig. 7d). The gouges are truncated by veins filled with pelagic sediments and sealed by upper Middle to Upper Jurassic radiolarian cherts and calpionella limestones, the latter deposited below the calcite compensation depth (Figs. 7b, 7c and 7e). These observations indicate that the mantle in Totalp was exhumed at the seafloor and that the conditions of exhumation were at deep water and deposited below the calcite compensation depth. $^{40}\text{Ar}/^{39}\text{Ar}$ ages on phlogopites give an age of 170.5 $\pm$ 0.4 Ma (Peters and Stettler, 1987), similar to the age obtained from the Tasna OCT (Manatschal et al., 2006), showing that exhumation occurred largely simultaneously at the two sites. Remnants of continent-derived clasts in the sediments overlying the exhumed mantle at Totalp suggest a proximity to the continental margin. Totalp has been interpreted as a part of the northern Adriatic OCT and to have represented the northern continuation of the Malenco-Platta OCT (Picazo et al., 2013). The Alpine metamorphic overprint in Totalp is below prehnite-pumpellyite facies.

The Malenco unit north of Sondrio (Fig. 3a) is a large mantle body of subcontinental origin (Mantle Type 1a in Picazo et al., 2016) that, in contrast to the Totalp ophiolite,

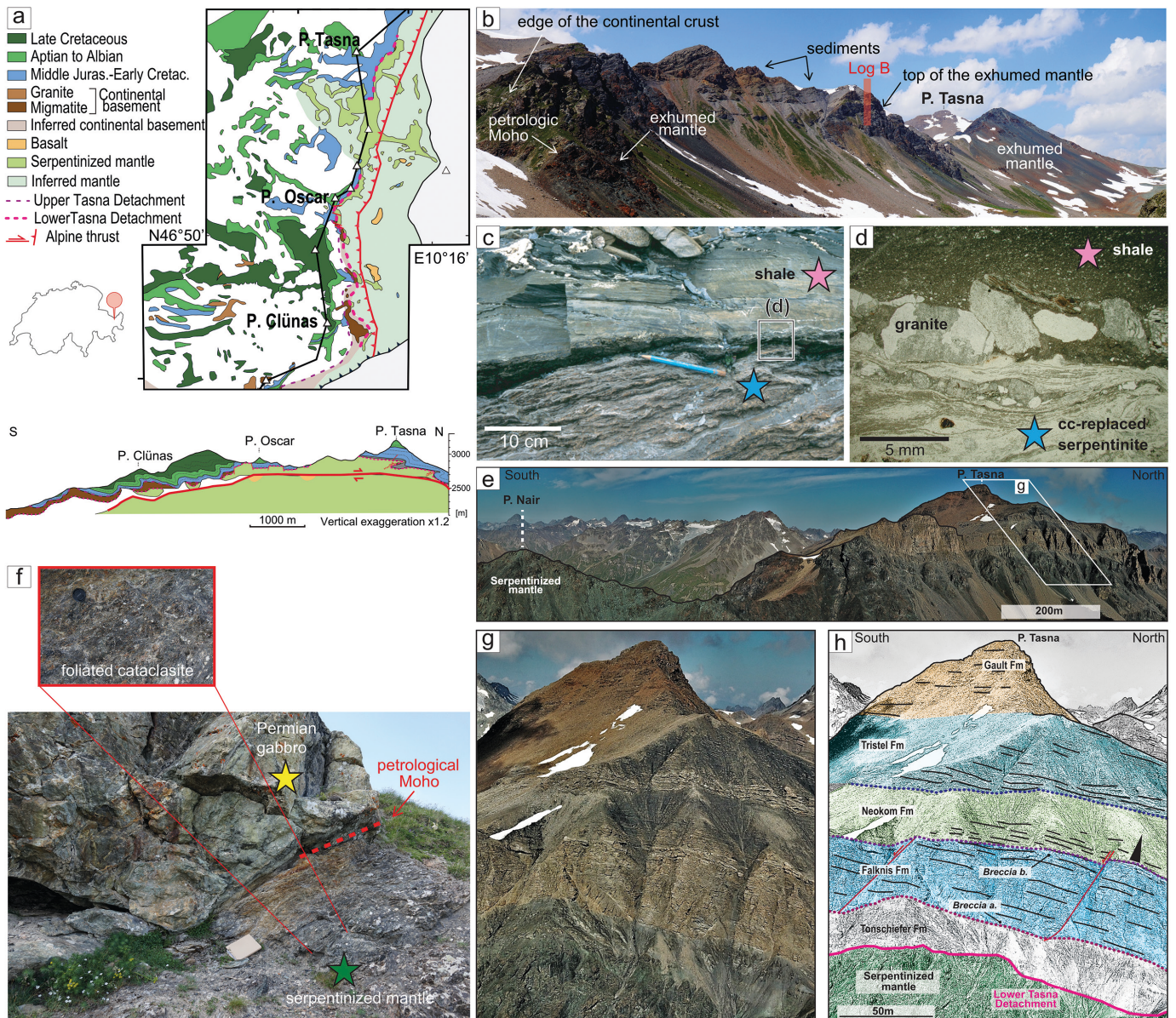


Fig. 6 - The Tasna OCT: a) Geological map of the Tasna area and a S-N directed transect (modified after Ribes et al., 2019b). b) View of the Tasna OCT looking northwards, showing the exposed transition from continental crust to exhumed mantle sealed by sediments (Log B corresponds to section shown in Fig. 5). c) The «Florineth outcrop» showing the contact between exhumed foliated mantle rocks (green star) stratigraphically overlain by deep water post-rift and pre-orogenic shales (yellow star). For outcrop location see Log B in (b). d) Thin section of the contact between exhumed mantle and sediments under plane polarized light (for location of the imaged contact see square in (c)). The mantle consists of chlorite and calcite that replaced a foliated serpentine. Remnants of chrome spinel (black) and pyroxene grains are preserved in the foliated mantle. The overlying sediments seal the contact, are undeformed and consist of shales containing reworked clasts of continental crust (granite). e) Panoramic view of the northern Tasna outcrop looking towards the west and showing the contact between the serpentinized mantle overlaid by the sedimentary sequence. f) Photograph showing the contact between the deformed mantle (yellow star) and the hydrated and deformed lower crust representing the petrological Moho; zoom shows foliated cataclasites from the contact. g) Zoom on the contact between the mantle and the overlying sediments with names of sediment formations shown in (h). Pictures taken from G. Manatschal and C. Ribes.

underwent lower amphibolite facies metamorphism during the Meso-Alpine phase of convergence (Trommsdorff and Evans, 1972). The mantle body is made of at least two Eo-Alpine thrust sheets that have, however, not yet been subdivided in mapping (Fig. 8a) (Trommsdorff, 2005). While one of them (Forno) contains basalts and radiolarian cherts (Peretti et al., 1992), indicating a seafloor exposure, the other (Malenco) shows a primary contact to the lower crustal rocks of the Margna unit (Fig. 8c; Hermann et al., 1997). Since the contact is welded by a Permian gabbro, it has been interpreted as a fossil, pre-rift Moho (for details see Hermann et al., 1997). P-T conditions determined from this fossil Moho

(Fig. 8b; Müntener et al., 2000; Villa et al., 2000) allowed to determine that the Moho was at 9 to 10 kbar during the Permian, i.e., before onset of rifting. This assumes an about 30 km thick crust with an equilibrated thermal gradient at onset of rifting. During Jurassic rifting, the thermal gradient significantly increased, as indicated by combined geochronological and petrological studies (see also Petri et al., 2023).

The Platta ophiolite in the Val Surres (Fig. 3c) is exposed over more than 200 km² and consists of two Eo-Alpine thrust sheets, referred to as the Upper Platta Unit and the Lower Platta Unit respectively (Fig. 9a). The Meso-Alpine metamorphic overprint grades from lower greenschist to prehnite-

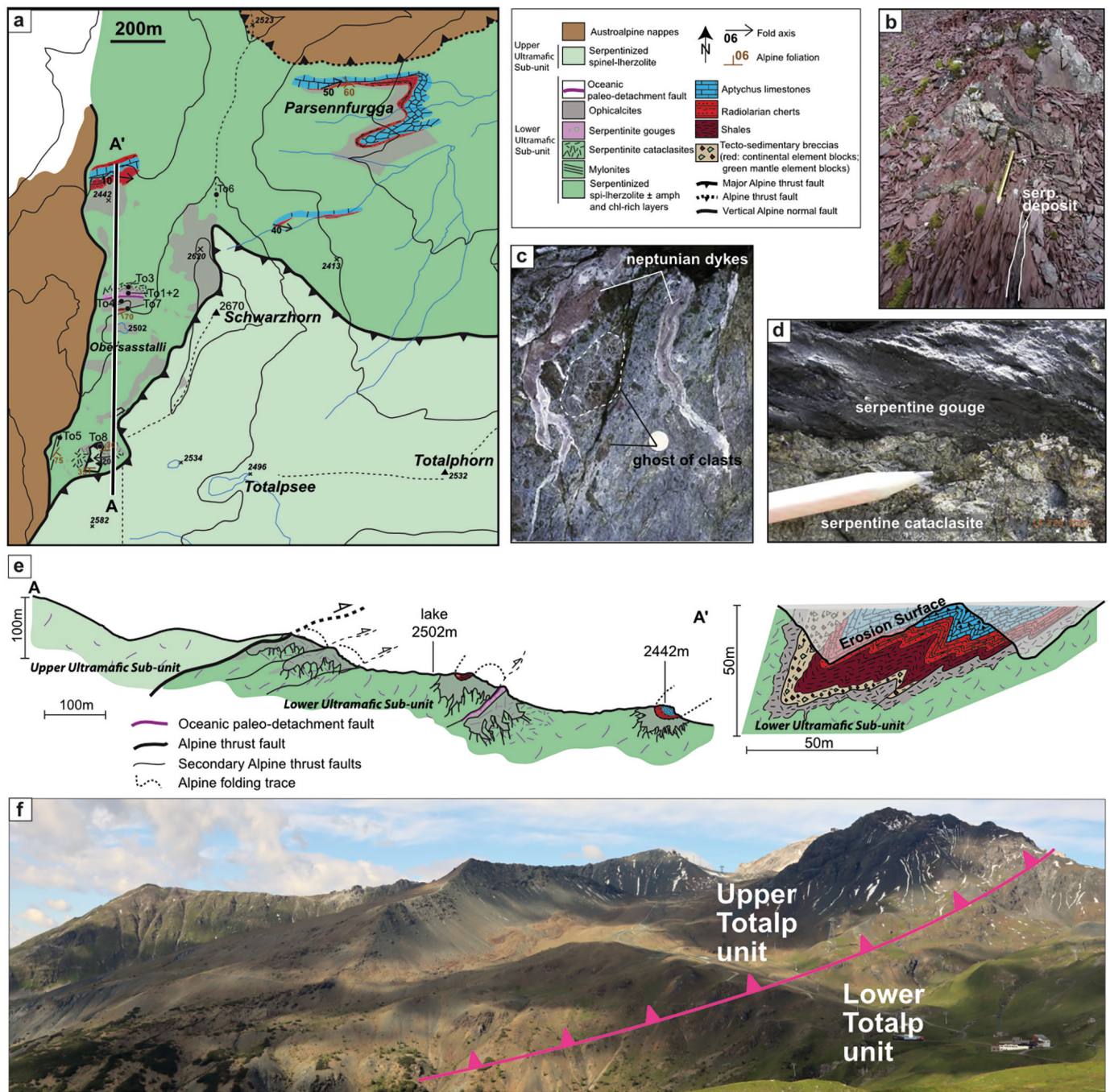


Fig. 7 - The Totalp ophiolite: a) Geological map of the Totalp area (modified after Picazo et al., 2013). b) Red shales and radiolarian cherts with reworked serpentinites occurring over the mantle. c) Neptunian dike crosscutting serpentinite cataclasites and filled with pelagic sediments of upper Middle to Upper Jurassic age. d) Serpentinite gouge in contact with serpentine cataclasites. e) N-S directed section across the Totalp ophiolite (for location see A-A' trace in (a)), showing two mantle units separated by a Meso-Alpine thrust. Note that the lower mantle is topped by ophicalcite and locally sealed by upper Middle to Upper Jurassic deep water radiolarian cherts and Aptychus limestones. To the right, a zoom into a section showing the tectonized top of the mantle, with tectono-sedimentary, carbonitized breccias (sedimentary ophicalcites) overlain by deep water sediments. f) Panoramic view of the Totalp ophiolite looking towards the SW. The Totalp ophiolite is subdivided in an Upper and Lower unit limited by a Meso-Alpine thrust (see also map in (a)).

pumpellyite in the north (Falotta), to upper greenschist facies south of Bivio (Evans, 1977; Ferreiro Mählmann, 1995). The Meso-Alpine tectonic overprint is weak and related to open folding. Since these folds affect the thrust contact between the two units, Epin et al. (2019) proposed a restoration based on a kinematic inversion of the Eo-Alpine nappe stack only, i.e., an E-W directed movement, placing the Upper Platta Unit in a more proximal (i.e., continent-ward) position compared to the Lower Platta unit. This restoration, shown in Figs. 9b and 9c,

enabled to restore a transition from an exhumed subcontinental mantle formed by a spinel lherzolite (mantle type 1a of Picazo et al., 2016) with little magma (Upper Platta Unit) to a magma-impregnated mantle (mantle type 2 of Picazo et al., 2016), showing an increasing volume of intrusive and extrusive magmatic additions oceanward (Lower Platta Unit; see Fig. 5). The limit between the two units is made of a shear zone, reactivated during Alpine convergence, that contains peridotite mylonites (Fig. 9c). These mylonites formed at 700 to 900°C, i.e., at

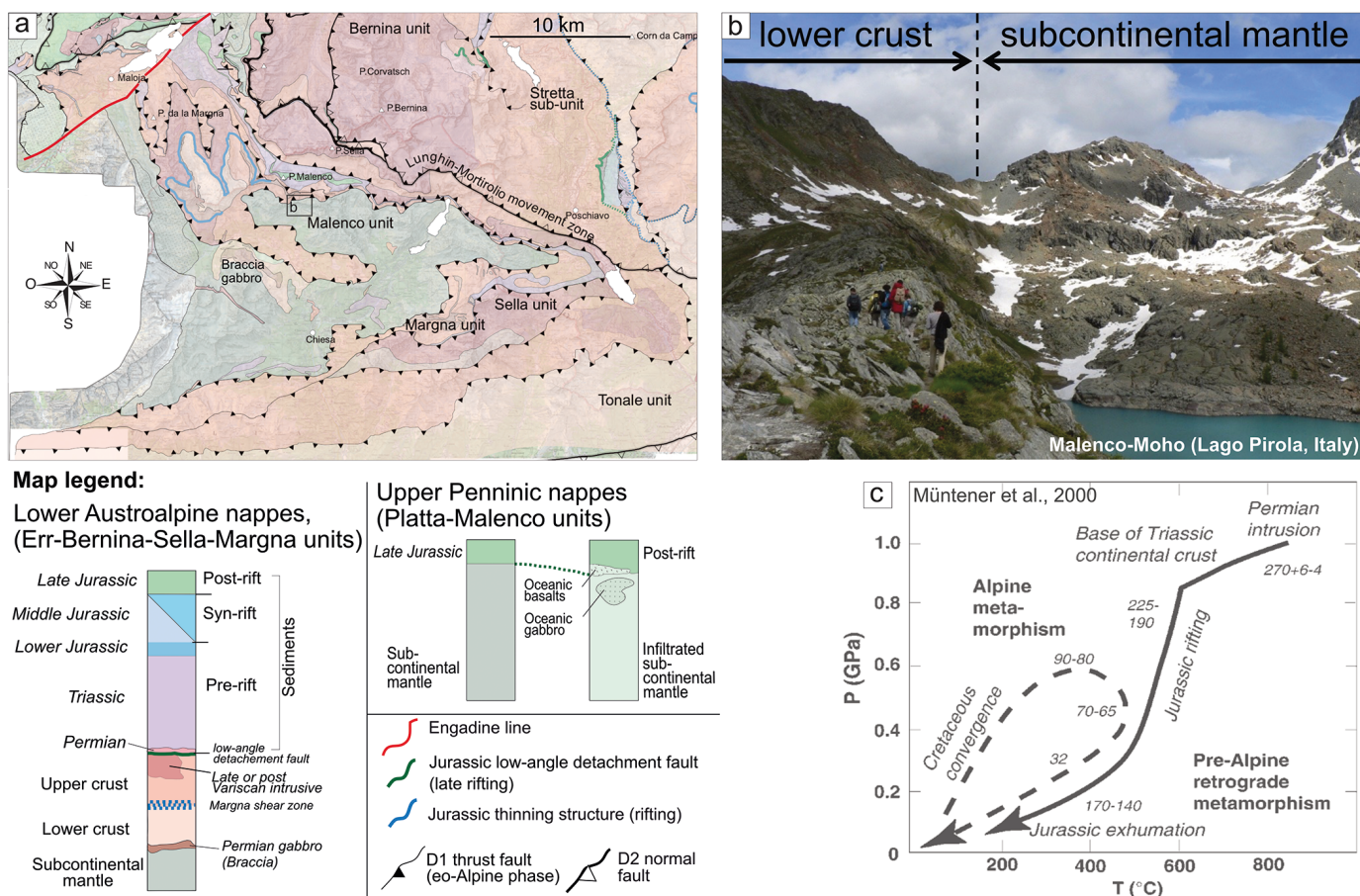


Fig. 8 - The Malenco unit. a) Geological map of the Malenco and surrounding units (from Mohn et al., 2012). b) Primary contact between the Malenco mantle and lower crustal rocks of the Margna unit showing a preserved Permian Moho. c) P-T-t diagram showing the evolution of the Malenco mantle-crust complex (Müntener et al., 2000). Two main paths have been reconstructed, one for the pre-Alpine and the other for the Alpine evolution.

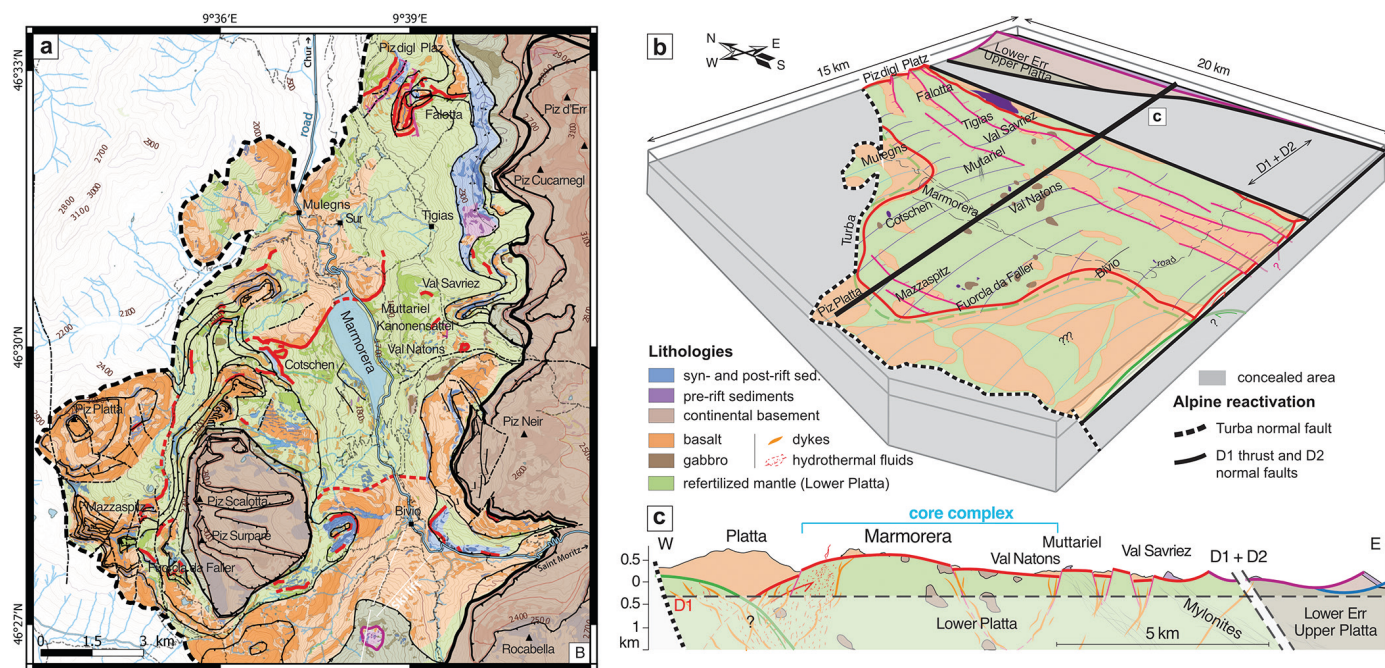


Fig. 9 - The Platta ophiolite (Fig.s taken from Epin et al., 2019). a) Geological map of the Platta nappe. b) 3D restoration of the Lower and Upper Platta Units based on a kinematic inversion (E-W directed) of the Eo-Alpine nappe stack (for details see text). c) E-W directed cross section across the reconstructed Lower and Upper Platta units (for location see trace in (b)). The reconstruction shows a transition from exhumed mantle overlain by extensional allochthons to an exhumed mantle overlain by extrusive magmatic rocks.

temperatures far higher than those reached during Alpine convergence. Although they have not been dated, their formation may have been linked to mantle exhumation (for discussion see Epin et al., 2019). These authors also mapped in detail an extensional detachment system that formed an oceanic core complex in the Lower Platta Unit (Figs. 9b and 9c).

The best outcrops preserving the detachment system are

exposed at Falotta (Figs. 10a, 10c and 10d) in the northern Platta nappe (Fig. 9a). Several sections along the Falotta ridge (Fig. 10b) show a top basement made of foliated cataclasites and gouges that are carbonatized at their top (see Figs. 10c to 10e). Along the tectonized exhumed mantle, tectono-sedimentary breccias containing reworked mantle (Figs. 10b and 10e), pelagic sediments (Fig. 10b), basalts (Figs. 10b

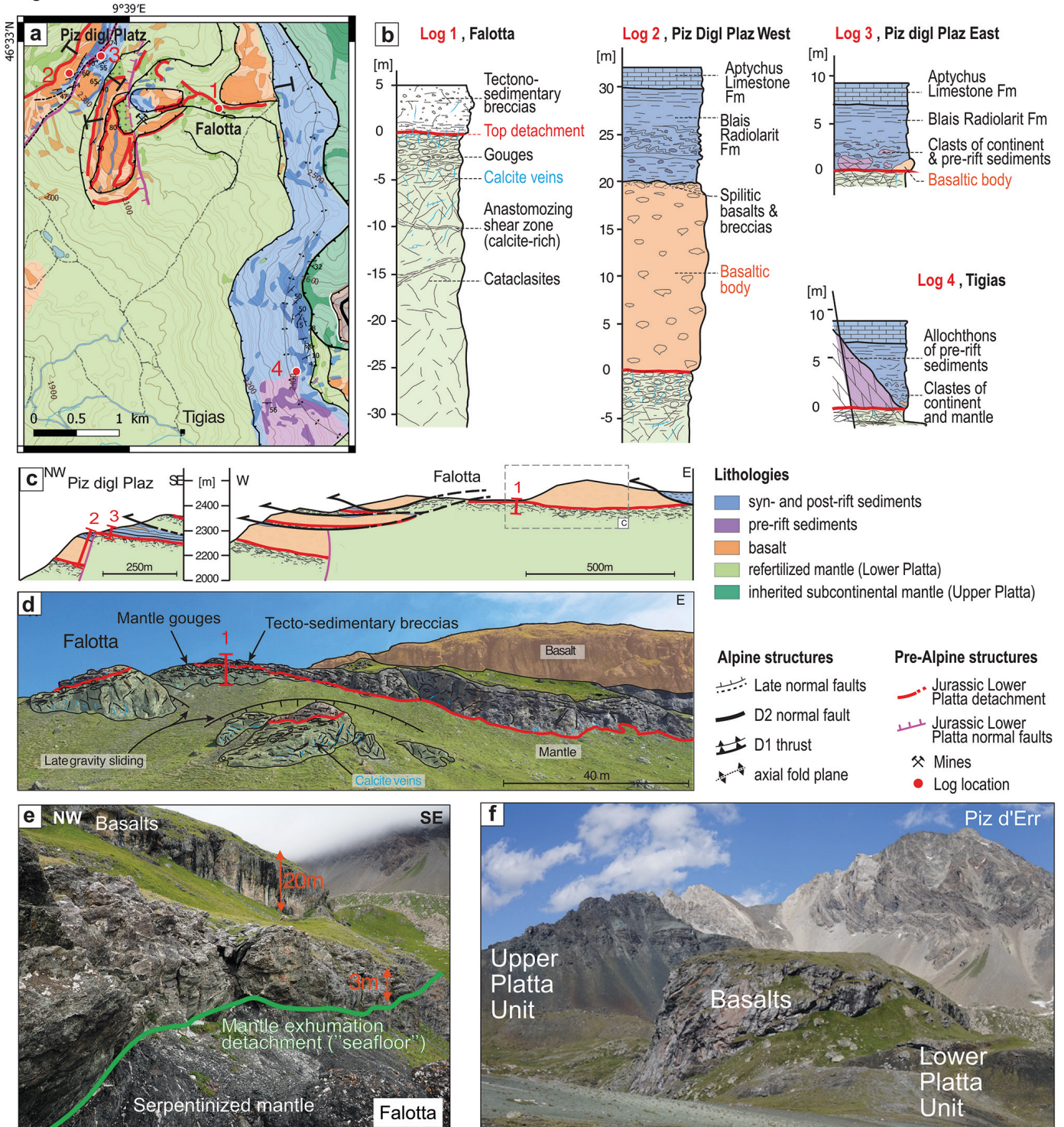


Fig. 10 - Focus on the area of Falotta within the northern Platta nappe (for location see Fig. 9a). a) Geological map of the Falotta ridge in the northern Platta nappe. b) Logs 1,2,3 and 4 along the Falotta ridge (for location see (a)), showing serpentinite cataclasites and gouges, overlain by either basaltic body, deep-water sediments or extensional allochthons consisting of pre-rift sediments. c) NW-SE section along the Falotta ridge showing location of Logs 2 and 3. d) View of the Falotta ridge. e) View of the top of the serpentinitized mantle corresponding to a detachment fault overlain by tectono-sedimentary breccias and basalts. f) Panoramic view showing the contrast between the exhumed serpentinitized mantle and the deformed basalts. In the back, the Upper Platta Unit and the Piz d'Err, the latter belonging to the continental/hyperextended rifted margin.

and 10f) or continent-derived blocks (Fig. 10b) can be found. The juxtaposition of so many different lithologies can be best explained by detachment fault-related exhumation of the mantle to the seafloor. Coltat et al. (2019, 2020) showed that the basalts overlying the mantle are foliated at their base and display extensional shear bands. These are in turn crosscut by carbonate-bearing veins showing a marine oxygen isotopic signature dated as Jurassic. Thus, the detachment faults in the Lower Platta Unit were syn-magmatic. The fact that continent-derived blocks overlie the mantle, similar to the extensional allochthon drilled along the Iberia margin, is incompatible with mantle exhumation at a mid-ocean ridge and supports mantle exhumation from underneath the continent.

The observations presented above show that the fossil Grischun-Malenco OCT preserves kilometre scale mantle outcrops, all of which preserve a basement comprising (from deepest to shallowest; Fig. 5) one or more of the following characteristics: (i) massive serpentinitized mantle with layers of pyroxenite and mylonite truncated by rare dolerite dikes (Desmurs et al., 2002), (ii) damage zones of fractured serpentinite with transverse veins of tremolite and calcite (Picazo et al., 2013; Epin et al., 2019; Coltat et al., 2020), (iii) gouge zones linked to extensional detachments, consisting of a serpentinitized peridotite matrix with fresh mantle and ophicalcite clasts, truncated by neptunian dykes and locally also flaser gabbros (Peters and Mathews, 1963; Schaltegger et al., 2002), (iv) sealing by Upper Jurassic-Lower Cretaceous pelagic sediments (radiolarites, turbidites) containing reworked clasts of serpentinite, ophicalcite, pre-rift continental sediments and continental crust (Dietrich, 1970; Ribes et al., 2019), disseminated allochthonous continental crustal blocks (Manatschal and Nievergelt, 1997; Picazo et al., 2013), and further oceanward, also syn-tectonic basalts (Coltat et al., 2020).

THE FATE OF THE SUBCONTINENTAL MANTLE IN THE GRISCHUN-MALENCO OCT

The fate of the subcontinental mantle is tightly linked to the Wilson Cycle, i.e., the geological life cycle of tectonic plates in which oceans disappear, giving birth to collisional orogens. This life cycle is characterized by a succession of tectonic regimes, constraining the physico-chemical conditions (T–P, water-rock, fO_2 , fluid and rock composition, permeability and porosity, fracturing and deformation, reaction kinetics...) of the involved mantle rocks, imprinting structural and compositional characteristics. These parameters, together with water supply, control serpentinitization processes and the associated potential generation of H_2 . The mantle rocks within the Grischun-Malenco area record a complete Wilson cycle, allowing to gain insights into the mantle history and the role of mantle-melt and mantle-fluid interactions. In the next two sections, we describe the fate of the mantle first by taking a tectonic and then a petrological-geochemical perspective. In this chapter, we aim to consolidate the key elements needed to investigate the Grischun-Malenco serpentinitization-sourced H_2 system, whose existence is confirmed by the detection of recent H_2 anomalies in the soil gas along the Engadin valley (Gasser et al., 2026; see discussion in the final part of this contribution).

The mantle in the Grischun-Malenco area: a tectonic perspective

The mantle rocks exposed in the Grischun-Malenco area have a long memory. The oldest event relevant to the present

study and well recorded in the mantle, crustal and sedimentary rocks is the collapse of the Variscan Orogen (Petri et al., 2017; Escudier et al., 2018). To what extent the Mesozoic rifting was the continuation of the post-orogenic collapse or the result of subduction in the Neo-Tethyan domain further to the east is debated.

Due to the magma-poor nature of the Alpine Tethys rifting, magmatic activity was limited to the ultra-distal domains of the OCT (see Fig. 5). If the Alpine Tethys reached the stage of steady-state seafloor spreading is still debated, as are the size of the oceanic domain and size of the subducted slab. However, the lack of unambiguous Penrose oceanic crust/ophiolite, the absence of a depleted oceanic mantle showing a genetic link to MOR-basalts, as well as the lack of evidence for a mature arc in the Alpine domain question the existence of a wide oceanic domain, a mature MOR, and a large subduction system in the Alpine Tethys domain (McCarthy et al., 2020). It has been suggested that the Alpine Tethys was part of an incomplete Wilson Cycle because of the lack of both oceanic crust remnants and a subduction-related magmatic arc (Chenin et al., 2018; Masini et al., 2024), and based on paleogeographic restorations (Frasca et al., 2024). Although this interpretation is still debated, there is a general agreement that most of the ophiolites exposed along the Alpine Tethys suture in Western Europe originate from OCTs rather than from MORs (Picazo et al., 2016).

The tectonic evolution of the Grischun-Malenco OCT and related mantle rocks from a post-orogenic collapse to a rift inversion orogen is well documented by geochronological-petrological and stratigraphic data and supported by field observations. However, how these units/mantle rocks were sampled within the Alpine nappe stack remains unclear. It appears that, except for the Lower Platta Unit, all sites (Tasna, Totalp and Upper Platta) derive from very proximal positions in the OCT (Fig. 5). Moreover, all sites except Malenco, preserve only the uppermost 400 to 500 m of the mantle sequence, suggesting that the thrust localized within already serpentinitized mantle. Hence, mantle rocks may have been essentially serpentinitized during the Jurassic rifting and the Tasna, Platta and Totalp units may have been emplaced in the Alpine nappe stack as “allochthonous mantle bodies” (see olive green units in Fig. 11).

As shown in Fig. 11, we propose that the proximity of the Malenco OCT to a segment boundary (the paleo-Insubric line) may have impacted its Alpine evolution. The lack of a high-pressure metamorphic overprint suggests that, during the Meso-Alpine subduction, the latter made a short cut between the Valais and the Piemonte basin (Figs. 4b; 11), keeping the Malenco as well as the Ivrea mantle bodies in the hanging wall of the Alpine subduction. According to this interpretation, the Malenco unit would have formed as a mantle wedge, whose top was subsequently thrust southward onto the Adrian micro-continent (Fig. 11). The implication is that a much larger and thicker (compared to Platta/Tasna/Totalp) mantle body could floor the Eo-Alpine Austroalpine units in Grischun-Malenco region (see red hatched domain in the map in the upper right corner in Fig. 11). This interpretation is similar to that made along the Pyrenees (Lescoutre and Manatschal, 2020), where inherited margin segmentation was shown to have controlled the fate of mantle rocks during convergence. In this framework, the Malenco unit may represent the emerged part of a larger mantle body with a largely non-serpentinitized mantle wedge (Fig. 11). This hypothesis needs, however, further testing.

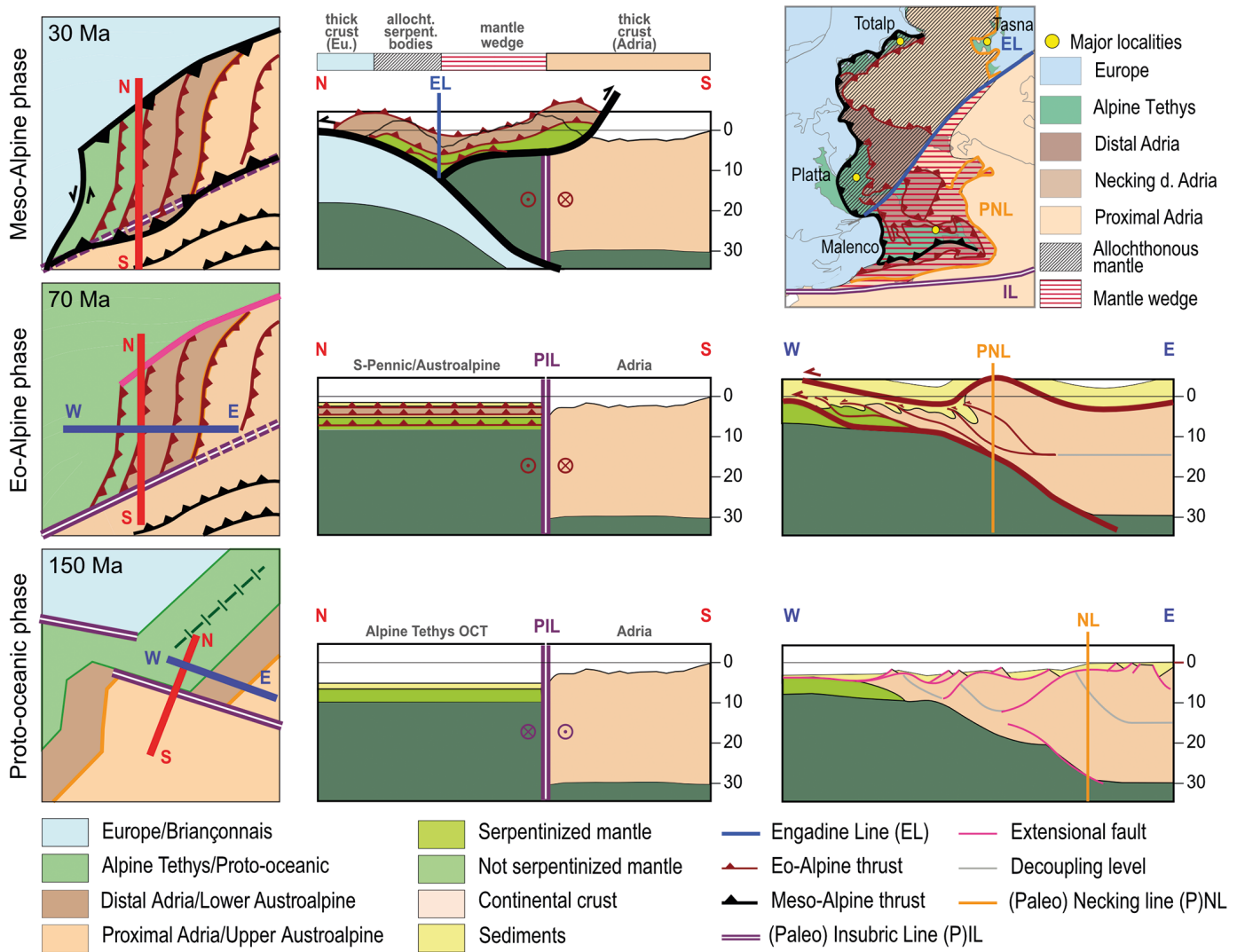


Fig. 11 - Conceptual tectonic model illustrating the evolution of the mantle from its emplacement at the seafloor during Jurassic rifting through Eo- and Meso-Alpine reactivation and its final emplacement in the rift-inverted orogen. The maps on the left side show the simplified paleogeographic situations for each stage, respectively the proto-oceanic (150 Ma), the Eo-Alpine (70 Ma) and the Meso-Alpine (30 Ma) stages. In the middle a N-S cross section for each convergence phase. On the right-side W-E cross sections for the proto-oceanic and the Eo-Alpine stages are shown. The map in the upper right corner shows a tectonic map of the Grischun-Malenco area. The black, cross-hatched area shows domains where smaller allochthonous bodies are interpreted to occur in the nappe stack, while the red, horizontal-hatched area corresponds to the area that is assumed to be floored by the larger mantle wedge.

The mantle in the Grischun-Malenco area: a petro-geochemical perspective

Extensive petrological and geochemical studies of the best-exposed fossil OCTs in Western Europe show significant differences between mantle rocks from MORs and OCTs. Whereas MOR-related mantle rocks tend to be relatively homogeneously depleted, the nature (enriched/depleted), exhumation pathways (pressure/temperature/time path), melting, melt interactions and hydration/alteration histories of mantle rocks from OCTs are more complex. Hence, whereas mantle inheritance is negligible at MORs, it may have a major influence on strain localization, magmatic evolution and serpentinization during formation of OCTs (Müntener and Manatschal, 2006; Zwaan et al., 2025; Ballay et al., 2025). Petrological and geochemical studies of mantle rocks derived from OCTs, combined with field observations from the Grischun-Malenco fossil OCT allowed to: 1) determine the evolution of mantle rocks during rifting, 2) reconstruct their

pre-Alpine position in the OCT, and 3) demonstrate that, depending on their proximal vs distal position within the OCT, the type of mantle, exhumation history and link to magmatic and aqueous fluids are different. And yet, getting insights into the pre-inversion melt- and hydration history of mantle rocks is a prerequisite to predict their potential as a source for H_2 .

Exhumation history and mantle-melt reactions documented in OCT mantle rocks

The contact of the Malenco mantle rocks with lower crustal rocks, welded by the Permian Braccia gabbro (Müntener and Hermann, 1996) (Fig. 8), constrain their proximal position in the OCT, as well as their position at the top of the lithospheric mantle, prior to rifting (Figs. 5 and 12). The widespread Permian magmatism (270–280 Ma) was presumably triggered by slab breakoff during the collapse of the Variscan orogen, which caused asthenosphere upwelling and partial melting. The resulting gabbros intruded the uppermost mantle and/or lowermost crust, and formed the so-called “Malenco

Moho" (Hansmann et al., 2001; Schaltegger and Brack, 2007) (Fig. 12). Simultaneously, gabbros and granitoids intruded the middle to upper crust and extrusive rhyolite were emplaced at the surface (Petri et al., 2017; Mohn et al., 2012). During asthenospheric upwelling, the lower part of the cold and heterogeneous SCLM partially melted, leaving a depleted mantle that subsequently underwent conductive cooling (e.g., McCarthy and Müntener, 2015; mantle type 1b in Picazo et al., 2016) (Fig. 12). Sm-Nd model ages show that this depletion occurred during the Permian (294 ± 16 Ma; Müntener et al., 2004). Similar gabbro bodies linked to the same Permian event can also be found in the Ivrea-Verbano Mafic Complex and in the Sesia-Lanzo area (Tribuzio et al., 1999).

In the units derived from the proximal OCT (e.g., Malen-

co, Totalp, Upper Platta, and Tasna; see Figs. 5 and Fig. 12), only the shallower SCLM, mainly composed of spinel-lherzolite interlayered with garnet-pyroxenites and rare harzburgite (mantle type 1a in Picazo et al., 2016), is preserved. Conversely, remnants of the pre-rift lower SCLM (Mantle type 1b in Picazo et al., 2016) can be found in the distal domain of the OCT (e.g., Lower Platta Unit; Fig. 5). During Jurassic exhumation, this depleted lower SCLM reacted with basaltic melt above an upwelling asthenosphere (Fig. 12). This formed plagioclase-lherzolites and subordinate depleted harzburgites equilibrated at high temperature (1150°C) within the plagioclase stability field (mantle type 2 in Picazo et al., 2016), with isotopic signatures identical to those of Jurassic MORB (McCarthy and Müntener, 2015). The plagioclase-

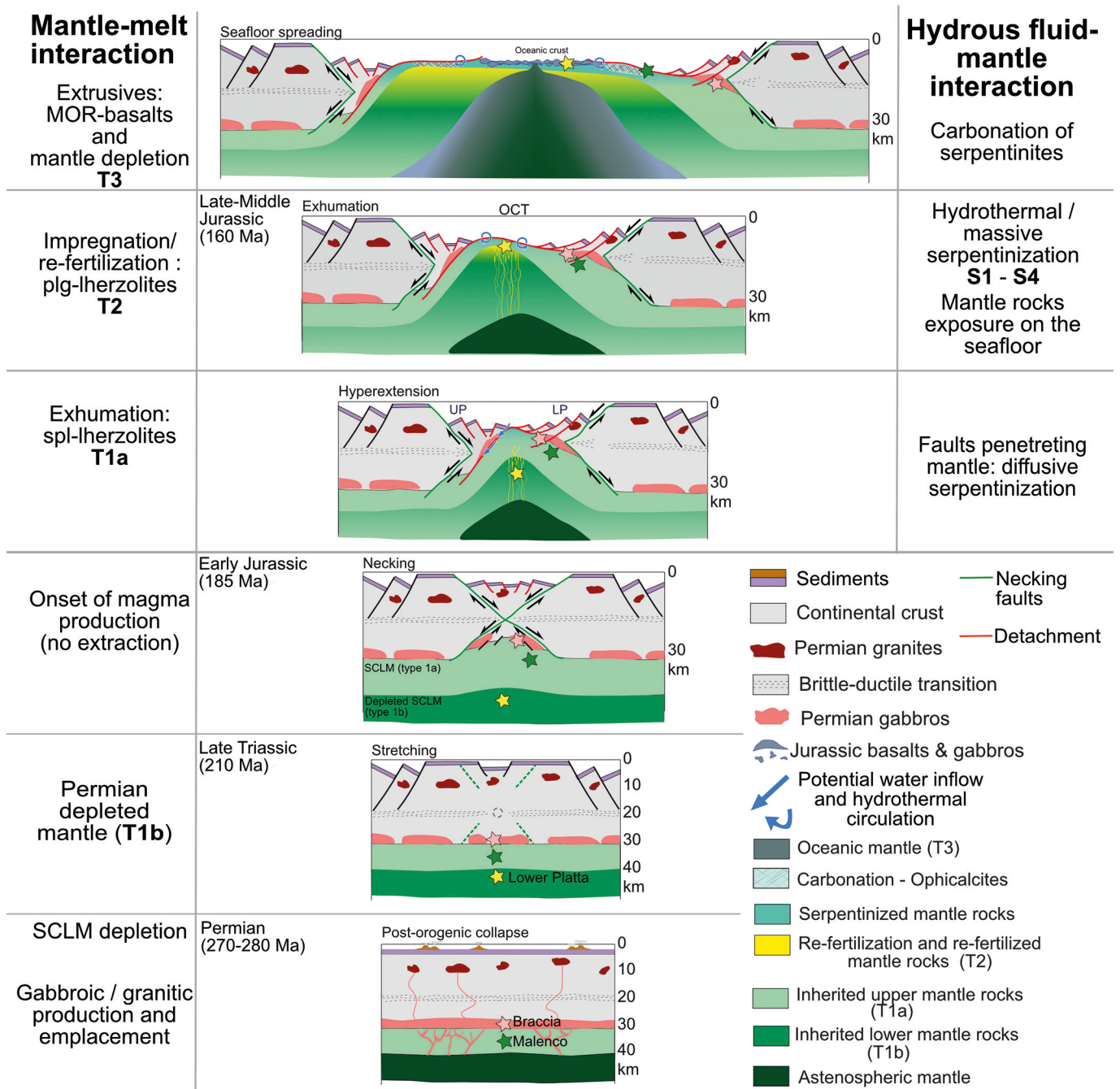


Fig. 12 - The evolution of mantle rocks and related mantle-melt and mantle-fluid interactions and processes occurring from post-orogenic collapse, to rifting and (proto-)oceanization.

herzolites document melt-rock reactions, so-called refertilization. Gabbros from the Lower Platta Unit have been dated at 161 ± 1 Ma with U/Pb on zircon (Schaltegger et al., 2002). Thermo-barometric data based on two-pyroxenes and single-orthopyroxene assemblages from the Upper and Lower Platta Units reveal an increase in equilibration temperatures from approximately 850°C at 0.8–1.2 GPa near the continent to >1000°C further oceanward (Desmurs et al., 2001; Müntener et al., 2010). Furthermore, extrusive material such as massive basalt flow, pillow basalts, basalt breccias and hyaloclastites exposed in the Lower Platta Unit show an increasing volume oceanward and are systematically aligned along late normal faults (Fig. 5; Amann et al., 2020).

The conceptual model of magma-poor rifting developed by Picazo et al. (2016) based on mantle rocks from Western Europe allows to link the nature of mantle rocks with their position in an OCT (Figs. 5 and 12). Ballay et al. (2025) showed that, despite a different pre-rift evolution, mantle rocks dredged along the Diamantina zone of the magma-poor SW Australian margin are consistent with the predictions of this model. Thus, the model of Picazo et al. (2016) may be applicable, at first order, to OCTs in general. Determining to what extent it can predict the distribution of mantle types in rift-inverted orogens needs further investigation.

Serpentinization during the formation and reactivation of an OCT

The mantle rocks in the Grischun-Malenco area are heavily serpentinized and locally also carbonatized, similar to the drilled and seismically imaged mantle rocks from the present-day Iberia OCT (Fig. 2b). Studies from slow-spreading MORs and the Iberia OCT show that serpentinization occurs during mantle exhumation and can reach as deep as 6 km. In the Grischun-Malenco fossil OCT, most studies focused on the carbonation process of serpentinites (ophicalcites), while the serpentinization process itself has been little investigated. At present, four hydration/carbonation events have been defined from the mantle rocks of the Grischun-Malenco OCT (Picazo et al., 2013; Coltat et al., 2019; Hochscheid et al., 2024): the first event, pre-dating serpentinization, consists of hydrothermal replacement of pyroxenes by amphiboles, at temperatures 400°C–700°C (Picazo et al., 2013). The second event is the Jurassic serpentinization of exhumed mantle. It represents the main hydration event and will be discussed in more detail below. The third event is interpreted as static carbonation of serpentinites under hot seawater (~100 °C) conditions, which would occur during final syn-magmatic mantle exhumation. This event would be responsible for the ophicalcite layer capping the exhumed mantle across the OCT (Früh-Green et al., 1990; Coltat et al. 2022). These three events are pre-Alpine and linked to the formation of the OCT, as indicated by: 1) geochemical data (oxygen stable isotope show a marine-derived fluid signature); and 2) geological observations (serpentinized clasts reworked in Jurassic sediments, and foliated serpentinized mantle rocks truncated by neptunian dikes filled with Jurassic sediments). The fourth and final event consists in serpentinization during rift inversion. This phase has been little investigated yet, despite its importance for the understanding H_2 systems in rift inversion orogens. It will be discussed in the final part of this contribution.

Hochscheid et al. (2024) investigated in detail the serpentinization process during the Jurassic mantle exhumation (i.e., the second event introduced in the previous paragraph). They identified a sequential succession of five generations of

serpentine veins, based on textures and variations of serpentine species in samples from the Grischun-Malenco OCT.

The first serpentine generation is linked to the formation of pseudomorphic serpentine mesh and bastite textures (S1, in Hochscheid et al., 2024). This first generation of serpentine is enriched by up to several orders in magnitude in FME (CS, B, Li, $\pm$ Rb), evidencing important oceanic hydrothermal activity. In addition, the observation that spinel is almost free of chlorite aureoles suggest that this first serpentinization occurred below 400°C and likely in the range of about 300°C.

The second generation of serpentinization results in polyhedral veins (S2) that can be found in clinopyroxene relics and bastite cleavages. The textural vicinity of polyhedral serpentine-andradite assemblage with clinopyroxene indicates that the latter is the source of Al. Most trace element concentrations are significantly depleted (except for boron) in these polyhedral veins, showing 1 to 2 orders of magnitude lower concentrations relative to bastite (S1) and primary clinopyroxene precursors. This suggests a high fluid-rock ratio, temperature <200–300°C, and a depth <5 km.

The three next generations occurred after the mantle rocks were almost fully serpentinized, likely at < 3 km, as suggested by Gillard et al. (2019). The results are banded veins (S3) mostly made of lizardite and polygonal serpentine, whereas chrysotile remains scarce. Locally, antigorite-bearing veins can also be observed (S4) in some fully serpentinized samples from Upper Platta, Tasna and in one sample from the Lower Platta Unit. All these veins are crosscut by later chrysotile crack-seal (S5), interpreted as the last serpentine generation and related to the mantle exposure at the seafloor.

Importantly, the number of serpentinization generations differs between the proximal and distal domains of the OCTs: a complete succession from S1 to S5 is recorded in the former case, while solely the S1 and S5 phases are recorded in the latter. This has been interpreted to reflect the complex interactions between serpentinization and the style of detachment faulting (a single, large-offset detachment fault in the proximal part, conversely to multiple, shorter and alternating extensional detachment faults in the distal part).

Sr isotope data show that serpentinization in hyperextended parts of the margin may have occurred below thin continental crust, via marine fluids with a crustal signature, whereas oceanward the mantle was hydrated by marine fluids without a crustal contamination (Hochscheid et al., 2022). The depth of the serpentinization front is difficult to estimate in fossil OCTs, however, from present-day OCTs, it is well established that it can reach down to 6 km below the seabed (see Fig. 2b). Moreover, the work of Hochscheid et al. (2022) support that serpentinization can occur already prior to exhumation at the seafloor, consistent with field observations. However, where and how seawater reaches the mantle remains unclear. Studies from Iberia show that brittle faults during hyperextension may play a major role in the serpentinization process, acting as pathways for marine water during mantle exhumation (Boddupalli et al., 2022). Moreover, the combination of anisotropic thermal contraction and tectonic stresses may have induced micro-fractures allowing for dynamic permeability triggering serpentinization at depth down to 6 km (Rouméjon and Cannat, 2014). Considering the evolution of serpentinization, it is generally assumed that initial diffusive serpentinization occurs where marine-derived water may diffuse along grain boundaries, at low water-rock ratios and high T (ca. 300°C), below a thin continent. Later fault-controlled massive serpentinization may occur under hydrothermal conditions near the seafloor.

In conclusion, five different generations of serpentinization, varying in terms of local temperature, pressure, water-rock ratio and fluid chemistry, have been identified in extensional setting forming OCTs (Hochscheid et al., 2024). As these occur prior to rift inversion, they are not in terms of H_2 potential in rift inversion orogens.

During the Meso-Alpine inversion, part of chrysotile and lizardite-bearing serpentinites underwent prograde metamorphic conditions turning them into a systematic sequence of antigorite-bearing and then antigorite-free assemblages, with progressive growth of olivine, amphiboles, pyroxenes and spinel (Tromsdorff and Evans, 1974). This prograde metamorphism, linked to convergence and inversion of the OCT, is far less understood compared to serpentinization linked to the formation of OCTs. It is important to note that the Grischun-Malenco OCT was in a hanging wall position relative to the subsiding Alpine Tethys slab (Fig. 11), escaping a high-pressure metamorphic overprint as well as serpentinite dehydration, antigorite breakdown, olivine formation, and H_2O release (Vils et al., 2011). To what extent mantle rocks from the Grischun-Malenco OCT were modified during convergence in the supra-subduction zone is little investigated and will be discussed in the next section.

A PERSPECTIVE FOR NATIVE H_2 EXPLORATION IN RIFT-INVERSION OROGENS

The Grischun-Malenco area: a future natural laboratory to study a serpentinization-sourced H_2 system

The first H_2 concentrations measured along the Engadin valley, reaching up to 1900 ppm, indicate the presence of both a deep groundwater flow system and a deep-seated H_2 ‘kitchen’ in the Grischun-Malenco area (Gasser et al., 2026). In contrast to many of the known sites such as the Mauléon Basin in the Western Pyrenees (Lefeuvre et al., 2021), the major advantage of the Grischun-Malenco area is that, due to late eastward tilting of the area, potential fossil kitchens and source rocks are exposed in the west and probable reservoirs and caprocks outcrop in the east. This allows to observe, probe and investigate all parts of a complete H_2 system over a relatively small area (several hundreds km^2). Moreover, the Engadin Fault, transecting the whole nappe stack, acts as a possible conduit for deep-water circulation, springs and H_2 in the dry-soil gas. While the nature (mantle type) of source rocks, their position in the nappe stack and the architecture of fault systems are relatively well understood (c.f. chapter 4 in this paper), the timing and conditions of H_2 production, as well as the plumbing system controlling water inflow and H_2 outflow are the subject of ongoing studies. In the following, we outline knowns and unknowns of the H_2 system in the Grischun-Malenco area and we present our strategy to progress on its understanding. To do so, we build on the elements that constitute an H_2 system. We first identify well-established knowledge based on our review of the Grischun-Malenco area, then we define the questions that drive our future research, and finally we outline our working hypothesis for future research. The aim of this final chapter is to highlight the importance of building an approach to understand a serpentinization-sourced H_2 system on a well-established field analogue.

Source rocks and kitchen in the Grischun-Malenco area

The nature of source rocks is well-defined for the Grischun-Malenco area and discussed above. It includes a large

diversity of ultramafic mantle rocks, including variably serpentinized spinel lherzolites or plagioclase lherzolite and pyroxenites, all of which show a SCLM mantle origin. Although large outcrops exist at the surface, the main question is how they can be projected at depth, underneath the Engadin valley, where the conditions of an active serpentinization source are potentially reached. Subsidiary questions that drive our ongoing research are:

- What is the fertility of the SCLM rocks in the Grischun-Malenco area? when and where did they serpentinize? and what is their potential for present-day H_2 production?
- Does the mantle wedge supposedly underlying the Grischun-Malenco area correspond to an active orogenic kitchen, at the origin of the H_2 detected along the Engadin valley?
- Can the hypothesis of a mantle wedge flooring the Engadin valley and the outcropping Malenco body (Fig. 11) be constrained by geological and geophysical data?

Our working hypothesis is that mantle rocks of the Grischun-Malenco area underwent strong serpentinization already during their emplacement along the OCT. As Tasna, Totalp, and Platta represent thin allochthonous sheets comprising only fully serpentinized mantle (see olive green units in Fig. 11), their value for H_2 exploration may be limited and therefore the northern side of the Engadin valley may not have a high H_2 potential (see map in Fig. 11). Conversely, due to its position near a rift segment boundary, the larger mantle wedge flooring the Malenco unit (dark green unit in Fig. 11) may have undergone less serpentinization and may preserve a higher H_2 potential. This body, if present, would be limited by the Engadin Fault in the north, the Paleo Insubric Line in the south and would be limited by the necking zone to the east (see map in Fig. 11). This mantle wedge could represent the active source/kitchen of the H_2 measured along the Engadin Fault. This interpretation has major implications for the H_2 exploration and requires further investigations.

In their latest 3D velocity model for the European Alps, Braszus et al. (2025; see their Fig. 5) show evidence for a high velocity body within the Austroalpine nappe stack, which could correspond to the eastward continuation of the Malenco mantle body. Other approaches that can be used to test this hypothesis are potential field data (gravity and magnetics) and related modelling.

A remaining question is if prograde serpentinization of already serpentinized mantle (allochthonous mantle) may correspond to an efficient H_2 production process, or if only serpentinization of deeper parts of the suggested, less serpentinized mantle wedge can account for the measured H_2 along the Engadin valley.

Water supply, H_2 plumbing system and potential reservoirs in the Grischun-Malenco area

A key structure in the Grischun-Malenco area is the Oligo-Miocene Engadin Fault that extends over > 100 km from SW-NE along the Engadin valley. Along this post Meso-Alpine structure, mineralized springs can be found at San Murezzan and Scuol (Balderer and Piatti, 2023; Bissing et al., 2006). These springs coincide with H_2 concentration measured along the Engadin Fault that can reach up to 1900 ppm, indicating the presence of both, a deep groundwater flow system and a deep-seated ‘kitchen’ (Gasser et al., 2026; Dimasi et al., 2026). These observations suggest that the Engadin Fault may control the regional hydrodynamics and likely also the hydrogen distribution along the Engadin val-

ley, which is the subject of an ongoing hydrodynamic modelling project. A key factor to identify and understand the location of the H₂ kitchen, fluid pathways and related water in- and H₂ out-flow is the understanding of the nappe stack in the Grischun area and its relation to the Engadin Fault. Thus, major questions are:

- Can water supply and the H₂ plumbing system be mapped? and is there a hydrodynamic link between potential ultramafic source rocks within a kitchen and potential reservoirs?
- What controls water supply and H₂ migration? and how can it be tested?
- Are there potential H₂ reservoirs in the Grischun area?

Our hypothesis is that there is a hydrodynamic link between the mantle body flooring the rift-inversion nappe stack, belonging to an eastward extension of the presumed Malenco mantle wedge. Whether the Engadin Fault can act as a possible conduit for deep water circulation, explaining the occurrence of springs and H₂ anomalies in the soil gas along the Engadin valley is a hypothesis that requires future investigations (Gasser et al., 2026). To test this hypothesis, we will use numerical hydrodynamic models performed on the Engadin Fault and surrounding area. While the occurrence of seeps along the Engadin valley may point to active H₂ kitchens, the main open question is if there are potential reservoirs in the Grischun-Malenco area. To answer to this question, it will be necessary to understand the 3D structure of the area, affected by the top-to-the-west Eo-Alpine event and the top-to-the-north Meso-Alpine event. Indeed, the succession of the two events created large-scale dome and basin style interference structures (Froitzheim et al., 1994). In this context, Triassic pre-rift evaporites may create cap rocks over dome structures south of Scuol, while Late Jurassic to Lower Cretaceous shales may act as cap rocks in the surroundings of San Murezzan in the upper Engadin valley.

Expected H₂ fluxes, volumes and production history in the Grischun-Malenco area

At present, we are still far from being able to quantify the fluxes and volumes of H₂ in the Grischun-Malenco area. Nevertheless, the potential H₂ fluxes estimated by the models of Albers et al. (2021), Liu et al. (2023), and Zwann et al. (2025), together with the direct measurements of native hydrogen reported by Gasser et al. (2026), are highly promising. Future studies aimed at continuously monitoring selected emission sites across the area will be crucial for better constraining the spatial and temporal variability of H₂ fluxes. In addition, considering the possible presence of a subsurface hydrogen reservoir, further investigations into the Fe redox state of serpentinites may provide key insights into the amount of past H₂ potentially generated during the formation and evolution of the OCT.

Zwann et al. (2025) presented a model in which H₂ production can be 20 times higher in rift inversion orogens than during the formation of OCTs. However, so far, no direct measurements support this prediction and we hope that the Grischun-Malenco OCT may be among the first areas where such models can be tested and calibrated.

FINAL REMARKS

Owing to its exceptional geological exposure and long history of multidisciplinary investigation, the Grischun-Malenco area has the potential to serve as a world class natu-

ral laboratory for H₂ exploration in rift inversion orogens. In particular, it allows to:

- investigate whether mantle rocks initially exhumed at magma-poor OCTs can continue to interact with fluids and generate H₂ during inversion and after their incorporation in a rift-inversion orogen;
- compare the H₂ potential of OCT ophiolites with those of MOR and SSZ ophiolites;
- test and calibrate the results and predictions of dynamic numerical models of H₂ systems;
- compare the parameters controlling a H₂ kitchen in a rift inversion orogen with those at present OCTs, MORs or SSZs;
- constrain the degree, depth, and mineralogical nature of serpentinization within OCT-derived mantle rocks during rift inversion, including the distribution of Fe(II)- versus Fe(III)-bearing serpentine assemblages, magnetite abundance, and redox-sensitive mineral phases;
- examine fluid availability and circulation in rift inversion orogens using hydrogeological modelling;
- investigate the sampling mechanism of mantle rocks during OCT inversion.

The main objective of this study was to demonstrate that H₂ systems cannot be understood only by looking at parts of the H₂ system. It also requires understanding the time-space dimension of potential hydrogen-producing systems, the location and quality of source rocks, the processes occurring in the H₂ kitchen and the parameters controlling them, as well as the plumbing systems and pathways of water circulation and free or dissolved gases to migrate from the source toward sealed reservoirs. To progress in the study of H₂ systems in rift-inversion orogens, understanding OCTs, their reactivation and the related fate of the mantle, as discussed in this paper for the Grischun-Malenco area are essential. Thus, the Grischun-Malenco fossil OCT, which records a well-preserved history of rift formation and inversion, may not only serve as a natural laboratory to understand OCT formation and inversion, but may also be used to investigate the potential of serpentinization-sourced H₂ in rift-inversion orogens.

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REFERENCES

- Albers E., Bach W., Pérez-Gussinyé M., McCammon C. and Frederichs T., 2021. Serpentinization-Driven H₂ Production from Continental Break-Up to Mid-Ocean Ridge Spreading: Unexpected High Rates at the West Iberia Margin. *Front. Earth Sci.*, 9: 673063. <https://doi.org/10.3389/feart.2021.673063>
- Amann M., Ulrich M., Manatschal G., Pelt E., Epin M., Autin J. and Sauter D., 2020. Geochemical characteristics of basalts related to incipient oceanization: The example from the Alpine-Tethys OCTs. *Terra Nova*, 32: 75-88. <https://doi.org/10.1111/ter.12438>
- Andreani M., Muñoz M., Marcaillou C. and Delacour A., 2013. μ XANES study of iron redox state in serpentine during oceanic serpentinization. *Lithos*, 178: 70-83. <https://doi.org/10.1016/j.lithos.2013.04.008>

- Anonymous, 1972. Penrose Field Conference on Ophiolites. *Geotimes*, 17 (2): 24-25
- Balderer W.P., Piatti E., 2023. The St. Moritz Mauritius mineral spring (Upper Engadine Valley, SE Switzerland): review of its importance by the joint facts of geological occurrence, archeology, health effects, chemical properties and long-term chemical stability. *Environ Earth Sci*, 82: 233. <https://doi.org/10.1007/s12665-023-10800-x>
- Ballay M., Ulrich M. and Manatschal G., 2025. The role of mantle inheritance and refertilization during breakup at magma-poor rifted margins: What can we learn from the SW-Australia margin? *Earth Planet. Sci. Lett.*, 653: 119212. <https://doi.org/10.1016/j.epsl.2025.119212>
- Bernoulli D., Weissert H., 2021. Oxygen isotopes in ophiolites: an ever-lasting controversy? *Int J Earth Sci (Geol Rundsch)* 110, 1-8. <https://doi.org/10.1007/s00531-020-01934-5>
- Bernoulli D., Manatschal G., Desmurs L., and Müntener O., 2003. Where did Gustav Steinmann see the trinity? Back to the roots of an Alpine ophiolite concept. In: Dilek, Y., and Newcomb, S. *Ophiolite concept and the evolution of geological thought*. *Geol. Soc. Am.*, v. 373. <https://doi.org/10.1130/0-8137-2373-6>
- Betlem P., Mohn G., Tugend J. and Manatschal G., 2023. High-resolution digital outcrop models of fossil-rifted margins: 3D imaging of extensional detachment systems. *First Break*, 41: 31-40. <https://doi.org/10.3997/1365-2397.fb2023032>
- Boddupalli B., Minshull T.A., Bayrakci G., Lymer G., Klaeschen D. and Reston T.J., 2022. Insights Into Exhumation and Mantle Hydration Processes at the Deep Galicia Margin From a 3D High-Resolution Seismic Velocity Model. *JGR Solid Earth*, 127: e2021JB023220. <https://doi.org/10.1029/2021JB023220>
- Boillot G., Grimaud S., Mauffret A., Mougénot D., Kornprobst J., Mergoil-Daniel J. and Torrent G., 1980. Ocean-continent boundary off the Iberian margin: A serpentinite diapir west of the Galicia Bank. *Earth Planet. Sci. Lett.*, 48: 23-34. [https://doi.org/10.1016/0012-821X\(80\)90166-1](https://doi.org/10.1016/0012-821X(80)90166-1)
- Boillot G., Recq M., Winterer E.L., Meyer A.W., Applegate J., Baltuck M., Bergen J.A., Comas M.C., Davies T.A., Dunham K., Evans C.A., Girardeau J., Goldberg G., Haggerty J., Jansa L.F., Johnson J.A., Kasahara J., Loreau J.P., Luna-Sierra E., Moulade M., Ogg J., Sarti M., Thuro J. and Williamson M., 1987. Tectonic denudation of the upper mantle along passive margins: a model based on drilling results (ODP leg 103, western Galicia margin, Spain). *Tectonophysics*, 132: 335-342. [https://doi.org/10.1016/0040-1951\(87\)90352-0](https://doi.org/10.1016/0040-1951(87)90352-0)
- Bonatti E., Hamlyn P. and Ottonello G., 1981. Upper mantle beneath a young oceanic rift: Peridotites from the island of Zabargad (Red Sea). *Geol.*, 9: 474. [https://doi.org/10.1130/0091-7613\(1981\)9<474:UMBAYO>2.0.CO;2](https://doi.org/10.1130/0091-7613(1981)9<474:UMBAYO>2.0.CO;2)
- Boudier F., Coleman R.G., 1981. Cross section through the peridotite in the Samail Ophiolite, southeastern Oman Mountains. *J. Geophys. Res.*, 86: 2573-2592. <https://doi.org/10.1029/JB086iB04p02573>
- Braszus B., Rietbrock A. and Haberland C., 2025. A 3D Velocity Model for the European Alps: New Insights into the Crustal Structure. *JGR Solid Earth*, 130: e2025JB031877. <https://doi.org/10.1029/2025JB031877>
- Burke K., 2011. Plate Tectonics, the Wilson Cycle, and Mantle Plumes: Geodynamics from the Top. *Annu. Rev. Earth Planet. Sci.*, 39: 1-29. <https://doi.org/10.1146/annurev-earth-040809-152521>
- Cadisch J., 1928. Geologische Beobachtungen im Gebirge zwischen Unterengadin und Panaun (Tirol). *Eclogae Geol. Helv.*, 21
- Cannat M., Fontaine F. and Escartín J., 2010. Serpentinization and associated hydrogen and methane fluxes at slow spreading ridges. In: Rona, P.A., Devey, C.W., Dymont, J., Murton, B.J. (Eds.), *Geophysical Monograph Series*. American Geophysical Union, Washington, D. C., pp. 241-264. <https://doi.org/10.1029/2008GM000760>
- Chenin P., Picazo S., Jammes S., Manatschal G., Müntener O. and Karner G., 2019. Potential role of lithospheric mantle composition in the Wilson cycle: a North Atlantic perspective. *SP*, 470: 157-172. <https://doi.org/10.1144/SP470.10>
- Coltat R., Boulvais P., Branquet Y., Collot J., Epin M.E. and Manatschal G., 2019. Syntectonic carbonation during synmagmatic mantle exhumation at an ocean-continent transition. *Geology*, 47: 183-186. <https://doi.org/10.1130/G45530.1>
- Coltat R., Boulvais P., Branquet Y., Richard A., Tarantola A. and Manatschal G., 2022. Moho carbonation at an ocean-continent transition. *Geology*, 50: 278-283. <https://doi.org/10.1130/G49363.1>
- Coltat R., Branquet Y., Gautier P., Boulvais P. and Manatschal G., 2020. The nature of the interface between basalts and serpentinized mantle in oceanic domains: Insights from a geological section in the Alps. *Tectonophysics*, 797: 228646. <https://doi.org/10.1016/j.tecto.2020.228646>
- Cornelius H.P., 1932. Geologische Karte der Err-Julier Gruppe 1:25000- in 2 Blättern, Schweiz. Geol. Komm., Basel, Spez Karte. Nr. 115 A+B
- Cornelius H.P., 1935. Geologische Karte der Err-Julier Gruppe: Das Baumaterial. *Beitr. Geol. Karte Schweiz N.F.* 70/1
- Cornelius H.P., 1950. Geologische Karte der Err-Julier Gruppe: Der Gebirgsbau-. *Beitr. Geol. Karte Schweiz N.F.* 70/2
- Debret B., Andreani M., Muñoz M., Bolfan-Casanova N., Carlut J., Nicollet C., Schwartz S. and Trcera N., 2014. Evolution of Fe redox state in serpentine during subduction. *Earth and Plan. Science Letters*, 400: 206-218. <https://doi.org/10.1016/j.epsl.2014.05.038>
- Decandia F. A.; Elter P., 1972. "La 'zona' ofiolitífera del Bracco nel settore compreso fra Levanto e la Val Graveglia (Appennino Ligure)". *Mem. Soc. Geol. Ital.*, vol., 11: pp. 503-530
- Deschamps F., Guillot S., Godard M., Chauvel C., Andreani M. and Hattori K., 2010. In situ characterization of serpentinites from forearc mantle wedges: Timing of serpentinization and behavior of fluid-mobile elements in subduction zones. *Chem. Geol.*, 269: 262-277. <https://doi.org/10.1016/j.chemgeo.2009.10.002>
- Desmurs L., Müntener O. and Manatschal G., 2002. Onset of magmatic accretion within a magma-poor rifted margin: a case study from the Platta ocean-continent transition, eastern Switzerland. *Contrib Mineral Petrol*, 144: 365-382. <https://doi.org/10.1007/s00410-002-0403-4>
- Diehl A., Anagnostou E., Monien P., Pape T., Meckel E.-M., Römer M., Mezri L., Bach W., Monien D., Hansen C., Röhler A., Streuff K., Palinkas S.S., Marcon Y., Barrenechea Angeles I., Kleint C., Knutsen S. and Bohrmann G., 2026. High H₂ production in sediment-hosted hydrothermal fluids at an ultraslow spreading mid-ocean ridge. *Commun Earth Environ*, 7: 12. <https://doi.org/10.1038/s43247-025-02962-2>
- Dietrich V., 1970 Die stratigraphie der Platta-Decke. *Eclogae geol. Helv.* 63/2 ; 631-771
- Dilek Y., Furnes H., 2011. Ophiolite genesis and global tectonics: Geochemical and tectonic fingerprinting of ancient oceanic lithosphere. *Geol. Soc. Am. Bul.*, 123: 387-411. <https://doi.org/10.1130/B30446.1>
- Dimasi F., Manatschal G., Chenin P., Ulrich M. and Gasser Q., 2026. The Grischun-Malenco fossil Ocean-Continent-Transition: the fate of the subcontinental mantle in a Wilson cycle and its significance for H₂ exploration. *EGU26-1017*
- Epin M.-E., Manatschal G., 2018. Three-Dimensional Architecture, Structural Evolution, and Role of Inheritance Controlling Detachment Faulting at a Hyperextended Distal Margin: The Example of the Err Detachment System (SE Switzerland). *Tectonics*, 37: 4494-4514. <https://doi.org/10.1029/2018TC005125>
- Epin M.-E., Manatschal G., Amman M., Ribes C., Clausse A., Guffon T. and Lescanne M., 2019. Polyphase tectono-magmatic evolution during mantle exhumation in an ultra-distal, magma-poor rift domain: example of the fossil Platta ophiolite, SE Switzerland. *Geol Rundsch*, 108: 2443-2467. <https://doi.org/10.1007/s00531-019-01772-0>
- Evans B.W., 1977. Metamorphism of Alpine Peridotite and Serpentinite. *Annu. Rev. Earth Planet. Sci.*, 5: 397-447. <https://doi.org/10.1146/annurev.ea.05.050177.002145>
- Ferreiro Mählmann R., 1995. The pattern of diagenesis and metamorphism by vitrinite reflectance and illite-"crystallinity" in

- Mittelbünden and in the Oberhalbstein, Part 1: the Relationship to stockwerk tectonics. *Schweiz. Mineral. Petrogr. Mitt.* <https://doi.org/10.5169/SEALS-57145>
- Florineth D. and Froitzheim N., 1994. Transition from continental to oceanic basement in the Tasna nappe (Engadine window, Graubünden, Switzerland): evidence for Early Cretaceous opening of the Valais ocean. *Schweiz. Miner. Petrogr. Mitt.*, 74, 437-448.
- Frasca G., Manatschal G. and Chenin P., 2024. Kinematic reconstruction of the Alpine Tethys and surrounding Mesozoic rifted margins. *Int J Earth Sci (Geol Rundsch)*, 113: 1053-1065 (2024). <https://doi.org/10.1007/s00531-024-02407-9>
- Froitzheim N. and Rubatto D., 2002. Continental breakup by detachment faulting: field evidence and geochronological constraints (Tasna nappe, Switzerland). *Terra Nova*, 10: 171-176. <https://doi.org/10.1046/j.1365-3121.1998.00187.x>
- Froitzheim N. and Eberli G.P., 1991. Extensional detachment faulting in the evolution of a Tethys passive continental margin, Eastern Alps, Switzerland. *GSA Bull.*, 102 (9): 1297-1308. [https://doi.org/10.1130/0016-7606\(1990\)102<1297:EDFITE>2.CO;2](https://doi.org/10.1130/0016-7606(1990)102<1297:EDFITE>2.CO;2)
- Froitzheim N., Schmid S.M. and Contt P., 1994. Repeated change from crustal shortening to orogen-parallel extension in the Austroalpine units of Graubünden. *Eclogae geol. Helv.* 87/2: 559-612.
- Früh-Green G.L., Weissert H. and Bernoulli D., 1990. A multiple fluid history recorded in Alpine ophiolites. *J. Geol. Soc. London*, 147: 959-970. <https://doi.org/10.1144/gsjgs.147.6.0959>
- Gasser Q., Manatschal G., Alt-Epping P., Gaucher E.C., Pierre S., Dimasi F. and Ulrich M., 2026. The link between deep groundwater flow and serpentinization-sourced H₂ production in rift inversion orogens: the example of the Engadine valley (SE-Switzerland). *EGU26*
- Gillard M., Tugend J., Müntener O., Manatschal G., Karner G.D., Autin J., Sauter D., Figueredo P.H. and Ulrich M., 2019. The role of serpentinization and magmatism in the formation of decoupling interfaces at magma-poor rifted margins. *Earth-Sci. Rev.*, 196: 102882. <https://doi.org/10.1016/j.earscirev.2019.102882>
- Hansmann W., Müntener O., and Hermann J., 2001. U-Pb zircon geochronology of a tholeiitic intrusion and associated migmatites at a continental crust-mantle transition, Val Malenco, Italy. *Schweiz. Mineral. Petrogr. Mitt.*, 81(2), 239-255.
- Hermann J., Müntener O., Trommsdorff V., Hansmann W. and Piccardo G.B., 1997. Fossil crust-to-mantle transition, Val Malenco (Italian Alps). *J. Geophys. Res.*, 102: 20123-20132. <https://doi.org/10.1029/97JB01510>
- Heron P.J., 2018. Mantle plumes and mantle dynamics in the Wilson cycle. *Geol. Soc. Spec. Publ.* SP470.18. <https://doi.org/10.1144/SP470.18>
- Hochscheid F., Coltat R., Ulrich M., Munoz M., Manatschal G. and Boulvais P., 2022. The Sr isotope geochemistry of oceanic ultramafic-hosted mineralizations. *Ore Geol. Rev.*, 144: 104824. <https://doi.org/10.1016/j.oregeorev.2022.104824>
- Hochscheid F., Ulrich M., Muñoz M., Boulvais P. and Manatschal G., 2024. Serpentinization as a Tape Recorder of (Dis)Continuous Mantle Exhumation along the Alpine Tethys Ocean-Continent-Transition. *J Petrol.*, 65: egae063. <https://doi.org/10.1093/petrology/egae063>
- Hölker A.B., Manatschal G., Holliger K. and Bernoulli D., 2002. Seismic structure and response of ocean-continent transition zones. *Mar. Geophys. Res.*, 23: 319-334.
- Hölker A.B., Manatschal G., Holliger K. and Bernoulli D., 2003. Tectonic nature and seismic response of top-basement detachment faults in magma-poor rifted margins. *Tectonics*, 22: 2001TC001347. <https://doi.org/10.1029/2001TC001347>
- Hsü K.J., Briegel U., 1991. Der Flysch, in: *Geologie Der Schweiz: Ein Lehrbuch Für Den Einstieg, Und Eine Auseinandersetzung Mit Den Experten*. Birkhäuser Basel, Basel, pp. 65-82. https://doi.org/10.1007/978-3-0348-8663-5_6
- Incerpi N., Martire L., Manatschal G., Bernasconi S.M., Gerdes A., Czuppon G., Palcsu L., Karner G.D., Johnson C.A. and Figueredo P.H., 2020. Hydrothermal fluid flow associated to the extensional evolution of the Adriatic rifted margin: Insights from the pre- to post-rift sedimentary sequence (SE Switzerland, N ITA-LY). *Basin Res.*, 32: 91-115. <https://doi.org/10.1111/bre.12370>
- Jackson O., Lawrence S.R., Hutchinson I.P., Stocks A.E., Barnicoat A.C. and Powney M., 2024. Natural hydrogen: sources, systems and exploration plays. *Geoenergy*, geoenergy2024-002. <https://doi.org/10.1144/geoenergy2024-002>
- Jagoutz O., Müntener O., Manatschal G., Rubatto D., Péron-Pinvidic G., Turrin B.D. and Villa I.M., 2007. The rift-to-drift transition in the North Atlantic: A stuttering start of the MORB machine? *Geology* 35, 1087. <https://doi.org/10.1130/G23613A.1>
- Khudeir A.A., Nicholson K., Rooney T. O., and El-Rus M.A.A., 2024. The origin of plagioclase lherzolite from Zabargad Island, northern Red Sea. In: Najeeb M.A. Rasul, Ian C.F. Stewart (Eds.). *Rifting and Sediments in the Red Sea and Arabian Gulf Regions* (pp. 215-241). CRC Press. <https://doi.org/10.1201/9781003321415>
- Klein F., Bach W., Jöns N., McCollom T., Moskowicz B. and Berquó T., 2009. Iron partitioning and hydrogen generation during serpentinization of abyssal peridotites from 15°N on the Mid-Atlantic Ridge. *Geochim. et Cosmochim. Acta*, 73: 6868-6893. <https://doi.org/10.1016/j.gca.2009.08.021>
- Lafay R., Baumgartner L.P. and Delacour A., 2023. Preservation of mantle heterogeneities and serpentinization signature during antigorite dehydration: The example of the Bergell contact aureole. *J. Metamorph. Geol.*, 41: 377-399. <https://doi.org/10.1111/jmg.12699>
- Lefevre N., Truche L., Donzé F., Ducoux M., Barré G., Fakoury R., Calassou S. and Gaucher E.C., 2021. Native H₂ Exploration in the Western Pyrenean Foothills. *Geochem Geophys Geosyst*, 22: e2021GC009917. <https://doi.org/10.1029/2021GC009917>
- Lescoutre R. and Manatschal G., 2020. Role of rift-inheritance and segmentation for orogenic evolution: example from the Pyrenean-Cantabrian system. *BSGF - Earth Sci. Bull.*, 191: 18. <https://doi.org/10.1051/bsgf/2020021>
- Liu Z., Perez-Gussinye M., García-Pintado J., Mezri L. and Bach W., 2023. Mantle serpentinization and associated hydrogen flux at North Atlantic magma-poor rifted margins. *Geology*, 51: 284-289. <https://doi.org/10.1130/G50722.1>
- Lymer G., Cresswell D.J.F., Reston T.J., Bull J.M., Sawyer D.S., Morgan J.K., Stevenson C., Causer A., Minshull T.A. and Shillington D.J., 2019. 3D development of detachment faulting during continental breakup. *Earth and Planet. Sci. Lett.*, 515: 90-99. <https://doi.org/10.1016/j.epsl.2019.03.018>
- Manatschal G., 2004. New models for evolution of magma-poor rifted margins based on a review of data and concepts from West Iberia and the Alps. *Int J Earth Sci (Geol Rundsch)* 93. <https://doi.org/10.1007/s00531-004-0394-7>
- Manatschal G. and Chenin P., 2023. Fossil rifted margins in the Alps. *Geological Field Trips and Maps.*, 15: 1-207.
- Manatschal G., Chenin P., Ghienne J., Ribes C. and Masini E., 2022. The syn-rift tectono-stratigraphic record of rifted margins (Part I): Insights from the Alpine Tethys. *Basin Res.*, 34: 457-488. <https://doi.org/10.1111/bre.12627>
- Manatschal G. and Nievergelt P., 1997. A continent-ocean transition recorded in the Err and Platta nappes (Eastern Switzerland). *Eclogae Geol. Helv.*, 90/3-28
- Manatschal G., Engström A., Desmurs L., Schaltegger U., Cosca M., Müntener O. and Bernoulli D., 2006. What is the tectono-metamorphic evolution of continental break-up: The example of the Tasna Ocean-Continent Transition. *J. Struct. Geol.*, 28: 1849-1869. <https://doi.org/10.1016/j.jsg.2006.07.014>
- Manatschal G., Froitzheim N., Rubenach M. and Turrin B.D., 2001. The role of detachment faulting in the formation of an ocean-continent transition: insights from the Iberia Abyssal Plain. *Geol. Soc. Lond., Spec. Publ.*, SP, 187: 405-428. <https://doi.org/10.1144/GSL.SP.2001.187.01.20>
- Manatschal G., Müntener O., 2009. A type sequence across an ancient magma-poor ocean-continent transition: the example of the western Alpine Tethys ophiolites. *Tectonophysics*, 473: 4-19. <https://doi.org/10.1016/j.tecto.2008.07.021>

- Masini E., Jammes S., Calassou S., Vidal O., Thion I., Manatschal G., Chevrot S., Ford M., Mouthereau F., Lacombe O. and The Orogen Team, 2024. Revisiting orogens during the OROGEN project: tectonic maturity, a key element to understand orogenic variability. *BSGF - Earth Sci. Bull.*, 195: 23. <https://doi.org/10.1051/bsgf/2024021>
- Masini E., Manatschal G. and Mohn G., 2013. The Alpine Tethys rifted margins: Reconciling old and new ideas to understand the stratigraphic architecture of magma-poor rifted margins. *Sedimentology*, 60: 174-196. <https://doi.org/10.1111/sed.12017>
- Masini E., Manatschal G., Mohn G. and Unternehr P., 2012. Anatomy and tectono-sedimentary evolution of a rift-related detachment system: The example of the Err detachment (central Alps, SE Switzerland). *Geol. Soc. Am. Bull.*, 124: 1535-1551. <https://doi.org/10.1130/B30557.1>
- McCarthy A., Müntener O., 2015. Ancient depletion and mantle heterogeneity: Revisiting the Permian-Jurassic paradox of Alpine peridotites. *Geology*, 43: 255-258. <https://doi.org/10.1130/G36340.1>
- McCarthy A., Tugend J., Mohn G., Candioti L., Chelle-Michou C., Arculus R., Schmalholz S.M. and Müntener O., 2020. A case of Ampferer-type subduction and consequences for the Alps and the Pyrenees. *Am J Sci*, 320: 313-372. <https://doi.org/10.2475/04.2020.01>
- Merdith A.S., Daniel I., Sverjensky D., Andreani M., Mather B., Williams S. and Vitale Brovarone A., 2023. Global Hydrogen Production During High-Pressure Serpentinization of Subducting Slabs. *Geochem Geophys Geosyst*, 24: e2023GC010947. <https://doi.org/10.1029/2023GC010947>
- Miró J., Ferrer O., Muñoz J.A. and Manatschal G., 2023. Role of inheritance during tectonic inversion of a rift system in basement-involved to salt-decoupled transition: analogue modelling and application to the Pyrenean-Biscay system. *Solid Earth*, 14: 425-445. <https://doi.org/10.5194/se-14-425-2023>
- Mohn G., Manatschal G., Beltrando M., Masini E. and Kusznir N., 2012. Necking of continental crust in magma-poor rifted margins: Evidence from the fossil Alpine Tethys margins. *Tectonics*, 31: 2011TC002961. <https://doi.org/10.1029/2011TC002961>
- Mohn G., Manatschal G., Müntener O., Beltrando M. and Masini E., 2010. Unravelling the interaction between tectonic and sedimentary processes during lithospheric thinning in the Alpine Tethys margins. *Int J Earth Sci (Geol Rundsch)*, 99: 75-101. <https://doi.org/10.1007/s00531-010-0566-6>
- Müntener O., 2000. Cooling History and Exhumation of Lower-Crustal Granulite and Upper Mantle (Malenco, Eastern Central Alps). *J Petrology*, 41: 175-200. <https://doi.org/10.1093/petrology/41.2.175>
- Müntener O., Manatschal G., 2006. High degrees of melt extraction recorded by spinel harzburgite of the Newfoundland margin: The role of inheritance and consequences for the evolution of the southern North Atlantic. *Earth Planet. Sci. Lett.*, 252: 437-452. <https://doi.org/10.1016/j.epsl.2006.10.009>
- Müntener O., Manatschal G., Desmurs L. and Pettke T., 2010. Plagioclase Peridotites in Ocean-Continent Transitions: Refertilized Mantle Domains Generated by Melt Stagnation in the Shallow Mantle Lithosphere. *J Petrology*, 51: 255-294. <https://doi.org/10.1093/petrology/egp087>
- Müntener O., Pettke T., Desmurs L., Meier M. and Schaltegger U., 2004. Refertilization of mantle peridotite in embryonic ocean basins: trace element and Nd isotopic evidence and implications for crust-mantle relationships. *Earth Planet. Sci. Lett.*, 221: 293-308. [https://doi.org/10.1016/S0012-821X\(04\)00073-1](https://doi.org/10.1016/S0012-821X(04)00073-1)
- Müntener O., Hermann J., 1996. The Val Malenco lower crust - upper mantle complex and its field relations (Italian Alps). *Schweiz. Mineral. Petrogr. Mitt.*, 0036-7699.
- Neal C., Stanger G., 1983. Hydrogen generation from mantle source rocks in Oman. *Earth Planet. Sci. Lett.*, 66: 315-320. [https://doi.org/10.1016/0012-821X\(83\)90144-9](https://doi.org/10.1016/0012-821X(83)90144-9)
- Osmundsen P.T., Péron-Pinvidic G., 2018. Crustal-Scale Fault Interaction at Rifted Margins and the Formation of Domain-Bounding Breakaway Complexes: Insights From Offshore Norway. *Tectonics*, 37: 935-964. <https://doi.org/10.1002/2017TC004792>
- Patten C.G.C., Coltat R., Junge M., Peillod A., Ulrich M., Manatschal G. and Kolb J., 2022. Ultramafic-hosted volcanogenic massive sulfide deposits: an overlooked sub-class of VMS deposit forming in complex tectonic environments. *Earth-Sci. Rev.*, 224: 103891. <https://doi.org/10.1016/j.earscirev.2021.103891>
- Peretti A., Dubessy J., Mullis J., Frost B.R. and Trommsdorff V., 1992. Highly reducing conditions during Alpine metamorphism of the Malenco peridotite (Sondrio, northern Italy) indicated by mineral paragenesis and H₂ in fluid inclusions. *Contr. Mineral. and Petrol.*, 112: 329-340. <https://doi.org/10.1007/BF00310464>
- Peron-Pinvidic G., Shillington D.J. and Tucholke B.E., 2010. Characterization of sills associated with the U reflection on the Newfoundland margin: evidence for widespread early post-rift magmatism on a magma-poor rifted margin: Post-rift magmatism on the Newfoundland margin. *Geophys. J. Int.*, Vol. 182: issue 1. <https://doi.org/10.1111/j.1365-246X.2010.04635.x>
- Peters P. C. and Mathews J., 1963. Gravitational radiation from point masses in a keplerian orbit. *Phys. Rev.*, 131(1), 435-440. <https://doi.org/10.1103/PhysRev.131.435>
- Peters T., 1963. Mineralogie und Petrographie des Totalserpentins bei Davos. *Schweiz. mineralog. petrogr. Mitt.*, 43 : 529-686.
- Petri B., Mohn G., Skrzypek E., Mateeva T., Galster F. and Manatschal G., 2017. U-Pb geochronology of the Sondalo gabbroic complex (Central Alps) and its position within the Permian post-Variscan extension. *Int J Earth Sci (Geol Rundsch)*, 106: 2873-2893. <https://doi.org/10.1007/s00531-017-1465-x>
- Petri B., Wijbrans J.R., Mohn G., Manatschal G. and Beltrando M., 2023. Thermal evolution of Permian post-orogenic extension and Jurassic rifting recorded in the Austroalpine basement (SE Switzerland, N Italy). *Lithos*, 444-445: 107124. <https://doi.org/10.1016/j.lithos.2023.107124>
- Picazo S., Malvoisin B., Baumgartner L. and Bouvier A.-S., 2020. Low Temperature Serpentinite Replacement by Carbonates during Seawater Influx in the Newfoundland Margin. *Minerals*, 10: 184. <https://doi.org/10.3390/min10020184>
- Picazo S., Manatschal G., Cannat M. and Andréani M., 2013. Deformation associated to exhumation of serpentinized mantle rocks in a fossil Ocean Continent Transition: The Totalp unit in SE Switzerland. *Lithos*, 175-176: 255-271. <https://doi.org/10.1016/j.lithos.2013.05.010>
- Picazo S., Müntener O., Manatschal G., Bauville A., Karner G. and Johnson C., 2016. Mapping the nature of mantle domains in Western and Central Europe based on clinopyroxene and spinel chemistry: Evidence for mantle modification during an extensional cycle. *Lithos*, 266-267: 233-263. <https://doi.org/10.1016/j.lithos.2016.08.029>
- Piccardo G.B., Müntener O., Zanetti A. and Pettke T., 2004. Ophiolitic Peridotites of the Alpine-Apennine System: Mantle Processes and Geodynamic Relevance. *Int. Geol. Rev.*, 46: 1119-1159. <https://doi.org/10.2747/0020-6814.46.12.1119>
- Pinto V.H.G., Manatschal G., Karpoff A.M., Masini E., Victor R.A., Viana A.R. and Ulrich M., 2023. Mass-Transfer and Fluid Flow along Extensional Detachment Faults in Hyperextended Rift Systems: The Examples of Tasna in the Alps, Mauléon in the Pyrenees, and Hobby High Offshore Iberia. *Geosciences*, 13: 374. <https://doi.org/10.3390/geosciences13120374>
- Pinto V.H.G., Manatschal G., Karpoff A.M. and Viana A., 2015. Tracing mantle-reacted fluids in magma-poor rifted margins: The example of Alpine Tethyan rifted margins. *Geochem Geophys Geosyst*, 16: 3271-3308. <https://doi.org/10.1002/2015GC005830>
- Planke S. and Eldholm O., 1994. Seismic response and construction of seaward dipping wedges of flood basalts: Voring volcanic margin. *J. Geophys. Res.*, 99(B5), 9263-9278. <https://doi.org/10.1029/94JB00468>
- Rampone E., Hofmann A.W., 2012. A global overview of isotopic heterogeneities in the oceanic mantle. *Lithos*, 148: 247-261. <https://doi.org/10.1016/j.lithos.2012.06.018>
- Rampone E., Hofmann A.W. and Raczek I., 1998. Isotopic contrasts within the Internal Liguride ophiolite (N. Italy): the lack of a genetic mantle-crust link. *Earth Planet. Sci. Lett.*, 163: 175-189. [https://doi.org/10.1016/S0012-821X\(98\)00185-X](https://doi.org/10.1016/S0012-821X(98)00185-X)

- Rampone E. and Sanfilippo A., 2021. The heterogeneous Tethyan oceanic lithosphere of the Alpine ophiolites. *Elements*, 17(1), 23-28. <https://doi.org/10.2138/gselements.17.1.23>
- Reston T.J., Krawczyk C.M. and Hoffmann H.-J., 1995. Detachment tectonics during Atlantic rifting: analysis and interpretation of the S reflection, the west Galicia margin. *SP*, 90: 93-109. <https://doi.org/10.1144/GSL.SP.1995.090.01.05>
- Ribes, C., Ghienne, J.-F., Manatschal, G., Decarlis, A., Karner, G.D., Figueredo, P.H., Johnson, C.A., 2019a. Long-lived mega fault-scarps and related breccias at distal rifted margins: insights from present-day and fossil analogues. *JGS* 176, 801-816. <https://doi.org/10.1144/jgs2018-181>
- Ribes, C., Manatschal, G., Ghienne, J.-F., Karner, G.D., Johnson, C.A., Figueredo, P.H., Incerpi, N., Epin, M.-E., 2019b. The syn-rift stratigraphic record across a fossil hyper-extended rifted margin: the example of the northwestern Adriatic margin exposed in the Central Alps. *Int J Earth Sci (Geol Rundsch)* 108, 2071-2095. <https://doi.org/10.1007/s00531-019-01750-6>
- Ribes C., Petri B., Ghienne J.-F., Manatschal G., Galster F., Karner G.D., Figueredo P.H., Johnson C.A. and Karpoff A.-M., 2020. Tectono-sedimentary evolution of a fossil ocean-continent transition: Tasna nappe, central Alps (SE Switzerland). *GSA Bull.*, 132: 1427-1446. <https://doi.org/10.1130/B35310.1>
- Robertson A.H.F., 2002. Overview of the genesis and emplacement of Mesozoic ophiolites in the Eastern Mediterranean Tethyan region. *Lithos*, 65: 1-67. [https://doi.org/10.1016/S0024-4937\(02\)00160-3](https://doi.org/10.1016/S0024-4937(02)00160-3)
- Agard P., 2024. Oceanic Subduction in the Alps. In: Rosenberg and N. Bellahsen (eds C.L.). *Geodynamics of the Alps 2. Sciences*. <https://doi.org/10.1002/9781394299539.ch4>
- Rouméjon S., Cannat M., 2014. Serpentinization of mantle-derived peridotites at mid-ocean ridges: Mesh texture development in the context of tectonic exhumation. *Geochem Geophys Geosyst*, 15: 2354-2379. <https://doi.org/10.1002/2013GC005148>
- Saunders A.D., Larsen H.C. and Wise S.W.Jr. (Eds.), 1998. *Proceedings of the Ocean Drilling Program*, 152 Scientific Results. <https://doi.org/10.2973/odp.proc.sr.152.1998>
- Schaltegger U., Brack P., 2007. Crustal-scale magmatic systems during intracontinental strike-slip tectonics: U, Pb and Hf isotopic constraints from Permian magmatic rocks of the Southern Alps. *Int J Earth Sci (Geol Rundsch)*, 96: 1131-1151. <https://doi.org/10.1007/s00531-006-0165-8>
- Schaltegger U., Desmurs L., Manatschal G., Müntener O., Meier M., Frank M. and Bernoulli D., 2002. The transition from rifting to sea-floor spreading within a magma-poor rifted margin: field and isotopic constraints. *Terra Nova*, 14: 156-162. <https://doi.org/10.1046/j.1365-3121.2002.00406.x>
- Schmid S.M., Bernoulli D., Fügenschuh B., Matenco L., Schefer S., Schuster R., Tischler M. and Ustaszewski K., 2008. The Alpine-Carpathian-Dinaridic orogenic system: correlation and evolution of tectonic units. *Swiss J. Geosci.*, 101: 139-183. <https://doi.org/10.1007/s00015-008-1247-3>
- Schmid S.M., Froitzheim N., 1993. Oblique slip and block rotation along the Engadine line. *Eclogae Geol. Helv.*, 86/2:569-593. <https://doi.org/10.5169/SEALS-167253>
- 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. <https://doi.org/10.1007/s00015-004-1113-x>
- Schuba C.N., Gray G.G., Morgan J.K., Sawyer D.S., Shillington D.J., Reston T.J., Bull J.M. and Jordan B.E., 2018. A low-angle detachment fault revealed: Three-dimensional images of the S-reflector fault zone along the Galicia passive margin. *Earth Planet. Sci. Lett.*, 492: 232-238. <https://doi.org/10.1016/j.epsl.2018.04.012>
- Secchiari A., Godard M. and Montanini A., 2025. Mantle Heterogeneity Generated by Melt Depletion and Melt-Rock Interaction: The West Iberian Margin Peridotites (ODP Leg 149 and 173). *Journal of Petrology*, 66: egaf005. <https://doi.org/10.1093/petrology/egaf005>
- Dilek Y. and Newcomb S., 2003. Ophiolite concept and the evolution of geological thought. *Geol. Soc. Am.*, 9780813723730. <https://doi.org/10.1130/0-8137-2373-6>
- Staub R., 1946. *Geologische Karte der Bernina-Gruppe und ihrer Umgebung im Oberengadin, Bergell, Val Malenco, Puschlav und Livigno*. Geologischen Kommission der Schweiz. Naturforschenden Gesellschaft.
- Steinmann-Bonn, G., 4. Vorträge und Diskussionen.
- Sutra E., Manatschal G., Mohn G. and Unternehr P., 2013. Quantification and restoration of extensional deformation along the Western Iberia and Newfoundland rifted margins. *Geochem Geophys Geosyst*, 14: 2575-2597. <https://doi.org/10.1002/ggge.20135>
- Tribuzio R., Thirlwall M.F. and Messiga B., 1999. Petrology, mineral and isotope geochemistry of the Sondalo gabbroic complex (Central Alps, Northern Italy): implications for the origin of post-Variscan magmatism. *Contrib. Mineral. Petrol.*, 136: 48-62. <https://doi.org/10.1007/s004100050523>
- Trommsdorff V. and Evans B.W., 1972. Progressive metamorphism of antigorite schist in the Bergell tonalite aureole (Italy). *Am. J. Sci.* 272, 423-437
- Trommsdorff V., Evans B.W., 1974. Alpine metamorphism of peridotitic rocks. *Schweiz. Mineral. Petrogr. Mitt.*, 54 333-352. <https://doi.org/10.5169/SEALS-42198>
- Trommsdorff V., Evans B.W., 1977. Antigortite-ophicarbonates: Contact metamorphism in Valmalenco, Italy. *Contr. Mineral. and Petrol.*, 62: 301-312. <https://doi.org/10.1007/BF00371017>
- Trommsdorff V., Montrasio A., Hermann J., Müntener O., Spillmann P. and Gieré, 2005. The Geological Map of Valmalenco. *Schweiz. Mineral. Petrogr. Mitt.*, 85: 1-13.
- Tucholke B.E., Sibuet J.-C. and Klaus A. (Eds.), 2006. *Proceedings of the Ocean Drilling Program*, 210 Scientific Results. <https://doi.org/10.2973/odp.proc.sr.210.2007>
- Trümpy R. 1975 Penninic-Austroalpine boundary in the Swiss Alps: a presumed former continental margin and its problems. *Am. J. Sci.*, 275-A, 209-238.
- V. Blanckenburg F., Villa I.M., Baur H., Morteani G. and Steiger R.H., 1989. Time calibration of a PT-path from the Western Tauern Window, Eastern Alps: the problem of closure temperatures. *Contr. Mineral. Petrol.*, 101: 1-11. <https://doi.org/10.1007/BF00387196>
- Vannucchi P., Bettelli G., 2002. Mechanisms of subduction accretion as implied from the broken formations in the Apennines, Italy. *Geology*, 30: 835. [https://doi.org/10.1130/0091-7613\(2002\)030%253C0835:MOSAAI%253E2.0.CO;2](https://doi.org/10.1130/0091-7613(2002)030%253C0835:MOSAAI%253E2.0.CO;2)
- Varga R.J., Moores E.M., 1985. Spreading structure of the Troodos ophiolite, Cyprus. *Geol.*, 13: 846. [https://doi.org/10.1130/0091-7613\(1985\)13%253C846:SSOTTO%253E2.0.CO;2](https://doi.org/10.1130/0091-7613(1985)13%253C846:SSOTTO%253E2.0.CO;2)
- Villa I.M., Hermann J., Müntener O. and Trommsdorff V., 2000. 39Ar-40Ar dating of multiply zoned amphibole generations (Malenco, Italian Alps). *Contrib. Mineral. Petrol.*, 140: 363-381. <https://doi.org/10.1007/s004100000197>
- Vils F., Müntener O., Kalt A. and Ludwig T., 2011. Implications of the serpentine phase transition on the behaviour of beryllium and lithium-boron of subducted ultramafic rocks. *Geochim. et Cosmochim. Acta*, 75: 1249-1271. <https://doi.org/10.1016/j.gca.2010.12.007>
- Warren J.M., Shimizu N., Sakaguchi C., Dick H.J.B. and Nakamura E., 2009. An assessment of upper mantle heterogeneity based on abyssal peridotite isotopic compositions. *J. Geophys. Res.*, 114: 2008JB006186. <https://doi.org/10.1029/2008JB006186>
- Weissert H.J., Bernoulli D., 1985. A transform margin in the Mesozoic Tethys: evidence from the Swiss Alps. *Geol Rundsch*, 74: 665-679. <https://doi.org/10.1007/BF01821220>
- Wernicke B. Low-angle normal faults in the Basin and Range Province: nappe tectonics in an extending orogen. *Nature* 291, 645-648 (1981). <https://doi.org/10.1038/291645a0>
- Whitmarsh R.B., Manatschal G. and Minshull T.A., 2001. Evolution of magma-poor continental margins from rifting to sea-floor spreading. *Nature*, 413: 150-154. <https://doi.org/10.1038/35093085>
- Wilson J.T., 1966. Did the Atlantic Close and then Re-Open? *Nature* 211, 676-681. <https://doi.org/10.1038/211676a0>

- Wilson R.C.L., Manatschal G. and Wise S., 2001. Rifting along non-volcanic passive margins: stratigraphic and seismic evidence from the Mesozoic successions of the Alps and western Iberia. *Geol. Soc. SP*, 187: 429-452. <https://doi.org/10.1144/GSL.SP.2001.187.01.21>
- Wilson R.W., Houseman G.A., Buitter S.J.H., McCaffrey K.J.W. and Doré A.G., 2019. Fifty years of the Wilson Cycle concept in plate tectonics: an overview. *Geol. Soc. SP*, 470: 1-17. <https://doi.org/10.1144/SP470-2019-58>
- Zwaan F., Brune S., Glerum A.C., Vasey D.A., Naliboff J.B., Manatschal G. and Gaucher E.C., 2025. Rift-inversion orogens are potential hot spots for natural H₂ generation. *Science AdvAnceS.*, 11(8), eadr3418. <https://doi.org/10.1126/sciadv.adr3418>

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