THE SYN-RIFT TECTONO-STRATIGRAPHIC RECORD OF RIFTED MARIGINS (PART 1): INSIGHTS FROM THE ALPINE TETHYS

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ABSTRACT

The tectono-stratigraphic evolution of rift systems is at present poorly understood, especially the one preceding the onset of oceanic seafloor spreading. Improving our understanding of the complex, polyphase tectonic evolution of the fossil Alpine Tethys, one of the best calibrated magma-poor rift systems worldwide, offers great potential for the interpretation of the distal part of global rifted margins, which notoriously lack data. In this paper, we propose a tectono-stratigraphic model for the former Alpine Tethys, whose remnants are exposed in the Alps of Western Europe. We fist review the historical evolution of some concepts grounding present knowledge on the Alpine- and global magma-poor rifted margins. Then we present a spatial and temporal template for the Alpine Tethys rift system using a "building block (BB)" approach. This new approach is powerful in that it can integrate high-resolution, structural, stratigraphic, thermochronological and petrological observations from dismembered outcrops into a margin-scale template compatible with the first-order seismic architecture defined at present-day, magma-poor rifted margins. The detailed analysis of the syn-rift sequence of the Alpine Tethys margins demonstrates that extension migrated and localized while evolving from the stretching to the necking phase. During hyperextension, rifting was asymmetric and controlled by in-sequence detachment faulting. Then, the rift system evolved back into a more symmetric, embryonic spreading system. With this contribution, we aim to allow readers without knowledge of the Alps to access to this unique "archive" preserving some of the world's best-exposed rift structures. Recognising these structures is critical to understand the origin of some new concepts used to explain present-day, deep-water rifted margins, and to interpret and predict the tectono-stratigraphic evolution during advanced stages of rifting.

Highlights:

Our "building block" approach enables us to upscale local outcrop observations into a global margin template

The syn-rift sequence of the Alpine Tethys margins is among the best calibrated worldwide

The observed rift migration - localization has far-reaching consequences for the interpretation of global rifted margins

Keywords: Alps, Alpine Tethys, tectono-stratigraphic evolution, polyphase rifting

INTRODUCTION

Why revisit the syn-rift sequence of the Alpine Tethys?

In the past two decades, our understanding of the architecture and evolution of rifted margins in general, and of the distal parts of magma-poor rifted margins in particular, have been greatly enhanced (Péron-Pinvidic and Manatschal, 2019). Field studies in the Alpine Tethys have played a key role in the development of new concepts. Indeed, there are few places where the syn-rift sequence of a conjugate, magma-poor rifted margin is so well exposed, including the most distal parts, and where rift-related structures have been examined in such detail. These studies, closely linked to the progress in seismic imaging and modelling of rifted margins, have enabled development and testing of many new concepts of rifted margin formation. They also helped understanding the latest stages of the rifting process (i.e., the breakup phase), the related tectono-stratigraphic evolution, as well as the resource potential in poorly calibrated distal margins. The spatial and temporal characterization of rifted margins is a prerequisite to generate better plate tectonic/geodynamic reconstructions, and to understand the formation of a plate boundary, a first-order plate tectonic process that remains yet little understood.

This paper focuses on the rift-related stratigraphy and tectonic evolution of the Jurassic Alpine Tethys rift system. Here we use the term "Alpine Tethys" to refer to the (proto-)oceanic domain(s) and related conjugate rifted margins separating the European-Iberian and African-Adriatic (micro)continents (Fig. 1a). We use the term rifting to refer to the process thinning the crust from its initial thickness (30 ± 5 km) to less than 30 km. We present an historical overview of the key observations and data that are at the origin of some recent concepts on rifted margin formation based on more than one century of research in one of the world's best investigated orogens. As this review can obviously not include all details and refer to all studies published over more than a century, we focus on the more recent discoveries, in particular on the distal parts of the Alpine Tethys margins.

Geological and paleo-geographical setting

From a broad-scale perspective, the Alpine Tethys formed contemporaneously with the subduction of the Paleo- and/or Neo-Tethys Ocean(s) to the east, and with the opening of the Central Atlantic to the west (Fig. 1b). Aside from the Alpine Tethys, other extensional basins such as the *Meliata-Vardar* and the *Pyrenean-Bay of Biscay* (Fig. 1a) formed between the Paleo- and/or Neo-Tethys and Atlantic domains, from the Late Triassic to Cretaceous (Handy et al., 2010). These (proto-) oceanic domains developed successively westwards, resulting in a complex, so-called *multi-stage*, plate-kinematic framework that will be discussed later.

The Alpine Tethys evolution is part of a *Wilson Cycle* that may have been incomplete, in the sense that neither seafloor spreading, nor subduction reached a steady-state evolution (Chenin et al., 2018a). It initiated at the end of the late- to post-orogenic collapse of the Variscan Orogen, which led to peneplanation in Western Europe, as recorded in the widespread Late Carboniferous to Permian depocenters. The stratigraphic development of these depocenters and their link to the Permian and Triassic volcanics and thick Triassic platforms observed in the

Adriatic and Briançonnais domains are ill constrained. At a super-regional scale, the Alpine Tethys rifting initiated in the Late Permo-Triassic in the Dinarides, Hellenides, Turkey, Iran and Oman (e.g., Stampli, 1990 ; Robertson & Searle, 1990). In the Vardar in Greece, rifted margins and fringing MORB crust is dated following the Permo-Triassic rift phase (van Hinsbergen et al., 2020). Rifting localized in the Alpine Tethys during the so-called *necking phase* in the late Sinemurian/Pliensbachian (185 ± 5 Ma) (Mohn et al., 2010). This phase corresponded to both major crustal thinning and the formation of a segmented rift system comprising three basins, namely from southwest to northeast, the Ligurian, Piemonte and Valais basins (Fig. 1a). These basins merged in a continuous, proto-oceanic domain, linking the Central Atlantic with the Tethys realm (Baumgartner, 2013) during the subsequent phase of mantle exhumation. Mantle exhumation initiated during the Callovian/Bathonian (165 ± 5 Ma) (Ribes et al., 2019) and was associated with incipient magmatic activity. Whether the Alpine Tethys eventually developed into a mature, steady-state spreading system remains debated. At present, observations and data do not support the existence of a mature Penrose crust in the Alpine Tethys domain, but that it existed cannot be excluded. The nature and width of the Alpine Tethys oceanic or proto-oceanic domain have direct implications on a second debate related to the nature of the subsequent Late Cretaceous to early Cenozoic Alpine subduction. While McCarthy et al. (2020) suggested that the Alpine Tethys was closed via an Ampferer-type subduction (i.e., closure of narrow hyperextended rift basins with immature subduction zones and without formation of Arc magmatic activity), Handy et al. (2010) proposed a more classical model involving subduction of a wider and mature oceanic domain. Whatever the nature of the oceanic domain(s) and subduction in the Alps, the fact is that there is little evidence for a mature oceanic domain and Pacific-type subduction. Indeed, most of the rocks exposed in the Alps are derived from the former Tethyan margins (Fig. 1c).

At present, remnants of the Alpine Tethys margins are scattered along the Alpine belt, over an area that extends from the Carpathians to the Apennines and further southwest in the Tell, Betics and Rif regions of northern Africa. In this paper we focus on examples that are assigned to the Adriatic margin and exposed in the Austroalpine and south Penninic nappes of southeastern Switzerland and northern Italy; and on the other hand, on the former European margin exposed in the Western and Central Alps of W-Switzerland, SE France and NW Italy (Figs. 1c and 1d). The northeastern and southwestern terminations of the Alpine Tethys (Fig. 1a) are less well understood due either to a more complex rift evolution or a stronger overprint by the later, subduction-related, back-arc extension (Pannonian Basin, Gulf of Lyon and Tyrrhenian Sea; Schettino and Turco, 2011). The link between the rift structures and the later Alpine reactivation, as well as how remnants of the former rifted margin where emplaced and partly preserved in the Alpine nappe stack is not directly addressed in this study, and we refer to the studies by Mohn et al. (2011); Beltrando et al. (2014) and Epin et al. (2017) for further discussion. A review discussing the role of rift inheritance in building collisional orogens can be found in Manatschal et al. (2021).

A major, so far unresolved problem in describing the Alpine Tethys is linked to the difficulty in proposing robust paleogeographic and kinematic reconstructions. The main problem arises from the kinematics of the Iberia plate (Vissers & Meijer, 2012; Barnett-Moore et al., 2016; Nirrengarten et al., 2018) because different positions of the Iberia plate imply different widths of the Alpine Tethys. First, whether the magnetic anomaly M0/J in the southern North Atlantic

represents an oceanic magnetic anomaly is debated. If it is not, it cannot be used for restorations. Second, most of the rifting west and north of Iberia occurred during the Cretaceous magnetic superchron and is, therefore, not recorded in the magnetic tape recorder. More recent studies (Nirrengarten et al., 2017; Szameitat et al., 2020) showed that the M0/J anomalies in the southern North Atlantic did not form on "true" oceanic crust, and can therefore not be used for kinematic restorations. As a consequence, older restorations for the Alpine Tethys relying on the M0/J magnetic anomaly as an isochron (e.g., Handy et al., 2010; Vissers et al., 2012; Van Hinsbergen et al., 2014) must be taken with care. Here we use the interpretation of Decarlis et al. (2018), who suggested a segmentation of the Alpine Tethys into two sub-basins (Ligurian and a Piemonte), separated by a Jurassic transform system, like Handy et al. (2010) (Fig. 1a). Based on this assumption, the Grischun transect discussed in this paper (B''–B''' section in Figs. 1a and 1c) was part of the Piemonte segment of the Alpine Tethys and was conjugate to the southeast European margin currently exposed in Sardinia and Calabria (Costamagna, 2016). Although this hypothesis needs to be further confirmed, we note that it is consistent with reconstructions by Angrand et al. (2020) and Le Breton et al. (2020).

Historical overview

As pointed out by Şengör (2014), the Alps of Western Europe are likely the place where most new concepts on the formation of rift and oceanic domains and their emplacement in orogens have been developed (Fig. 2). Major steps in the evolution of the Alpine Tethys and the characterisation of paleogeographic domains were the pioneering works of Suess (1883; Fig. 2a), Steinmann (1905; Fig. 2b) and Argand (1916; Fig. 2c). Concerning the compressional reactivation, Bertrand (1884) and Haug (1892) were among the first to demonstrate the evidence of "nappes" in the Alps. Haug (1892) associated the emplacement of the nappes with the deposition of the Oligocene Flysch deposits. Termier (1899) then demonstrated that the Alps were formed by a stack of different "nappes". Haug (1909) and then Argand (1916) defined a succession of pre-nappe geosynclines and geanticlines in the Alps, which were the precursors of what we now refer to as rift basins and rifted margins. Haug (1909) also described the occurrence of breccias on the flank of the geanticlines, which he interpreted to result from submarine slumps that were interbedded with deeper marine sediments of the two neighbouring geosynclines.

The start of a more modern view of rifted margins was initiated in the 1960's with the studies of Elter and Lemoine (Figs. 2d and 2e). Lemoine (1961, 1967) reconsidered the ideas proposed by Haug (1909), and showed that the structure and related stratigraphy observed in the Alps resulted from Jurassic and Cretaceous extension. In the same period, Bernoulli (1964) mapped the first fault-bounded rift basin in the southern Alps (the Generoso Basin). Field observations from the Alpine Tethys were compared with the first DSDP drilling results in the Central Atlantic, other present-day rift basins, and seismic images of the Bay of Biscay (Montadert et al., 1979; Weissert & Bernoulli, 1985). With the advent and success of *Plate Tectonics*, it was generally accepted in the early 1980's that the Alpine Tethys was floored by "Penrose-type" oceanic crust and was flanked on both margins by latest Triassic to Late Sinemurian, fault-bounded rift basins (Lemoine et al., 1987; Eberli, 1988, Bertotti et al., 1993). As a consequence, stratigraphic contacts between mantle and sediments or between mid-crustal rocks and sediments, nicely described as "pre-Alpine" prior to Plate Tectonics (e.g., Steinmann, 1905;

Decandia & Elter, 1969; Dietrich, 1970; Trümpy, 1975), were reinterpreted as being Alpine (Hsü & Briegel, 1991). The fact that the ophiolites looked peculiar and did not fit into the classic three-layered, Penrose-type oceanic crust led the community to assume that they were heavily overprinted, destroyed or subducted during Alpine convergence.

It was only in the late 80's and early 90's, when serpentinized mantle rocks were drilled offshore Iberia (Boillot et al., 1987), and detachment systems were described in the Southwestern United States (Wernicke, 1985), that geologists started to reconsider previously reported field observations of exhumed mantle (Decandia & Elter, 1969, 1972; Florineth & Froitzheim, 1994; Lagabrielle, 1994) and detachment faults (Froitzheim & Eberli, 1990; Froitzheim & Manatschal, 1996). These concepts were reintroduced in the interpretations of the Alpine Tethys (Lemoine et al., 1987; Froitzheim & Eberli, 1990; Lagabrielle & Cannat, 1990) and applied to present-day "magma-poor" rifted margins (Whitmarsh et al., 2001).

The significant progress in understanding rifted margins accomplished during the last decades (e.g., 1990-2020) is intimately linked to the development of new, high-resolution seismic imaging methods and numerical modelling (Péron-Pinvidic and Manatschal, 2019). However, access to and comparison with field analogues (Whitmarsh et al., 2001; Lavier & Manatschal, 2006) were fundamental in establishing new concepts for rifted margins. Seismic imaging of entire rifted margins and attempts to model the way they form provided a first-order understanding of rift evolution. However, without drillhole data from deep-water rifted margins, which enabled us to compare the nature of contacts (unconformities or faults) as well as document ages and depositional settings of sediments, it would not have been possible to identify the processes occurring during the final stage of rifting, immediately prior to lithospheric breakup and seafloor spreading. Conversely, it would not have been feasible to establish new concepts on the tectono-stratigraphic understanding of rifting based on the fragmented observations derived from the Alps only. Thus, it was historically (and it is still) the combination of onshore and offshore geological studies that enabled development and constraints to be placed on new concepts for the processes occurring at higher ß-factors when extending the crust and/or lithosphere.

FROM DISPERSED OUTCROPS TO THE ARCHITECTURE OF THE ALPINE TETHYS

The Alpine Tethys margins have been partly accreted and subducted during the multi-stage Cretaceous and Tertiary Alpine compressional events. Thus, when referring to Tethyan margins in the Alps, we actually mean "remnants" of the former margins, now embedded in the Alpine nappe stack. Restoring the former margins of the Alpine Tethys relies on the one hand on the recognition of its remnants, and on the other on our ability to relocate them within the pre-Alpine rift template. Such a reconstruction is neither easy, nor is there a unique solution.

In the following section, we explain how to build a template for the Alpine Tethys margins. In particular, we describe: (1) the concept of "building blocks" (BB); (2) how to locate the BB in the spatial Alpine Tethys margin framework; and (3) how reliable the proposed template is and

what data are missing to improve and better constrain the understanding of the Alpine Tethys tectono-stratigraphic evolution. A major aim of this paper is to integrate the concepts and their derived terminologies used to describe the Alpine Tethys margins into a coherent language accessible to readers from different geological backgrounds, including those who are not familiar with Alpine geology. In order not to overwhelm the reader with local details, names of facies, structures or nappes that sometimes change across national or language borders, we mention them as sparingly as possible and refer to the original papers where the reader can find further details and explanations.

Datasets and building blocks

To restore the Alpine Tethys rifted margins, we define so-called "building blocks" (BB) (Fig. 3 and Tab. 1). BBs are ideally kilometre-scale outcrops, where primary rift relationships between basement rocks, fault structures and syn-rift stratigraphic levels are preserved. BBs provide therefore information about the: (1) nature of the basement (continental crust, exhumed mantle or fully magmatic crust); (2) depositional environments and stratigraphic thickness, and hence indications on accommodation, which can be used as a proxy for first-order crustal thickness by applying isostatic principles (e.g., Tugend et al., 2014); and (3) geometry and age of rift structures. In the Alps, seven types of BBs can be described. In the following, we refer to them as BB1, BB2, … BB7, and exemplify each one with one or several type-localities (Figs. 3a, 3d and 3e and Tab. 1).

BB1 (Fig. 3a and Tab. 1) displays classical tilted blocks and half graben bounded by high-angle, normal faults. Normal faults affect a 30 ± 5 km thick crust, including possible pre-rift sedimentary layers. The syn-tectonic deposits thicken and diverge towards the bounding faults, and the corresponding depocenter can be several tens of kilometres in width and several kilometres in depth (see dark blue layer in BB1; Fig. 3a). Crustal extension is typically low (ß < 1.5), and the total accommodation is minor, as indicated by the facies of the syn- and post-rift sediments, in line with a bathymetry remaining shallow to moderately deep (< 500 m). The type locality of BB1 is the Il Motto block in the Upper Austroalpine unit exposed near Livigno in northern Italy (Eberli, 1988) (Figs. 4d and 4e). Other examples are the Generoso Basin in the Southern Alps (Bernoulli, 1964) and the Bourg d'Oisans basins in the Western Alps (Lemoine et al., 1986). BB1 is the most classical building block of rifted margins and failed rifts. It has been extensively recognized and described from both intracontinental rifts and proximal rifted margins since the 1960's. (e.g., Gawthorpe & Leeder, 2000; Gupta et al., 1998).

BB2 (Fig. 3a and Tab. 1) shows crustal-scale shear zones typically juxtaposing upper and lower crustal levels via the attenuation of ductile crustal layers, responsible for major crustal thinning/necking. An example of BB2 is the Eita shear zone and Grosina detachment fault, exposed in the Middle Austroalpine Grosina/Campo Nappe at the Swiss-Italian border (Mohn et al., 2012; 2014) (Figs. 3d et 3e). The link between basement structures and the stratigraphic record is, however, not well constrained in this area. More recent studies in the Mont Blanc Massif (Western Alps; Ribes et al., 2020a) and in the Cusio-Biellese Zone (Southern Alps; Beltrando et al., 2015; Decarlis et al., 2018) both considered as examples of BB2 ((Figs. 3d et 3e), enabled to investigate the surface expression and its link to the sedimentary evolution during lithospheric/crustal necking. Both sites display evidence for mid-crustal basement exhumation linked to detachment faults, erosion and deposition of basement-derived material in shallow marine silicilastic sequences. The isostatic evolution recorded in the BB2 is complex

and suggests uplift, followed by rapid subsidence and sediment aggradation. The total accommodation and tectono-sedimentary evolution related to BB2 are yet little investigated and will be discussed in the accompanying paper (Chenin et al. same volume).

BB3 (Fig. 3a and Tab. 1) displays a major unconformity, also referred to as "the Briançonnais unconformity". This prominent syn-rift unconformity covers the tilted and eroded Triassic and lower Jurassic platform carbonates and is draped by upper Middle to Upper Jurassic pelagic carbonates. It is recognized throughout the Western and Central Alps in the so-called Briançonnais nappes (Lory 1860; 1866; Kilian, 1891; Haug, 1909; Debelmas, 1955; and Lemoine, 1961) and represents a major characteristic of the former distal European margin. Crustal thickness of this block is difficult to determine, but by comparison with present analogues, we reckon it to be 20 ± 5 km. BB3 is typically affected by high-angle faults with minor offset. The type locality of BB3 is the Fond Froid – Lac de l'Ascension area in the Briançonnais nappes (Figs. 4d and e), near the city of Briançon (southeastern France; Claudel and Dumont, 1999).

BB4 (Fig. 3a and Tab. 1) comprises successive, in-sequence long-offset extensional detachment faults responsible for exhumation of mainly upper crustal levels at the seafloor (for details see Epin and Manatschal, 2018). The exhumed basement is locally overlain by allochthonous fragments of upper crust and pre-rift and early syn-rift sediments. These structures are covered by syn-tectonic and post-tectonic deep-water sediments (for details see BB4 in Fig. 3a). The type-locality of BB4 is the Err-detachment system exposed in the Lower Austroalpine Err Nappe north of the Julier Pass (Figs. 4d and e) (e.g., Froitzheim & Eberli, 1990; Manatschal & Nievergelt, 1997; Masini et al., 2012; Epin & Manatschal, 2018). Another nearby example is the Bernina detachment system (Mohn et al., 2012) (Figs. 4d and e).

BB5 (Fig. 3a and Tab. 1) is the least known block and, in contrast to the others, it is not preserved in one single outcrop. A good description of the tectono-sedimentary relationships is given in Ribes et al. (2019b). The main characteristic of BB5 is the occurrence of major breccia bodies of Jurassic and/or Upper Cretaceous age that occur preferentially along the boundary between the Briançonnais and the Piemonte units, or in units that are interpreted to derive from the Valais basin (Fig. 4a). These breccias, first described by Haug (1909) and later by Lemoine (1961; 1967), were interpreted as related to one or more submarine slopes that resulted from either large faults or flexure. Ribes et al. (2019b) subsequently linked these breccias to submarine mega-fault scarps that are more favourably formed along an upper plate setting (Masini et al., 2013; Haupert et al., 2016; Ribes et al. 2019b). Type localities of BB5 are the Breccia Nappe in the Préalpes (Chessex, 1959; Badoux, 1962; Hendry, 1972; Weidman, 1972; Escher et al., 1993; Steffen et al., 1993) (Figs. 4d and e). Other examples are the Monte Galero breccia system (Decarlis et al., 2015) and the Falknis breccia (Ribes et al, 2020b).

BB6 (Fig. 3a and Tab. 1) displays tectonically exhumed serpentinized mantle capped by extensional detachment faults and ophicalcites, which are then overlain by deep-water, typically silica-rich sediments. The nature of the mantle is subcontinental (Mantle-type 1 of Picazo et al., 2016). The type locality is the Tasna ocean-continent transition (OCT) exposed north of Scuol in the Lower Engadin valley (Florineth & Froitzheim, 1994; Manatschal et al., 2006; Ribes et al. 2020b) (Figs. 4d and e). Other examples are the Upper Platta unit (Epin & Manatschal, 2018), Northern Lanzo (Kaczmarek & Müntener, 2008) or the External Ligurides (Marroni et al., 2002).

BB7 (Fig. 3a and Tab. 1) shows magmatic additions that form simultaneous to mantle exhumation along high- and low-angle faults (for detailed descriptions see Manatschal et al., 2011; Epin et al., 2019; Coltat et al., 2020). The exhumed, subcontinental mantle mantle is infiltrated, i.e., reacted with rift-related magma, but did not melt and is not genetically linked with the overlying basalts (Mantle-type 2 of Picazo et al., 2016). The OCT-basalts are related to incipient magma production (Amann et al., 2020). The first sediments overlying this domain are either tectono-sedimentary breccias reworking exhumed mantle, or radiolarian cherts (Ribes et al., 2019a). The type-locality is the Lower Platta Unit exposed in the Surses valley in Grischun (Demurs et al., 2001) (Figs. 4d and e). Other examples are the Chenaillet Ophiolite (Manatschal et al., 2011) (Figs. 4d and e), Southern Lanzo (Müntener & Piccardo, 2003) or the Internal Ligurides (Tribuzio et al., 2004).

Not all observations derived from field studies in the Alps are considered in terms of BBs, and yet they are important for the restoration of the former Alpine Tethys rifted margins. Examples include the discovery of a fossil Moho in the Malenco unit (Hermann et al., 1997), and lower crustal granulites linked to the intrusion of Permian gabbros in the Ivrea zone (Quick et al., 1992; Barboza et al., 1999) and in the Sondalo region (Petri et al., 2016). These exposures allowed us to understand the pre-rift crustal structure and inheritance as well as to better understand the pre-rift lithospheric conditions, to determine the basins exhumation history, and to assess the Pressure-Temperature-time (PTt) evolution of the basement rocks during rifting.

Building a spatial template for Alpine Tethys rifted margins

There are two ways to reconstruct a spatial template of the former Alpine Tethys margins. The first one is to restore the Alpine nappe stack back to its initial pre-orogenic state. This approach was first used by Argand (1916) (Fig. 2c), who was one of the first to consider a mobilistic view and to describe a succession of adjacent paleogeographic domains each one with a characteristic stratal record. More recently, Beltrando et al. (2014) and Epin et al. (2017) defined diagnostic criteria to recognize remnants of the former rifted margins in the Alpine orogen and discussed how they can be restored back to the pre-orogenic stage. However, these authors did not yet develop the BB approach proposed here. A second way to restore fossil rifted margins is to define a margin template based on isostatic considerations linked to geological observations (nature of basement, top-basement, sediments as well as depositional environments and sedimentary thickness; for a discussion of the approach see Tugend et al., 2014). This approach resulted in the definition of rift domains. Linking this approach with the average width of "modern" rift domains observed at present-day rifted margins (Chenin et al., 2017), and assuming that the processes generating the margins are roughly similar, allows us to place all the BBs of the Alpine Tethys conceptually along a modern margin template (red line profiles in Fig. 3a). The BB approach presented in this study enables us to add to the definitions of domains the key geological information that can be expected in each of the domains. By combining all these approaches we can use the observations made in the Alps to establish a more generic description of rifted margins and their evolution, a concept that will be used and tested in the accompanying paper (part 2) of Chenin et al., in volume).

BB1, the "tilted blocks", have been imaged since the 1970's in the proximal margin (Montadert et al., 1979). Until the late 1980's, the entire margin was assumed to be formed by such structures. Only with the discovery of exhumed mantle along the Iberia margin (Boillot et al.,

1987) made it clear that BB1 cannot explain the whole crustal structure of a magma-poor rifted margin.

Lemoine et al. (1987) was the first to propose the existence of extensional detachment faults in the Alps, but it was Froitzheim & Eberli (1990) who provided first field evidence for the occurrence of such structures that characterize BB4. From the 1990's onwards, the structures related to the former Adriatic margin in the Grischun transect (Figs. 1a and 3b) have been decrypted. Eberli (1988) and Froitzheim & Eberli (1990) demonstrated that the proximal and distal margins were controlled by different fault systems, namely pre-Sinemurian high-angle faults in the proximal margin and post-Sinemurian detachment faults in the distal margin.

Lemoine et al. (1987) and Froitzheim & Manatschal (1996) proposed that the Alpine Tethys margins had to be asymmetric based on the mapping of extensional detachment faults. Although Decandia and Elter (1969) had already mentioned the existence of exhumed mantle, Florineth and Froitzheim (1994) and Manatschal and Nievergelt (1997) presented field evidence for extensional detachment faults related to mantle exhumation in the Tasna and Platta nappes, which led to the definition of BB6 and BB7. Many studies had investigated the petrology of magmatic and mantle rocks (Piccardo et al., 1990; Rampone et al., 1995, 1997; Müntener et al., 2004), however the tectonic link between mantle exhumation along detachment faults and syn-magmatic activity was only evidenced by Desmurs et al. (2001) and Epin et al. (2019) for the Lower Platta unit (BB7), and by Manatschal and Müntener (2009) and Manatschal et al. (2011) for the Chenaillet Ophiolite.

While the existence of exhumed mantle and related structures have been described and generally accepted in the 1990's and early 2000's, the mechanisms of crustal thinning were, at that stage, still poorly understood. The first models suggested that crustal thinning was controlled by simple shear (Wernicke, 1985) and detachment systems (e.g., Lemoine et al., 1987; Froitzheim & Manatschal, 1996). It was only Mohn et al. (2012) who identified evidence for the necking process (BB2 fingerprints) based on field observations. Ribes et al. (2020) then described the tectono-sedimentary evolution of this block, highlighting how and when the crust underwent major crustal thinning.

Understanding and linking crustal thinning (BB2), mantle exhumation (BB6), and uplift and subsidence of the future distal margin (BB3) during the evolution of the Alpine Tethys rifting became possible thanks to the use of numerical modelling (Chenin et al., 2019, 2020). Finally, to link massive breccia-bodies with rift models and define corresponding BB5, a detailed tectono-stratigraphic investigation of the distal European margin was necessary (Ribes et al., 2019b). Thus, it took more than 50 years to find and define the BBs, the combination of which led to restore the first-order architecture of the Alpine Tethys margins.

Eventually, geologists identified and described BB's all over the Alps; however, it was only in the Grischun transect (Figs. 1a and 3b) that the relative spatial template of the different blocks could be directly restored by kinematic restoration of the Alpine nappe stack (Epin et al., 2017). This exceptional preservation is due to the fact that all of the Adriatic margin remained in the upper plate of the Alpine subduction and that it was most-likely located against a major pre-Alpine transform system (the paleo-Insubric line of the peri-Adriatic system; Fig. 4a) (Manatschal & Nievergelt, 1997; Mohn et al., 2011; Epin et al. 2017). Indeed, in the Grischun transect, five out of seven of the BBs have been identified in the nappe stack, each one in a different nappe (Figs. 4d and e). The restoration of the nappe stack back to the pre-Alpine stage

(for details see Epin et al., 2017) enabled us to put the building blocks back to their relative positions, with BB1 in the Ortler Nappe belonging to the proximal margin, BB2 in the Grosina-Campo Nappe belonging to the necking zone, BB4 in the Err-Bernina Nappes belonging to the hyperextended domain, and BB6 in the Upper Platta Unit and BB7 in the Lower Platta Unit belonging respectively to the inner and outer part of the exhumed mantle domain (Fig. 3b). The restoration of this nappe stack enabled us to assess the spatial distribution of these BBs across the margin, but not to establish the detailed continuity and dimensions of the margin along strike.

Concerning the European margin of the Alpine Tethys (Figs. 4d and e), BB1 occurs in the proximal margin exposed in the Western Alps (Bourg d'Oisans). BB3, BB5 and BB6 in the distal margin units exposed within the Penninic Nappes, and BB7 in the Chenaillet Ophiolite. Remnants of BB5, the least understood BB, are preserved all along the Central and Western Alps at the distal position of the Briançonnais domain and include the Falknis Breccia, the Breccia Nappe, and the Monte Gallero Breccia (Decarlis et al., 2015; Ribes et al., 2019b). A comprehensive restoration like that proposed for the Grischun transect is, however, not possible for the European margin. The reason is that this margin has been more heavily affected by multi-stage Alpine deformation. Indeed, most of the former distal parts of the European margin were either subducted or destroyed during the Alpine collision. Moreover, the change in kinematics from N-S to E-W-directed convergence renders the restoration of the nappe stack in the Western Alps difficult (Rosenbaum et al., 2002).

From 2D sections to a map view of the Alpine Tethys margins

In order to reconstruct the three-dimensional architecture of the Alpine Tethys rift system, the lateral continuity of the margins must be integrated. This requires us to first determine the extent of distinct rift domains along dip (proximal, necking, hyperextended and exhumed mantle/proto-oceanic domains (Fig. 3a)), and then to correlate and map them along strike. If we assume that the width/scales of the Alpine margins are comparable to those of present-day rifted margin domains (Chenin et al., 2017), we can also hypothesize paleogeographical maps and sections of the former margins, and locate the BBs in such sections/maps in future studies.

A next step is to determine whether or not the rift system was segmented, and if so, to locate the position of the main transfer zones. BB3 and BB5, which are characteristic of an upper plate margin (hanging wall of the main extensional detachment system during hyperextension; e.g., Haupert et al., 2016), are missing in the Grischun transect. This, together with the polarity of exhumation faults (BB4; i.e., location of fault breakaways and transport direction), leave little doubt that the distal part of the Grischun transect belongs to a lower plate margin (footwall of the main extensional detachment system during hyperextension; Epin & Manatschal, 2018). Based on an evaluation of the distribution of BB3, which is diagnostic for an upper plate margin, Decarlis et al., (2018) proposed a change in the polarity from an upper- to a lower-plate margin across a transfer fault that correspond to the Peri-Adriatic Insubric system. This observation enabled us to define a pinpoint along the Adriatic margin, which can be linked to the corresponding pinpoint on the conjugate European margin. Unfortunately, this pinpoint has not yet been located on the European margin, which makes a restoration of the Alpine Tethys non-unique for the time being. Our preferred view, which needs however to be confirmed by future studies, is that the conjugate pinpoint lies at the southern limit of Sardinia and corresponds to the paleo Iberia-European plate boundary. In such an assumption, the conjugate of the Grischun

lower plate transect would correspond to the Sardinia-Calabria section (Fig. 4). If correct, the Sardinia-Calabria section would represent an upper-plate margin. Furthermore, following this model, the Southern Alps and the Apennine (former Southern Adria margin), would correspond to an upper plate margin and be conjugate to the Ebro/Balearian (lower plate) margin during Jurassic rifting (Fig. 4a).

THE SYN-RIFT TECTONO-STRATIGRAPHIC RECORD OF THE ALPINE TETHYS

With the BB approach explained in the previous chapter, it is possible to locate outcrops back into the spatial template of the former Alpine Tethys margins. Some outcrops give access to rocks derived from different pre-rift crustal and mantle levels, and thus provide information on the thermal, spatial and isostatic evolution of the rift system. Such information is recorded by the petrological, thermochronological and stratigraphic data., which enable us to: 1) define the conditions and timing of crustal thinning, mantle exhumation and onset of magma production, 2) characterise the type of mantle and magma involved, and 3) describe the different spatial isostatic/bathymetric evolution of rifting. In this section we describe how the tectono-stratigraphic record of some of the key outcrops can help unravelling the chronostratigraphic, structural and isostatic evolution of rifting.

The stretching phase recorded in the proximal domains (BB1)

The former proximal domains of the Alpine Tethys margins are preserved in the Dauphiné and Helvetic nappes on the European margin, and in the Upper Austroalpine nappes and Southern Alps on the Adriatic margin (Fig. 1). These domains are characterized by numerous half-graben basins (Fig. 4c), some of the most emblematic are described below.

The Bourg d'Oisans Basins (Figs. 4d, 4e and 5a) located at the European margin include three tilted blocks, namely from west to east the La Mure, the Taillefer and the Grandes Rousses. These basement blocks are bounded by master faults, the best exposed and described being the Ornon normal fault east of the Taillefer Block (Fig. 5a). The Ornon Fault had an approximate throw of 1500 m (Barféty, 1985) and largely controlled the formation of a c. 15 km-wide half-graben. Chevalier et al. (2003) showed that diffuse extension initiated along numerous small faults with limited throw and low stain-rate between the Hettangian and the Sinemurian, and that these structures were widely distributed across the entire future proximal domain. Extension then localized in Early Sinemurian, and most of the 1500 m throw was rapidly accumulated along the single Ornon fault linked to a fast tectonic subsidence (Fig. 5a). Similar to the other neighbouring half-graben basins, the syn-rift sedimentary record of the Bourg d'Oisans Basin grades from thin and shallow marine platform deposits on fault block crests, to thick and deeper (locally detrital) basinal deposits made of interbedded calcarenites and hemipelagic to pelagic marls towards the master fault. Based on lithofacies and faunas, the inferred maximum bathymetry of these European half graben depocenters was about 100-250 m. Their tectono-stratigraphic architecture revealed that they remained underfilled, an interpretation supported by the local occurrences of olistoliths made of pre-rift and basement rocks next to normal fault scarps. During the Sinemurian–Pliensbachian, rifting ceased throughout the future proximal European margin, and the major rift faults were sealed. At that

time, depositional depths increased to 250–400 m in basins that record the subsequent progradation of carbonate platforms from late to post-rift times (Chevalier, 2002).

The Il Motto Basin (Figs. 4d, 4e and 5b) was located at the former northern proximal Adriatic margin. This basin is one out of several fault-bounded rift basins exposed in the Upper Austroalpine Ortler Nappe (Eberli, 1988). It exposes a high-angle master fault bounded by a half-graben extensional basin preserving the relationships between the pre-, syn- and post-tectonic sediments (Eberli, 1987; Froitzheim, 1988; Conti et al., 1994; Ribes et al., 2019a). The syn-tectonic sediments are made of Early Jurassic megabreccias that grade upsection and away from the master fault into finer breccias and then calciturbidites. The megabreccias include reworked carbonates sourced from the emerged and eroded pre-rift cover of the adjacent fault scarp. It is important to note that the absence of clastic sedimentation implies that basement rocks were never exposed and reworked at this stage in the syn-rift sediments. The syn-tectonic sediments are interleaved with hemipelagic carbonates and shales dated as Early Hettangian to Late Sinemurian (Furrer, 1985; Eberli, 1985; 1988). The master fault is sealed by ammonite-bearing carbonates dated as Late Sinemurian to Early Pliensbachian. A younger marker horizon, corresponding to the Toarcian Oceanic Anoxic Event (T-OAE; 183 Ma) occurs within the post-tectonic sequence (Ribes et al. 2019a). Lithofacies, faunas and ichnofacies recorded in background sediments indicate water depths in the range of 50–200 m during rifting, and deeper conditions (several hundreds of meters) during the post-tectonic phase (Eberli, 1987). Thus, the environments remained relatively shallow even after rifting, compared to the future distal margins. The overall thinning- and fining-upward sequence is interpreted to reflect both an aggradation-dominated setting (instead of a prograding fan), a progressive decrease of redeposited sediments with respect to background sedimentation and a starvation of the sedimentary system, most likely related to a deepening of the setting, and because the Adriatic micro-continent became disconnected from continent-derived sedimentary sources (Eberli, 1987).

The Monte Generoso Basin (Figs. 4d, 4e and 5c) is one of several rift depocenters that have been identified on the former southern Adriatic proximal margin. These depocenters formed from Norian time onward; however, major normal faults began to separate half-graben and 30–50 km wide horsts only during the Rhetian (Bernoulli, 1964; Bertotti et al., 1993). For the best-investigated Monte Generoso Basin, Bertotti (1991) showed that its master fault (the Lugano-Val Grande fault zone) penetrated basement and soled out at mid-crustal levels. Since the whole domain has not been significantly thickened during Alpine convergence, the present crustal thickness may not be much thicker than at the end of rifting. Thus, the Generoso Basin is likely to have formed over a crust that was > 25 km thick. Rifting was linked to hemipelagic and pelagic sequences, interleaved with calciturbidites, which were deposited with typical *half-graben related, wedge-shaped* architecture. These sequences include spongolitic, calcarenite and mud-rich turbidites with deepening upward facies, as well as megabreccias and olistoliths in the vicinity of major fault scarps. Tectonic activity decreased drastically during the Sinemurian and ceased during the Pliensbachian.

In summary, the syn-tectonic sedimentary record in the Bourg d'Oisans, Il Motto and Monte Generoso Basins displays wedge-shaped deposits from latest Triassic to Sinemurian–Pliensbachian time. In the temporal framework of the Alpine Tethys rifting, this corresponds to the early syn-rift history referred to as *the stretching phase*. From Pliensbachian–Toarcian time

onward, the three basins and their surrounding proximal domains recorded passive infill, i.e., the upper part of the syn-rift has a post-tectonic depositional geometry. The proximal domains, however, continued to subside but remained at relatively shallow water conditions, suggesting that the underlying curst remained relatively thick, i.e., likely > 25 km.

The necking phase recorded in the necking/distal domains (BB2 & BB3)

The necking phase has been described in the Mont Blanc region (Ribes et al., 2020a) on the European margin, in the Cusio–Arona region in the Southern Alps (Beltrando et al., 2015) and in the Austroalpine Campo–Grosina nappe (Mohn et al., 2010). However, since there is no sedimentary record in the latter, it will not be further described. All these domains are located between the proximal and distal domains of the Alpine Tethys margins. The syn-rift stratigraphy of the necking phase is also preserved in the Briançonnais domain near Briançon, and at the Sostegno-Fenera region in the Biellese in Northern Italy. Below we discuss the syn-necking evolution of the different sites.

The Mont Blanc region (Figs. 4d, 4e and 6a) has been interpreted to preserve the necking domain of the former European margin (Masini et al., 2013; Ribes et al., 2020a). In contrast to more proximal regions that display half-graben deposits, the syn-rift record of the necking domain is more complex. The pre-rift (Triassic) and early syn-rift (Lower Jurassic) sediments are either lacking, or are discontinuous and occur as allochthons. In the past, the lack of the pre- and early syn-rift sediments was interpreted to result either from non-deposition, or from post-depositional uplift and erosion. Where present, pre- and early syn-rift sediments were assumed to represent the primary autochthonous sedimentary cover of the Mont Blanc Massif (Landry, 1978). More recently, Ribes et al. (2020a) emphasized that the basement of the Mont Blanc is locally topped by pre-Alpine black gouges and cataclasites. They suggested that these rocks indicate the presence of a major extensional detachment fault, which would be responsible for the exhumation of the Mont Blanc granite and polymetamorphic basement to the seafloor. In this interpretation, the Mont Blanc Massif corresponds to a core complex domal structure linked to the tectonic creation of a new depositional surface, referred hereafter as “new real estate”. The extensional detachment system has also been interpreted to be responsible for crustal thinning (for examples see Mohn et al., 2012 and Ribes et al., 2020a). Exhumation is best documented by early to mid-Jurassic siliciclastic sediments, the so-called *Grès Singuliers*. These sediments rework the above-mentioned gouges/cataclasites and underlying basement, and unconformably overlie the basement. Laterally, they overly conformably Lower Jurassic carbonates (Ribes et al., 2020a). Note that the siliciclastic *Grès Singuliers* are surrounded by a depositional setting that is dominated by carbonates (Trümpy, 1971). Nevertheless, the detrital zircon provenance analysis reported in Ribes et al. (2020a) indicates that the *Grès Singuliers* are locally sourced from the Mont Blanc and Aiguilles Rouges basement. Evidence for several cycles of erosion and re-sedimentation within these deposits indicate a complex depositional environment and explain the relative maturity of sandstones, despite the local sourcing. This is in line with a significant tectonic exhumation and sub-aerial exposure of the local basement during the necking phase. Additionally, sedimentary structures found in the *Grès Singuliers* testify to a tidal influence, which further supports a shallow marine depositional environment (Fig. 6a). The local siliciclastic source for the *Grès Singuliers* became inactive from the Toarcian–Aalenian onward, either due to the cessation of the Mont Blanc extensional detachment, and/or to the drowning of the European necking zone (Ribes et al., 2020a). The

559 overlying Middle- and Upper Jurassic syn-rift deposits are post-tectonic (i.e., deposited in a
560 non-tectonic setting; see Part 2 by Chenin et al., same volume, for definition and discussion of
561 syn-rift vs. pre/syn/post-tectonic). These post-tectonic deposits correspond to progradational
562 and aggradational carbonate platforms indicating that the area subsided, although the overall
563 crust remained thick enough to support shallow marine conditions on the proximal part of the
564 necking domain. In contrast, on the distal part, a major deepening is documented by the
565 occurrence of either thicker Upper Jurassic to Early Cretaceous post-rift sediments, or by the
566 occurrence of deep-water turbidites. A comparable situation can be found all along the external
567 massifs in the Western Alps.

568 ***The Cusio–Biellese region (Fig s. 4d, 4e and 6c)*** lies in Northern Italy at the transition between
569 the proximal and distal southern Adriatic margin. This region displays a complex syn-rift
570 stratigraphic record that was interpreted by Beltrando et al. (2015) and Decarlis et al. (2018) to
571 be linked to crustal necking. In this region, Sinemurian shallow-marine carbonates and
572 sandstones (the so-called San Quirico Sandstone) unconformably overlie a karstified Triassic
573 platform in the west (Sostegno and Fenera) and basement in the east (Gozano and Lavorio;
574 Berra et al., 2009; Beltrando et al., 2015). The analysis of the San Quirico Sandstone indicates
575 that it has been sourced from a local basement (Permian volcanic rocks and Variscan
576 metamorphic basement), suggesting basement emersion in the Cusio–Biellese region. The
577 occurrence of zircon grains with fission track ages of 177 ± 6 Ma in the San Quirico Sandstone,
578 with a depositional age of Late Pliensbachian to Toarcian (~ 182 Ma), suggests that the
579 deposition of this sandstone was contemporaneous with basement exhumation (Beltrando et al.,
580 2015). This observation is similar to observations made in the *Grès Singuliers* at Mont Blanc
581 (see previous section; Fig. 6a) and suggests that the Cusio-Biellese region necking may also
582 have been linked with the development of extensional detachment faults and core complex
583 structures. Although such structures have not yet been identified in the Cusio–Biellese region
584 due to poor exposure, the fission track ages suggest tectonic exhumation associated with erosion
585 (Decarlis et al., 2018). The surrounding depositional environment remained shallow-marine,
586 and no coeval sub-aerial uplift of the more proximal parts are reported during the necking stage,
587 ruling out the possibility of long-wavelength dynamic topography (Flament et al., 2013). It is
588 also important to note that the whole domain is sealed by post-tectonic carbonates of
589 Pliensbachian age (Berra et al., 2009; Decarlis et al., 2017). This shows a complex stratigraphic
590 record of the syn-necking depositional sequence. This sequence is characterized by an
591 unconformable base and a conformable boundary with the overlying post-tectonic sediments.

592 ***The Briançonnais domain (Fig s. 4d, 4e and 6b)*** belongs to the distal part of the European
593 margin. During the necking stage, this domain was part of the keystone (H-block) before its
594 delamination and fragmentation between the two margins (Lavier & Manatschal, 2006; Masini
595 et al., 2013; Haupert et al., 2016). Restorations of this domain suggest that it was several tens
596 of kilometres wide and extended over several hundred kilometres along strike. Early Jurassic
597 emersion is documented by a regional unconformity and karstification of pre-existing shelf
598 carbonates, resulting in a major, regional, syn-rift stratigraphic gap (De Graciansky et al., 2011).
599 This stratigraphic unconformity contrasts with the continuous sedimentary record of the
600 adjacent areas, which were subsiding at this time (Claudel & Dumont, 1999; Decarlis & Lualdi,
601 2008). The onset of emersion occurred at the earliest during the Sinemurian, which is the age
602 of the youngest marine carbonates affected by the karst (Tricart et al., 1988). Drowning of the
603 Briançonnais domain started at the latest during the late Bathonian (~ 165 Ma), since shallow

marine carbonates of this age locally overlie the karst (Claudel & Dumont, 1999). Due to the existence of widespread pelagic limestones of Callovian age (~164–161 Ma) draping the entire Briançonnais domain, rapid drowning and deepening was commonly assumed (e.g., Claudel & Dumont, 1999; De Graciansky et al., 2011). More recently, however, Haupert et al. (2016) suggested that drowning may have started earlier but was not recorded because passive infill was restricted to the lows on either side of the Briançonnais High. The pelagic nature of the sediments draping the Briançonnais domain does not necessarily indicate a fast subsidence and/or a deep water, since pelagic sediments can be deposited in relatively shallow water depth (below wave base) on isolated highs disconnected from sedimentary sources. The regionality of the Jurassic karst, and the consistent nature and age of the overlying sediments, suggest that both emersion and drowning were, from a geological timescale perspective, largely synchronous over the entire Briançonnais domain and occurred during the necking phase.

In summary, the observations from the Mont Blanc Massif and the Cusio–Biellese region and the Briançonnais domain show that: 1) the base of the syn-tectonic sequence is conformable over the proximal domain, whereas it is unconformable in the necking domain where core complexes formed (e.g., new real estate over the necking domain) and over the syn-rift karst capping the Briançonnais High (BB3); 2) the necking domains and the keystone (H-block) between them were local regions of either siliciclastic deposits (sandstones) due to local sub-aerial exhumation of basement rocks going along with erosion/deposition, or karstification of the pre-rift carbonate platform; 3) water-depth remained relatively shallow during the necking phase and the thickness of related syn-tectonic sediments is therefore limited; and 4) the transition into the overlying post-tectonic sediments is conformable where sedimentation rates remained high, and unconformable where starvation occurred due to the fast subsidence post-dating necking.

The hyperextension phase exposed in the distal domains (BB4, BB5 and BB6)

Exposures of the former hyperextended and exhumed mantle domains of the European margin occur in the Sub-, Lower- and Middle Penninic nappes, and the Pre-Piemonte units, which are, except the Tasna OCT (Ribes et al. 2020b), strongly overprinted by Alpine deformation. In contrast, the distal domains of the former Adriatic margin are much better preserved and are exposed in the Lower Austroalpine Err and Bernina Nappes, and the South Penninic Upper Platta Unit (Epin et al., 2017). In the western Southern Alps, there are some exposures in the Canavese Zone that may represent remnants of the former hyperextended margin (Beltrando et al., 2014; Decarlis et al., 2017). Due to the complex, segmented margin architecture, the along-strike distribution of the hyperextended domain is complex, in particular along the European distal margin. For instance, former studies suggested that the Valais Basin formed during Cretaceous rifting, simultaneous with the Bay of Biscay (Frisch, 1979; Stampfli, 1993; Handy et al., 2010), despite a Jurassic age of the basin was already proposed by Steinmann (1994) (for details see Pfiffner, 2014). A Jurassic age for the Valais Basin is supported by the syn-tectonic sediments in this basin that are Middle Jurassic and mantle exhumation dated late Middle Jurassic (Ribes et al. 2020b). In this study we propose that the Valais Basin formed as a segmented, en-echelon, hyperextended basin simultaneous with the Ligurian and Piemonte basins. In a subsequent stage (after the late Middle Jurassic) these basins connected, giving birth to the Alpine Tethys proto-oceanic domain (for paleogeographic evolution see Fig. 4).

The Tasna OCT (Figs. 4d, 4e and 7a) exposes a well-preserved relict of the most distal part of the European margin (western edge of the Briançonnais continental ribbon) and its transition into the exhumed mantle domain of the former Valais Basin (Trümpy, 1980). The Tasna Nappe was intensively studied by Florineth & Froitzheim (1994), Manatschal et al. (2006), and more recently revisited by Ribes et al. (2020b). The Tasna OCT preserves upper- and lower, pre-rift continental crust that is juxtaposed along an extensional detachment, the Upper Tasna Detachment. It is noteworthy that middle crustal material is missing in this section (Ribes et al. 2020b). Continent-wards (i.e., towards the Briançonnais in this area), a stratigraphic interface can be defined between the upper crust, made of a polymetamorphic Variscan basement, and pre-rift Triassic dolostones, and Lower Jurassic syn-rift limestones. This succession is part of a block that is interpreted to represent an extensional allochthon (e.g., Fig. 4 in Ribes et al. 2020b). Oceanwards (i.e., towards the north), the top basement is strongly tectonized and covered with tectono-sedimentary breccias including clasts of Triassic dolomites and of the underlying, exhumed basement. Top basement is therefore interpreted as a detachment fault surface (Ribes et al., 2020b). Two main detachment faults have been identified: the Upper Tasna Detachment between the lower crust and upper crust, or lower crust and syn-tectonic sediments where the upper crust is lacking; and the Lower Tasna Detachment between mantle and the base of the lower crust, or the mantle and syn- or post-tectonic sediments where the mantle was exhumed to the seafloor (Florineth & Froitzheim, 1994). The first post-tectonic sediments deposited onto the syn-rift tectono-sedimentary breccias throughout the Tasna OCT are dark shales. They are locally interbedded with sandstone beds that also seal the allochthon block located further south in the section. The syn-tectonic sediments are interpreted to be late Lower Jurassic to Upper Jurassic (Ribes et al., 2020b). This is in line with Ar/Ar cooling ages yielding an age of 170.5±04 Ma obtained from phlogopites. These phlogopites are derived from a spinel websterite from within the mantle lying in the footwall of the Lower Tasna Detachment (Manatschal et al., 2006, see also the discussion in Ribes et al. 2020b).

In the nearby Falknis nappe, which has been interpreted to sample the continent-ward continuation of the Tasna OCT (i.e., the Briançonnais platform), massive breccias interfinger with syn-rift sediments in the Tasna OCT, and are therefore interpreted as contemporaneous (Ribes et al., 2020b). These breccias were interpreted to reflect the long-lasting existence of a mega-fault scarp that is characteristic for an upper-plate margin (e.g., BB5; Ribes et al. 2019b). The breccias are also interlayered with a starved sediment horizon, comprised of radiolarian cherts, which marks the termination of rifting. It also suggests deep depositional environments (below the Carbonate Compensation Depth) at the end of rifting in the Tasna OCT.

The Bernina and Err Nappes (Figs. 4d, 4e and 7b) preserve the most distal part of the North-Adria margin. The Err Nappe was the first place in the Alps where rift-related detachment faults were discovered (Froitzheim & Eberli, 1990). The Err detachment system was subsequently studied by Manatschal & Froitzheim (1996), Manatschal & Nievergelt (1997), Masini et al. (2011, 2012), Epin et al. (2017) and Epin & Manatschal (2018). A second major detachment system has been described in the Bernina nappe and was referred to as the Bernina detachment system (Mohn et al., 2011, 2012). The Err detachment system is made of at least four, in-sequence detachment faults (namely the Err, Jenatsch, Agnel and Upper Platta detachment faults), whose length and size of associated breakaway blocks decrease oceanward (Epin & Manatschal, 2018). The last detachment is responsible for mantle exhumation exposed in the Upper Platta Unit. The detachment faults are characterized by diagnostic black gouges and green cataclasites (Manatschal, 1999), which separate the massive, little deformed but hydrated

basement (continental crust or subcontinental mantle) in the footwall either from allochthonous blocks of continental crust and/or pre-rift sediments, or from late syn- to post-rift sediments (Masini et al., 2012). These detachment faults reached the seafloor at low angles (< 15°), as shown by the low angle between the exhumation surface and the overlying sediments (Epin & Manatschal, 2018; Fig. 7b). The lack of quartz mylonites along the detachment fault suggests that deformation occurred in the brittle regime, at relatively low temperature (< 300 °C; Manatschal, 1999). Crustal basement exhumed in the Err Nappe corresponds to pre-rift upper crust, pre-rift lower crust has not been reported so far.

The Err detachment system is characterized by a discontinuous record of pre-rift sediments, complex, discontinuous syn-tectonic sedimentary deposits, and continuous post-rift sediments (Masini et al., 2012; Epin et al., 2017; Ribes et al. 2019a). The tectono-stratigraphy of the syn-tectonic sediments is well preserved in the so-called Samedan Basin (Masini et al., 2011, 2012; Epin & Manatschal, 2018). In this basin, pre-rift sediments are only found as allochthonous blocks overriding a detachment fault (e.g., Bardella allochthon; Fig. 7b). Based on structural and stratigraphic relationships, and structural restorations of Alpine sections, Masini et al. (2011) suggested that the Samedan Basin initiated as a classical half graben basin. Continued extension on the high-angle fault led to its flattening and to the exhumation of deeper basement levels. At this stage, the initial high-angle fault had become an extensional detachment fault whose inactive portion lied at a low-angle to the seafloor. In such an example, the syn-tectonic sediments were deposited directly onto exhumed basement (new real estate). Those sediments are composed of siliciclastic, basement-derived, immature and locally derived breccias that directly overlie the detachment system (e.g., member A of the Saluver Fm. of Finger et al., 1978). In contrast, the sediments near the hanging wall block are exclusively made of carbonate breccias sourced from the adjacent allochthonous block (e.g., Bardella Fm.; Fig. 7b). The different composition of the coeval early syn-tectonic sediments have been interpreted to reflect a change from hanging wall-derived breccias composed of Triassic pre-rift carbonate clasts to footwall-derived breccias made of basement clasts as the result of the exhumation of basement rocks along the detachment fault flooring the basin (Masini et al., 2011). These sediments are overlain by a succession of fining- and thinning-upward turbiditic deposits that grade upwards into hemipelagic sediments and radiolarian cherts, recording sediment starvation and deepening of the basin once detachment faulting locally stopped (for details see Masini et al., 2011).

The Canavese zone in northern Italy preserves remnants of the distal part of the South-Adria margin. Although the sedimentary record of the Canavese zone is poorly exposed and was largely dismembered during the Alpine orogeny, its similarity with that of the Err nappe prompted Ferrando et al. (2004) to interpret it as an equivalent distal part (hyperextended domain). It was subsequently studied by Decarlis et al. (2013) and Beltrando et al. (2015). Recently, Decarlis et al. (2017) suggested, based on tectono-stratigraphic and paleo-geomorphological studies, that the Canvese zone belongs to an upper plate margin, and thus that it would be more comparable with the Tasna OCT. The Canavese displays two types of exhumed basement: an amphibolite-grade basement with shallow intrusions of Permian granitoid, interpreted as pre-rift upper crust; and a migmatitic basement with mafic granulite intrusions, recognized as a pre-rift lower crust (Ferrando et al., 2004). The Middle Jurassic syn-tectonic sedimentary deposits include both matrix-supported breccias dominated by basement clasts and matrix-supported breccias rich in Triassic dolostone clasts. Both facies overly tectonized, exhumed basement covered with tectono-sedimentary breccias (Ferrando et al.,

2004). Middle Jurassic breccias are overlain by Middle- to Late Jurassic radiolarian cherts (Bill et al., 2001). Thus, the overall observations show similarities to the Tasna OCT.

In summary, Falknis-Tasna and Err-Bernina display a comparable tectono-sedimentary record controlled by extensional detachment faults. While Err-Bernina belong to a lower plate margin, Falknis-Tasna are part of an upper plate margin (Fig. 7c). However, it is important to note that these sites were not conjugate although the may have belonged to the same margin segment (Fig. 4). All sites presented here display: 1) dismembered pre-rift and early syn-rift sediments only preserved in allochthonous and breakaway blocks; 2) exhumed basement along extensional detachment faults overlain by syn-tectonic tectono-sedimentary breccias containing clasts of the underlying exhumed basement; 3) evidence for deepening and starvation, which we here link to the hyperextension phase. Apart from these similarities, there are also some differences. In the Bernina-Err example (Figs. 7), which belongs to a lower plate margin (Epin & Manatschal, 2018), detachment faults cut from the upper crust directly into mantle and the lower crust is missing. In contrast, at the upper-plate margins (e.g., Tasna OCT and Canavese), lower crustal rocks are exhumed (Fig. 7c).

The proto-oceanic domains of the Alpine Tethys (BB7)

Remnants from the proto-oceanic domain are found all along the Alpine belt in the South Penninic units that constitute the Alpine suture (Fig. 1c). The best-preserved exposures of the proto-oceanic domain, that escaped subduction and a related high-pressure metamorphic overprint, are exposed in the Lower Platta Unit in SE-Switzerland and in the Chenaillet Ophiolite in the French-Italian Alps (Fig. 8).

The Lower Platta unit (Figs. 4d, 4e and 8a) belongs to the south Penninic units exposed in SE-Switzerland. It samples an exhumed mantle domain that includes magmatic additions. This domain can be restored back to the northern Adriatic distal margin. It was extensively studied by Dietrich (1969), Manatschal & Nievergelt (1997), Desmurs et al. (2001, 2002), Schaltegger et al. (2002), Münetner et al. (2004), and more recently by Epin et al. (2017, 2019), Coltat et al. (2019a, 2019b, 2020) and Amann et al. (2020). The Platta Nappe can be subdivided into two units based on their lithology, namely the Upper- and Lower Platta Units (Desmurs et al., 2002) (Fig. 8c). The Upper Platta Unit corresponds to the most proximal part of the exhumed mantle domain. It is comprised of inherited subcontinental lithospheric mantle with minor magmatic additions, and a few overlying continental allochthons. In this study, we consider it as part of the hyperextended domain (Epin & Manatschal, 2018). In contrast, the more distal Lower Platta Unit is made of (re-)fertilized mantle, i.e., a mantle that reacted with percolating magma (for details see Müntener et al., 2004), with an increasing volume of intrusive and extrusive magmatic bodies oceanward (Fig. 8c). It also preserves remnants of a proto-Oceanic Core Complex (OCC; Epin et al., 2019). The entire exhumed mantle domain is characterized by intense hydrothermal fluid activity and precipitation of metalliferous mineralization (Coltat et al., 2019a, 2019b). Extensional structures found in the lower Platta Unit are characterized by polyphase extensional detachment faults, truncated by late, high-angle normal faults (Fig. 8c; Epin et al., 2019; Coltat et al., 2020). They include serpentinite cataclasites and serpentinite gouges, topped by ophicalcites and overlain by tectono-sedimentary breccias, which are typical fingerprints of Jurassic detachment faults (Epin et al., 2017). An idealized section through the footwall of a Platta detachment fault includes, from base to top (see Fig. 8a section 1): (1)

783 foliated massive serpentinized peridotite or gabbro; (2) serpentinized peridotite or gabbro
784 cataclasites marked by fractures and veins filled with syn-kinematic chlorite and serpentinite;
785 the intensity of cataclastic deformation increases upward, passing into (3) serpentinite gouges
786 (fault core).

787 The first sediments overlying the detachment surface are tectono-sedimentary breccias and
788 ophicalcites (see section 3 in Fig. 8a; Desmurs et al., 2001; Epin et al., 2019). The latter form
789 in a post-exhumation stage at low temperature (< 100–150°C), except where they are overlain
790 by basalts resulting in higher formation temperatures (see section 2 in Fig. 8a; Coltat et al.,
791 2020). The next sedimentary sequence (see Fig. 8b sections 2 and 3) is made of red clays and
792 radiolarian cherts that include also hydrothermal cherts and reworked, continent-derived
793 material. These sediments are dated Bajocian to Kimmeridgian in the Alpine Tethys (Bill et al.,
794 2001; Baumgartner, 2013). The upper part of the radiolarian cherts overlies, and thus post-dates
795 the basalts and tectono-sedimentary breccia in the exhumed mantle domain. The basalts that
796 show a T-MOR composition (Desmurs et al., 2002), also referred to as OCT basalts by Amann
797 et al. (2020), have been interpreted to be syn-tectonic based on the observation of basalts
798 thickening into high-angle faults and basalts that are deformed during mantle exhumation (Epin
799 et al., 2019; Coltat et al., 2020) (see also sections 2 and 3 in Fig. 8b).

800

801 ***The Chenaillet Ophiolite (Figs. 4d, 4e and 8b)*** displays pillow lavas with a MORB signature
802 overlying mafic plutonic rocks and serpentinized subcontinental mantle (Mantle type 2, i.e.,
803 refertilized mantle of Picazo et al., 2016). The first tens to hundreds of meters of the exhumed
804 mantle are affected by brittle deformation and pervasive hydrothermal circulation. Pillow lavas
805 are undeformed, implying they were emplaced after mantle exhumation, during a subsequent
806 phase of high-angle normal faulting (Manatschal et al., 2011) (see observation at Cima le Vert;
807 Fig. 8b). Manatschal et al. (2011) suggested that these faults served as feeder channels for the
808 extrusives. The first observed sediments overly the exhumed mantle and/or intrusive mafic
809 rocks (see observation at La Loubatière; Fig. 8b). They include breccias, graded sandstones and
810 siltstones that are exclusively made of mantle-derived materials, and to a lesser extent gabbro-
811 and continent-derived material. Rare basaltic clasts are found in these sediments, which were
812 emplaced by gravitational processes over the exhumed mantle. This implies formation of
813 topography during mantle exhumation similar to present-day OCC at mid ocean ridges
814 (MacLeod et al., 2009). At the Chenaillet Ophiolite, syn-magmatic sediments are rare, apart
815 from hyaloclastites and subordinate siliciclastic sediments that are interbedded within the
816 volcanic sequence (Masini, pers. com). No younger, Upper Jurassic to Upper Cretaceous post-
817 rift sediments are described.

818 In summary, the tectono-sedimentary record of the Lower Platta Unit and the Chenaillet
819 Ophiolite, both preserving remnants of proto-oceanic crust, shows that: (1) mantle exhumation
820 was achieved via slip on successive extensional detachment faults later affected by high-angle
821 normal faults; (2) topography was created during mantle exhumation and resulted in
822 gravitational sedimentation; (3) the late normal faults may have served as feeder channels for
823 the overlying volcanic sequences; (4) no pre-rift or early syn-rift deposits exist in the exhumed
824 mantle domain; and (5) the first syn- to post-magmatic sedimentary deposits (radiolarian cherts)
825 show the importance of fluids (hydrothermal cherts), reworking (distal turbidites and/or
826 contourites), and pelagic sedimentation (radiolarites).

READING THE TECTONO-STRATIGRAPHIC TAPE RECORDER OF THE ALPINE TETHYS

A Wheeler diagram for the Alpine Tethys margins

In this section we describe the syn-rift mega-sequence within a margin-scale Wheeler diagram, which is an excellent tool to represent the tectono-sedimentary evolution during the entire rift event (Fig. 9). Ribes et al. (2019a) subdivided the syn-rift mega-sequence into four tracts, the stretching-, necking-, hyperextension-, and proto-oceanic tracts. In order to compare our results to seismic sequences from present-day rifted margins, we use here tectonic sequences (TS) that replace the "tracts" terminology previously proposed (for definition and discussion of TS, see accompanying paper by Chenin et al., same volume). Each TS encompasses all the sediments deposited during the period of activity of the corresponding rift phase. Thus, it represents a chronostratigraphically significant package of sediments related to a distinct phase of the basin evolution. Each TS includes syn- and post-tectonic packages that are diachronous along the margin, the former linked to faults, the later sealing faults or showing passive infill of rift-related relief. Using this approach allows us to describe the sedimentary development during rifting and to link the kinematic evolution to sediment deposition. This approach relies on the stratigraphic tape recorder to describe the evolution of rifting from incipient rifting to final break-up. The first prerequisite is that sediments can be attributed to a specific rift domain, a second is that a time frame for the different rift events, faults, TS, and magmatic additions can be defined. However, in contrast to present-day margins where timelines (reflective horizons in a reflection seismic section) can be followed from the proximal towards the distal parts, in the case of the Alps, this time frame is more difficult to establish. For the Grischun transect (Fig. 3b), Ribes et al. (2019a) proposed global or regional events that can be used as timelines to correlate across the margin. These lines are the Rhaetian (base of the syn-rift sequence, ~200Ma), the Toarcian Oceanic Anoxic Event (~185Ma), the Bajocian-Bathonian bio-Siliceous Event (~165Ma) and the Tithonian Carbonate Event (~155Ma). It is, however, important to note that the tectonic events are not necessarily synchronized with these time markers.

In this paper, we use the following ages for the successive rift phases in the Alpine Tethys domain that are based on the studies of Masini et al. (2013) and Ribes et al. (2019a): 200±5 Ma for onset of rifting, 185±5 Ma for necking; 175±5 Ma for onset of hyperextension along the distal margin, 165±5 Ma for onset of tectono-magmatic accretion in a proto-oceanic domain. Ages may in fact differ between the various rift segments of the Alpine Tethys. Here we mainly refer to the central, i.e., the Piemonte segment. It is important to note that the age of onset of hyperextension is ill-defined. Note also that we define only the onset of mantle exhumation, but not the onset of seafloor spreading, since in the Alpine Tethys there is no direct evidence for steady-state seafloor spreading.

Apart from the time frame, we also need to insist on the definition of syn-rift vs. syn-tectonic that is exemplified within our Wheeler diagram. Syn-rift corresponds to the time between onset and end of rifting, in our example between 200 ± 5 Ma and 165 ± 5 Ma (Fig. 9). Syn-tectonic corresponds more specifically to a sedimentary sequence that is deposited during extension and involving syn-fault deposition. In contrast, pre-tectonic and post-tectonic refer to sediments that are deposited during the syn-rift time interval, but that precede or post-date active faulting in a given place. Another important notion introduced already before, but fundamental to the understanding of the Wheeler diagram shown in Fig. 9, is the concept of "*new real estate"*. It

refers to newly created surfaces offered to potential deposition, which are either due to tectonic exhumation along extensional detachment faults or related to accretion of new oceanic crust. Introducing "new real estate" is a major modification to the classical Wheeler diagrams used in basin analysis, and has major implications for the description of the time-space relation between the stretching, necking, hyperextended and proto-oceanic tracts (for more details see Chenin et al. this volume). In the Wheeler diagram shown in Fig. 9, we also represent the seven BBs. For the proto-oceanic tract, we also include the extrusive magmatic additions that were the main syn-tectonic depositional sequence.

Linking the tape recorder with the rift evolution

Rift onset in the western Tethys realm is difficult to define, since rifting nucleated in different areas at different times: in the east and south (Meliata/Vardar) during the Permo-Triassic, in the Alpine Tethys at the end of Triassic, and in the southern North Atlantic/Pyrenean domain in the Late Jurassic-Early Cretaceous (Figs. 1b and 4). In this study we focus on the Alpine Tethys and more precisely, the Piemonte segment.

During the stretching phase (latest Triassic to late Sinemurian/early Pliensbachian: 200 ± 5 to 185 ± 5 Ma), extension was distributed over a wide area, i.e., from the Cevennes in France to the Trento-plateau in Northern Italy, with the development of many half-graben/graben (e.g., Bourg d'Oisans, Generoso and Il Motto Basins; Fig. 10d). All these depocenters were bounded by listric normal faults that were at a high angle in the upper crust and are interpreted to sole out in the middle ductile crust (see Bertotti, 1991). The total amount of extension accommodated during this event may have been minor. Considering the Alpine Tethys, Bertotti et al. (1993) calculated ß values of 1.22 for this stage. Even if some basins may have accommodated several kilometres of syn-tectonic sedimentary deposits, the overall crustal thinning remained moderate and widely distributed.

The necking phase initiated during the late Sinemurian to early Pliensbachian (185 ± 5 Ma). It was associated with the cessation of distributed extension, local uplift of the future distal domain, and subsequent localization of extension and fast subsidence (Fig. 10c). This evolution resulted in a complex stratigraphic record of the necking stage recorded by the necking TS. Local uplift, some few hundreds of meters at maximum, and first occurrence of exhumation faults on both sides of a keystone (H-Block) resulted in major unconformities that are recorded at the transition between the proximal and future distal margins (Mont Blanc at the European margin and Cusio–Biellese and Campo-Grosina at the Adriatic margin). Uplift of the domain in-between, the so-called Briançonnais domain, can also be observed, resulting in a major unconformity that can be mapped along the margin and that is of necking age. Numerical modelling suggests that necking-related uplift occurs when the upper lithospheric mantle, considered as the strongest layer within the lithosphere, yields beneath a little-thinned continental crust (Chenin et al., 2019, 2020). This event is followed by a flexural rebound that can potentially lead to the emersion of formerly marine regions. In the Alps, this event occurred after the Late Sinemurian and before the Toarcian, i.e., most likely during the Pliensbachian (18 5 ±5 Ma). As a consequence, the base of the necking TS is characterized by a conformable contact over the proximal domain that seals the stretching phase faults, and an unconformable contact over the future distal parts of the margin (for example see the Bardella allochthon, Fig. 7b). The top is either conformable or, in sediment-starved margins like the Alpine Tethys, paraconformable due to a delayed passive infill (onlaps on rift-related residual topography).

The hyperextension phase (Fig. 10b) is well documented in the Lower Austroalpine Err and Bernina Nappes, which belong to the distal northern Adriatic margin, and in the Tasna OCT, which belong to the distal European margin. These domains are formed by a crustal wedge that is interpreted to taper to zero due to the action of in-sequence extensional detachment faults that propagate towards the future site of breakup. Hyperextension was the only rift phase during which deformation was clearly asymmetrical, resulting in an upper and a lower plate margin. At this stage, the entire rifted area was subsiding. While the proximal parts, which were tectonically inactive, subsided thermally, the distal parts are interpreted to have subsided due to a combination of crustal thinning (tectonic subsidence) and thermal equilibration (thermal subsidence). The successive in-sequence detachment faults that developed during the hyperextension phase rooted in the mantle and eventually led to the exhumation of mantle to the seafloor (Fig. 10b). Hyperextension and mantle exhumation occurred during and after the Toarcian anoxic event, but before the deposition of the radiolarian cherts, namely in the 180 to 165 Ma time interval. Sedimentation occurred simultaneous to fast subsidence, resulting in a general deepening of the depositional environments. While in the lower plate margin breccias are mainly linked to exhumation faults flooring the hyperextended basins, the upper plate margin shows massive breccia-bodies linked to long-lived mega-fault scarps lying between the residual keystone block (BB3) and the hyperextended domain (BB5) (Ribes et al. 2019b; Figs. 3a and 7c).

The proto-oceanic phase (Fig. 10a) initiated with the first extrusion of magma that post-dates initial mantle exhumation. Both are intimately related with extensional faulting (detachment and high-angle normal faults) and hydrothermal activity. Recent studies show that the first exhumed mantle at the tip of a magma-poor margin is the subcontinental lithospheric mantle that was underlying the pre-rift continental crust (mantle-type 1 of Picazo et al., 2016). In more advanced stages of exhumation, deeper parts of the subcontinental mantle can be exhumed (mantle-type 2 of Picazo et al., 2016). This type of mantle shows two important features: i) it was depleted; i.e., it melted during the Permian (e.g., Rampone et al., 1998; Müntener et al., 2004; McCarthy & Müntener, 2015) and/or showed inherited depleted heterogeneities (Tribuzio et al., 2004; Sanfilippo et al., 2019); and ii) it was infiltrated by magma during subsequent rifting (e.g., Rampone et al., 1997, 2020; Piccardo *et al.*, 2004, 2007; Müntener et al., 2010). In the Alpine Tethys, mantle exhumation was associated with minor magmatic activity, sometimes interpreted as embryonic seafloor spreading (Manatschal & Müntener, 2009; Manatschal et al., 2011; Epin et al., 2019; Jagoutz et al., 2007; Lagabrielle et al., 2015). The magma-poor nature of the Alpine Tethys OCT may have originated due to Permian depletion (Chenin et al., 2017), which was linked to a massive magmatic event throughout Western Europe following the Variscan orogenic collapse (Bonin et al., 1998; Petri et al., 2017 cum references). The Jurassic rift-related infiltration may have been protracted, with a magmatic plumbing system that built from the base of the lithosphere to the top. It is assumed to have initiated with asthenospheric melt infiltration at ca. 185 Ma and to have reached the surface with first magma extrusions (basalts) and shallow intrusions (gabbros) at about 165 Ma (Desmurs et al., 2001, 2002; Schaltegger et al., 2002). Recent studies on the first basalts (Renna et al., 2018; Amann et al., 2020) showed a complex magmatic evolution during the mantle exhumation phase, partially controlled by the inherited mantle lithosphere composition. At present, there is no evidence that the Alpine Tethys developed a mature, steady-state spreading system (Picazo et al., 2016). The radiolarian cherts that are dated from Bajocian to Kimmeridgian (Bill et al., 2001) were deposited during the accretion of the proto-oceanic

domain. These sediments formed at deep marine conditions below the calcite compensation depth and are time equivalent to pelagic, but not necessarily very deep sediments on the more proximal parts of the sediment-starved Adriatic microcontinent.

Rift phases and their stratigraphic record

Observations from the Alpine Tethys presented in this paper clearly show that the syn-rift stratigraphic record is complex and cannot be explained by the simple, monophase rift model proposed by McKenzie (1978). The Alpine Tethys stratigraphic tape recorder shows evidence for an abrupt switch from distributed (stretching) to localized (necking) deformation during the Sinemurian/Pliensbachian (185 ± 5 Ma). In contrast, precisely identifying the transition from necking to hyperextension in time and space is difficult in the Alpine system, while the transition is spatially well defined at present rifted margins where the crust is thinned to less than 10 km and the whole crust is in the brittle domain (Sutra et al., 2013; Nirrengarten et al., 2016). Pinto et al. (2015) showed that a characteristic of the hyperextension phase is the occurrence of mantle-derived fluids percolating faults and sediments and leaving a geochemical signature. Another major switch occurs when magma becomes the dominant phase, which in the Alpine Tethys occurs in the Bathonian to Callovian (165 ± 5 Ma) and coincides with the proto-oceanic phase.

Link between rift phase and tectonic sequences

A major conclusion of this paper is that each of the four rift phases results in a distinct syn-tectonic sedimentary record and can be described by the four successive stretching-, necking-, hyperextension- and proto-oceanic TS (see also accompanying paper by Chenin et al. this volume). The reason is that during each phase accommodation is created in a different way (Fig. 10). The stretching TS is linked to the accumulation of sediments showing characteristic syn-tectonic, wedge-shaped architectures in distributed fault-bounded basins (Fig. 10d). The subsequent necking, hyperextension and proto-oceanic TS (Figs. 10c to 10a) have been little investigated so far, but show diagnostic features reflecting their distinct structural and isostatic evolution. The necking phase is characterized by a localization of extension simultaneous to local uplift of a keystone and along hinge zones, and formation of exhumation faults at both extremities, shortly followed by fast subsidence. As a consequence, the necking tract has an unconformable base, accommodation is controlled by the interplay of detachment faults and uplift/subsidence in disconnected and transient depocenters, and its top is conformable if sedimentation rates are high. The hyperextension tract forms in a rapidly subsiding basin during in-sequence stepping of extensional detachment faults towards the site of future breakup. As a consequence, this tract is post-tectonic over the future proximal margins, the syn-tectonic sequence is stepping ocean-wards on the lower plate but remains stationary over the location of exhumation in the upper plate. Horizontal accommodation results from the formation of new real estate and vertical accommodation from rapid subsidence. This combination of the simultaneous creation of vertical and horizontal accommodation results in banana-shaped sequences often referred to as “sag” basins in the present-day hyperextended magma-poor rifted margins. The proto-oceanic TS is more complex, often sediment-starved, and includes syn-tectonic magma emplacement. The most characteristic observation is that of flip-flop faults create highs and lows, which lows becoming highs during subsequent stages. This explains two

main observations: 1) detachment faults are truncated by younger high-angle faults, and 2) the occurrence of breccias and debris flows at the break away of younger faults, i.e., over highs.

Link between deformation and the syn-rift stratigraphic record

A key in controlling the way accommodation is created (i.e., horizontal vs. vertical) is the geometry of faults. This geometry depends on the bulk crustal/lithospheric rheology, which in turn controls the strain localization, and hence shape and width of crustal necking zones (Chenin et al., 2018b). However, stratigraphic architecture depends also on the availability of sediments and the relation between sedimentation and extension rates. In the Alpine system, sedimentation during early rifting was controlled by carbonates and thus not controlled by a significant siliciclasitc source. Locally, basins may have been disconnected and a local-derived siliciclastic source evolved (e.g., *Grès Singuliers* in the example of the Mont Blanc system; Fig. 6a). During hyperextension, gravitational processes resulted in the deposition of breccias, debris flows and turbidites. In the case of the Adriatic margin, distal parts were not fed from the continent, and pelagic and hemipelagic sedimentation, together with reworking of exhumed mantle and magma emplacement, became the dominant depositional processes. It is important to mention that the Alpine Tethys example is sediment starved and underfilled. The fill of a humid clastic run-off dominated basin could look very different as discussed in Part 2 by Chenin et al. (this volume).

From a structural point of view, two main ways of accommodation creation can be envisaged. Either by listric, concave-upward normal faults or by concave-downward extraction/detachment faults (Wilson et al., 2001; Mohn et al., 2012; Petri et al., 2019). While the first fault type creates fault-bounded basins, the latter fault type results in the creation of new real estate. In this case, basins become both deeper and wider with increasing extension, with syn-tectonic sediments directly overlying new real estate (Wilson et al., 2001; Gillard et al., 2015). It is also important to determine how faults are linked to local flexure and regional isostasy, which define not only the morphology of top basement, but also the relative timing between extension and the creation of accommodation. During the stretching phase accommodation was created mainly by faults, whereas post-rift thermal subsidence was of minor importance. This is what can be seen in the stretching domain in the proximal margins of the Alpine Tethys. During the subsequent necking phase, the morphotectonic evolution was complex and controlled by the formation of a keystone (for a description see Chenin et al., 2019, 2020), but, on the scale of the rift system, it was symmetric. Examples of this stage are documented in the Mont Blanc and Briançonnais areas along the European margin, and in the Cusio–Biellese region on the Adriatic margin (Fig. 6). During the following hyperextension stage, however, the morphotectonic evolution of the two conjugate systems was very different. On the lower plate margin (northern Adria), accommodation was controlled proximaly (proximal/inner) by thermal subsidence while distally (distal/outer) it was controlled by the formation of new real estate between breakaway blocks and extensional allochthons (e.g., Epin & Manatschal, 2018) (Fig. 7). In contrast, the upper plate showed formation of mega-fault scarps, which were linked to the formation of prominent and long-lasting mega-breccias and gravitational systems that faced oceanward a domain of new real estate (see the 2 settings of type-2 basins in Fig. 5 of Masini et al., 2013). As a consequence, these breccias interfinger with deep marine sediments at their tips (see Fig. 9 in Ribes et al., 2019b). Some of the breccias may also have been deposited over exhumation faults and were moved away and were disconnected from their source on the conjugate margin (see Fig. 8 in Epin et al., 2019). Examples are the

Bernina-Err systems or the lower plate and the Falknis-Tasna for the upper plate setting (Ribes et al., 2019b) (Fig. 7c). During the formation of the proto-oceanic domain, the system returned to a more symmetric state and detachment faults showed an interplay between exhumation and high-angle faulting (Manatschal et al., 2011). This deformation phase, which is observed in the Platta nappe (Epin et al., 2019), is reminiscent of that observed at slow spreading mid-ocean ridges (Sauter et al., 2013; Cannat et al., 2019).

Syn-tectonic fluids and their link to rift evolution

Little attention has been paid so far to fluids and their link to the rift evolution and realted syn-rift sediments. Pinto *et al.* (2015) and Incerpi *et al.* (2017, 2020) showed that the nature of fluids was intimately linked to hydrothermal activity during Alpine Tethys rifting. Incerpi *et al.* (2020) showed that the fluid signature changed from the necking to the hyperextension phase. During the necking stage, marine-derived fluids interacted with crustal rocks resulting in Si-rich fluids. Pinto et al. (2015) showed that during the hyperextension phase, marine-derived fluids circulated along faults down into the exhuming mantle and ware channelled back to the seafloor along detachment faults, forming kilometre-scale hydrothermal cells. These fluids interacted with the serpentinizing mantle and transported mantle-derived V, Cr, Ni along faults back to the seafloor. This is well-documented by enrichment of fault rocks and the overlying syn-tectonic sediments in these mantle-derived elements (Pinto et al., 2015). Coupling the fluid history with the diagenetic evolution of the syn-rift sediments, as proposed by Incerpi et al. (2020), may not only enable us to define the depositional setting and the rift domain in which a sediment has been deposited, but also to use new techniques, such as U-Pb on cements to date the age of syn-tectonic sequences. Moreover, potential links between the widespread development of siliceous sediments and organisms, i.e., radiolarite, and tectonic exhumation and related Si-rich fluids may exist (Pinto et al., 2017).

ALONG STRIKE VARIABILITY OF THE ALPINE TETHYS RIFT SYSTEM

Our description of the Alpine Tethys rift system and of its evolution is mainly based on a few building blocks (BBs), most of which are located in the central Piemonte segment of the Alpine Tethys (Figs. 1a and 4). However, this 2D view underscores the non-cylindricity and 3D complexity of the Alpine Tethys, which can be regarded from different scale perspectives.

From a large-scale perspective, the Alpine Tethys is only one out of at least three rift systems, referred to as *Meliata/Vardar/E-Mediterranean, Alpine Tethys*, and *Iberia/Pyrenees/Bay of Biscay* (Fig. 1b). The spatial overlap of these multistage rift systems makes it difficult not only to determine the timing of rift onset in individual areas, in particular where such systems overlap, but also to unravel the subsidence history, since the post-rift of one stage can correspond to the pre-rift of the next stage. An example is, for instance, the thick Triassic dolostones in the Adria and Briançonnais domains, which are syn- to post-rift with respect to the Meliata/Vardar, but pre-rift with respect to the Alpine Tethys (violet sediments in Fig. 10e). Other examples are the Cretaceous extensional systems that are linked to the Pyrenean phase of rifting, which overlap Jurassic rift domains in the European margin (Tavani et al., 2018). At present, the partitioning of extension between these rift systems remains little constrained since no undisputed data exist on the width, rates, or the detailed kinematic movements of any of

these interacting systems. Our preferred view is that the Alpine Tethys rifting initiated during the latest Triassic (200 ± 5 Ma) and stopped in the Late Jurassic time as a failed, approximately 300 to 400 km-wide, proto-oceanic domain (Li et al. 2013).

At the scale of the Alpine Tethys, three segments can be distinguished, the *Ligurian*, *Piemonte* and *Valais* basins (Figs. 1a and 4). Thermochronological and stratigraphic data suggest that these basins may have started to become well-defined structural entities during the Sinemurian/Pliensbachian (Fig. 4b), and may have merged into a unique, proto-oceanic or oceanic domain, which is referred to as the Alpine Tethys, during the Callovian/Bathonian (Baumgartner, 2013) (Fig. 4a). However, many questions remain open, especially about the southern Ligurian domain. To date, it remains unclear whether this basin had a Triassic precursor basin and if it was linked to the eastern Mediterranean, as suggested by its thick and locally deep Triassic sequences (Speranza et al., 2012). The Alpine Tethys rift system may have had overstepping accommodation zones, similar to what has been proposed for the Cretaceous basins in the Pyrenean domain (Lescoutre & Manatschal, 2020). The formation of continental ribbons such as the Briançonnais, separating two V-shaped hyperextended domains that were set up as overstepping accommodation zones and merged during breakup, may be a reasonable explanation. This hypothesis remains yet to be confirmed by field data. However, it is interesting to note that in the Biscay and Pyrenean domains, rift segment centres of hyperextended basins are often completely reactivated (subducted). In contrast at rift segment boundaries rift structures remain preserved in the mountain belt. This has been explained by thrusts forming shortcuts to link one segment to another (Lescoutre & Manatschal, 2020; Manatschal et al., 2021). This may explain why the best-preserved rift structures occur on both sides of the Peri-Adriatic system (e.g., Insubric line that is the boundary between an upper and a lower plate; Decarlis et al., 2017) or are linked to the Briançonnais block. In any case, whatever the actual architecture of the Alpine Tethys looked like, it was clearly not cylindrical. The relationships between the Ligurian and Piemonte segments of the rift system appear, in contrast, simpler and seem to coincide with the paleo-Insubric transfer system.

The complex paleogeography of the former Alpine Tethys rift system is not very different from that observed at many Atlantic margins. The paleogeography of the Alpine Tethys rift system has important implications on how and where sediments were transported into the deep margins (e.g., Ribes et al., 2019b). The segmented paleogeography of the Alpine Tethys can partly explain why the Alpine terminology is so complex and the paleogeographic domains cannot be correlated along the Alps in a simple way. Thus, most of the controversies based on correlations between Alpine units and domains may be solved, or at least better defined, when the complex pre-Alpine paleogeography and segmentation are better understood.

THE SYN-RIFT STRATIGRAPHIC ARCHITECTURE OF THE ALPINE TETHYS: AN OUTLOOK

The Alps have been the origin of many ideas and concepts presently used not only in orogenic belts, but also at rifted margins (De Graciansky et al., 2011). Long before rifted margins were seismically imaged, Alpine geologists proposed that the sediments were deposited in large basins, first called geosynclines, and later rift basins. Research over the past decades show that the Alps are not so much influenced by the subduction of an oceanic domain, but more by the reactivation of former rifted margins. Research on rifted margins has mainly been triggered in the last years by the energy industry and the related progress in reflection seismic imaging and numerical modelling. However, the Alps have played a critical role in the latest development of understanding distal rifted margins with the discovery and description of the hereby described "building blocks" / BBs, their integration in a margin template and the access of a data set and observations that are not accessible at present-day rifted margins. This enabled us to develop a model to describe the tectono-stratigraphic evolution of a magma-poor rifted margin. A prerequisite for such a model is to integrate time into a spatial reconstruction. This can be done by relying on two types of data. On one hand, petrological and thermochronological data provide insight into the PTt path of basement rocks. On the other hand, sedimentary deposits act as a tape recorder of the evolving deformation and depositional environments. Whenever timelines can be identified throughout the margin, they give insight into the migration of deformation through time along the margin (e.g., Ribes et al., 2019a). In addition, with the development of the BB approach it was possible to build generic sections across margins. As each BB represents a "frozen" structural template with specific structural, stratigraphic, thermochronological and petrological characteristics, the comparison between the different BB characteristics provides insights into the temporal evolution of the entire rift system. This methodology enabled Masini et al. (2013) and Ribes et al. (2019a) to demonstrate the migration of rift activity from the future proximal margins towards the future distal margins, and to point out the onset of rifting in the Alpine Tethys domain, the crucial moment of necking, and the timing of first magma-production in the exhumed domain. Moreover, it allowed them to identify different rift phases, and to define rift domains and the specific time periods during which they formed.

However, the study of rifted margins worldwide, in particular of their distal parts, is notoriously limited by the lack data. While many high-resolution 3D seismic blocks of distal margins became recently available to researchers, and although numerical modelling is able to reproduce some of the key rift structures in 2D and/or 3D, the access to samples from these domains remains the biggest issue. Deep-sea drilling is expensive and remains exceptional; where available, it is generally restricted to structural highs, rarely transecting deep depocenters and/or penetrating the underlying basement. Therefore, a major asset for research on rifted margins in the Alps is the possibility to put specific outcrops into the framework of a present-day rifted margin, to further calibrate the new models and to make predictions of how the new concepts can be used to make projections from well calibrated proximal to undrilled distal domains. However, there are also limitations to the extent the Alpine Tethys can be used to compare with other margins. Future research will need to better define the 3D spatial framework and temporal development of rifting processes. This includes the semi-quantitative analysis of vertical and horizontal movements during rifting, the characterization of the successive deformation events, and the recognition of related depositional systems. Part II of this review (Chenin et al., this volume) will build on observations and concept derived from the Alps to propose a more generic model that will then be tested/discussed using global examples of present-day rifted margins.

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Charlotte Ribes: Writing – review & editing, Conceptualization, Investigation
Emmanuel Masini: Writing – review & editing, Conceptualization, Investigation

Data Availability Statement:
Data sharing is not applicable to this article as no new data were created or analyzed in this study.

FIGURE CAPTIONS

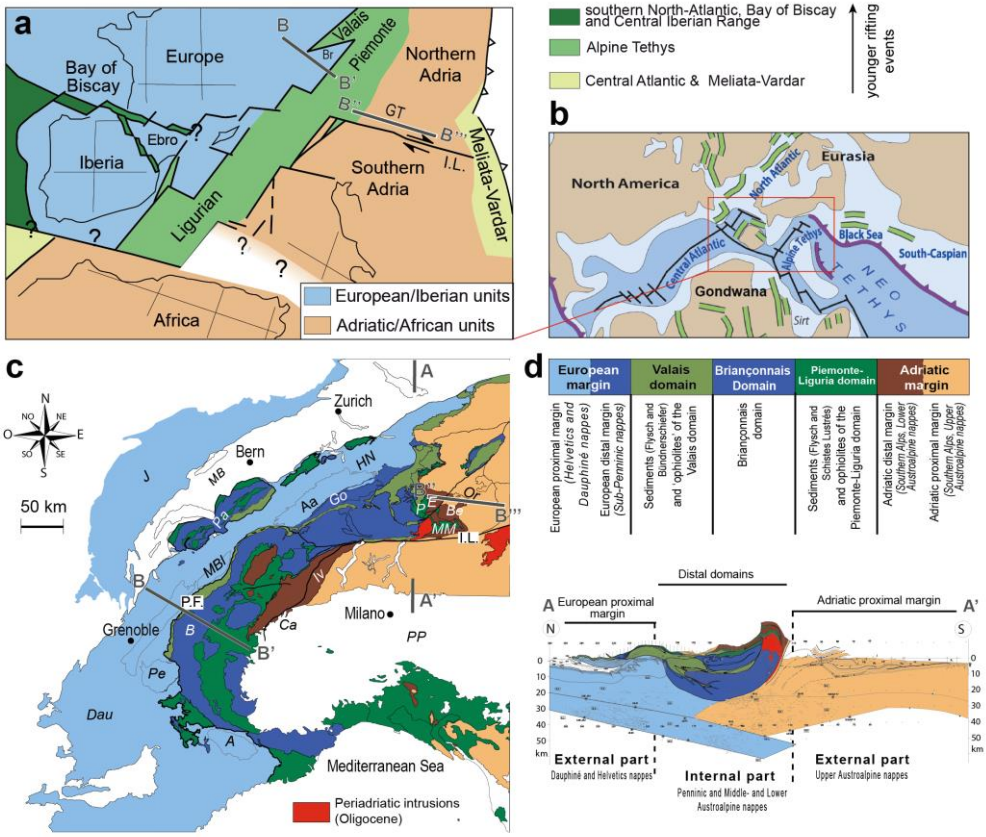


Fig. 1. (a) Schematic paleogeographic map of the Tethys – Atlantic domain during Early Cretaceous showing three main rift-systems (Meliata-Vardar; Alpine Tethys (Liguria, Piemonte, Valais); and southern North Atlantic with the Bay of Biscay-Pyrenean and Central Iberian Range) and surrounding major plates (Africa and Europe) and microplates (Iberia, Ebro, Southern Adria and Northern Adria) (modified after Manatschal and Müntener, 2009). (b) Paleogeographic map of the western Tethys and Central and North Atlantic system during Early Cretaceous (modified after Frizon de Lamotte et al., 2015). The red box shows the outline of the area shown in Fig. 1a. (c) Tectonic map of the Alps in Western Europe showing the distribution of the main paleogeographic rift domains of the Alpine Tethys in the Alpine orogen (modified after Schmid et al., 2004). (d) Interpretation of the NFP 20 seismic section across the Central Alps showing the position of the main paleogeographic rift domains in the Alpine section (modified after Schmid et al., 1996). For location of the section A-A' see (c). The B–B' and the B''–B''' transects correspond to sections across the former European margin and the Grischun transect (GT) across the northern Adria margin that will be presented in Figs. 3, 9 and 10. Note that these two transects are not conjugate margins but are interpreted to belong both to the Piemonte rift segment. Abbreviations used in Fig. 1: A: Argentera Massif, Aa: Aar Massif, B: Briançonnais Nappes, Be: Bernina Ca: Canavese Nappe, Dau: Dauphiné Nappes, E: Err Nappe, Go: Gotthard Massif, HN: Helevetic Nappes, Iv: Ivrea, J: Jura, MB: Molasse Basin, MBl: Mont Blanc Massif, MM: Malenco-Margna Nappes, Or: Ortler Nappe, P: Platta Nappe, Pa: Prealps, Pe: Pelvoux Massif, PP: Po Plain.

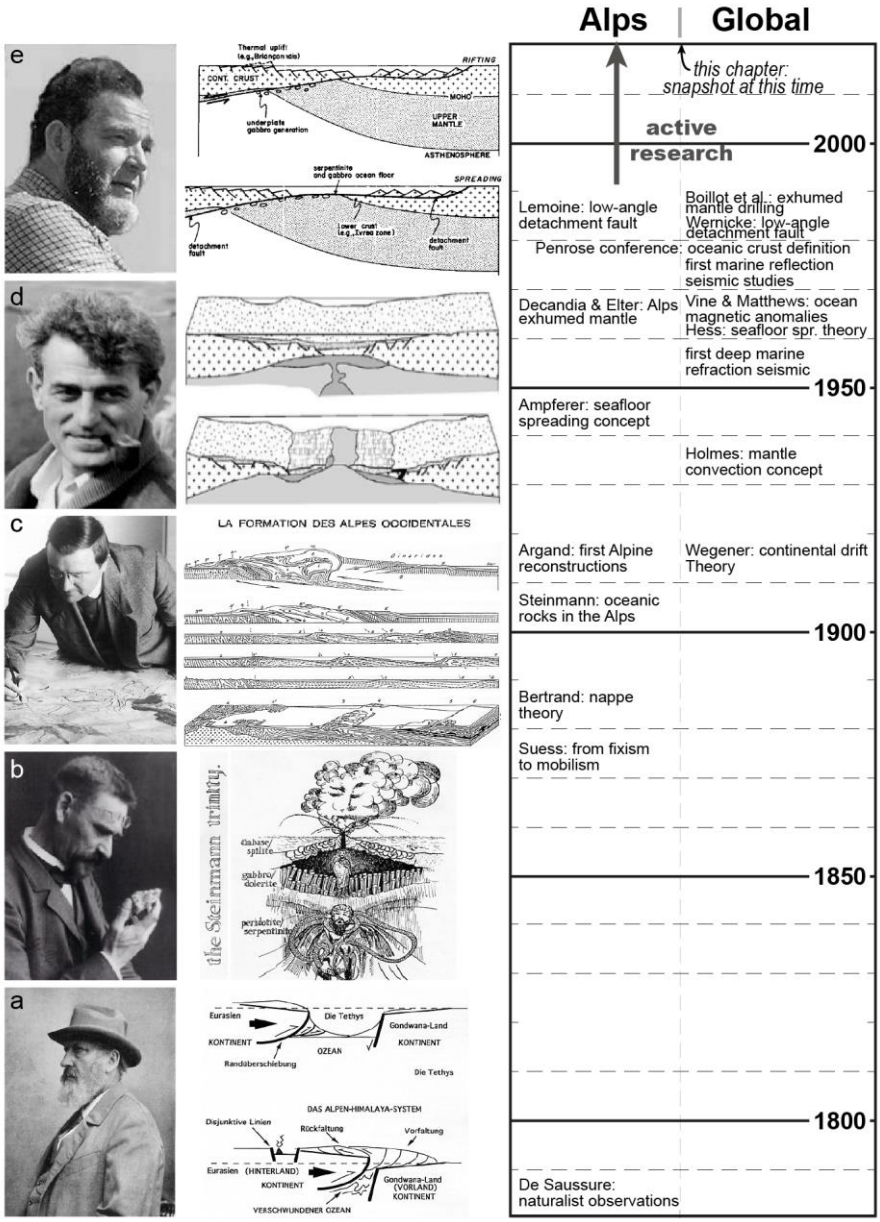


Fig. 2: Evolution of concepts and important players of the "Alpine Tethys": (a) Eduard Suess was among the first to recognize the existence of former basins in the Alpine domain, which he named Tethys; figure from Suess (1875). (b) Gustave Steinmann was among the first to recognize and map the serpentinized peridotite–"diabase"–radiolarite association (the Steinmann trinity) throughout the Alps and to interpret it as a remnant of a fossil deep ocean floor; figure from Coleman (1977). (c) Emile Argand was among the first to propose detailed tectonic and paleogeographic restorations by applying a mobilistic view to the Alpine system; figure from Argand (1916). (d) Piero Elter was the first who suggested mantle exhumation and therefore the magma-poor nature of the Alpine Tethys; figure from Decandia and Elter (1972). (e) Marcel Lemoine was at the forefront of the present-day interpretation of the Alpine Tethys as a magma-poor, polyphase rifted margin; figure from Lemoine et al. (1987).

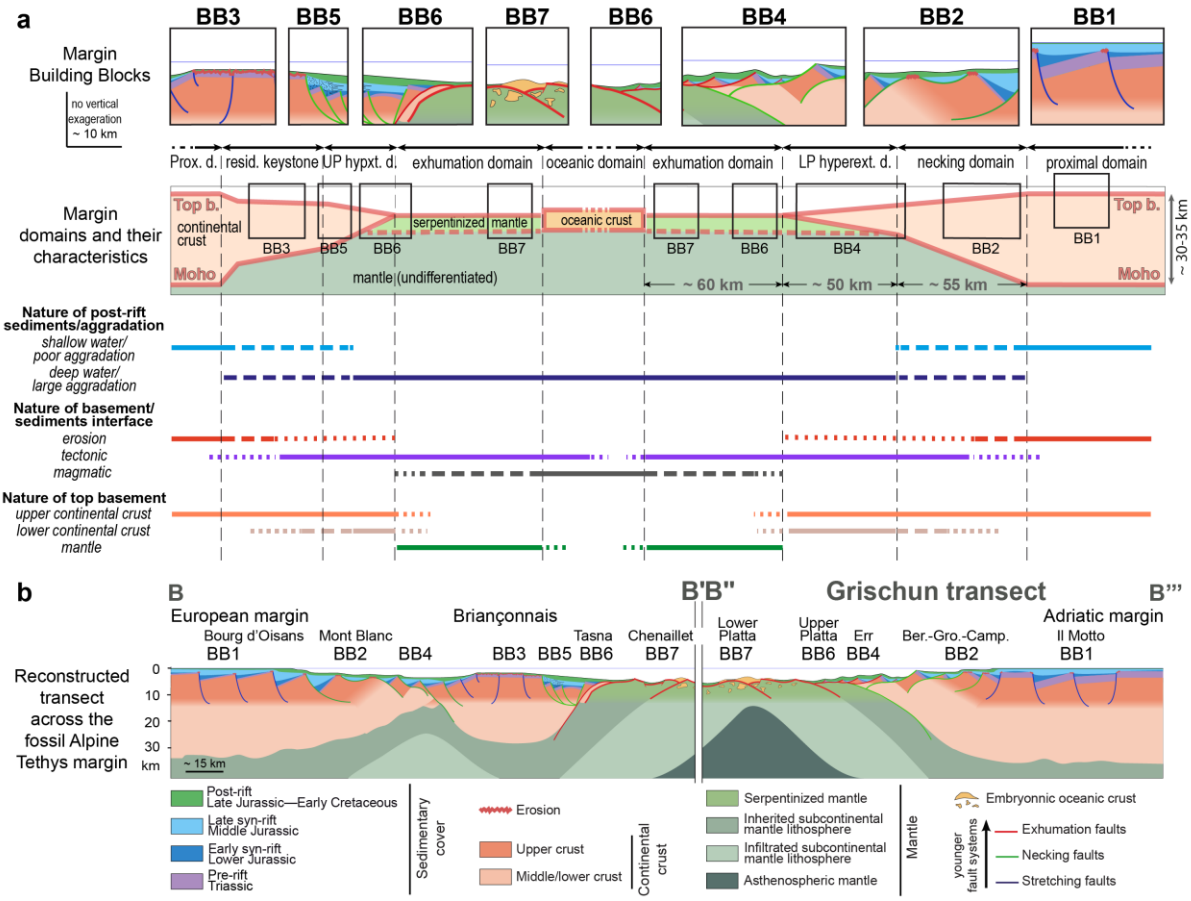


Fig. 3: The Building Block (BB) concept applied to the Alpine Tethys margins: (a) Schematic section across a conjugate magma-poor rifted margin pair and location of the building blocks (BB) (see text for details). The nature of top basement, post-rift sediments, and of their interface vary across the margin and is diagnostic to define rift domains (see Tugend et al., 2014). b) Synthetic reconstruction of a composite transect across the Alpine Tethys rift system (see Fig. 1 for location of B–B' and B''–B''' transects) and location of BBs and projected position of type localities.

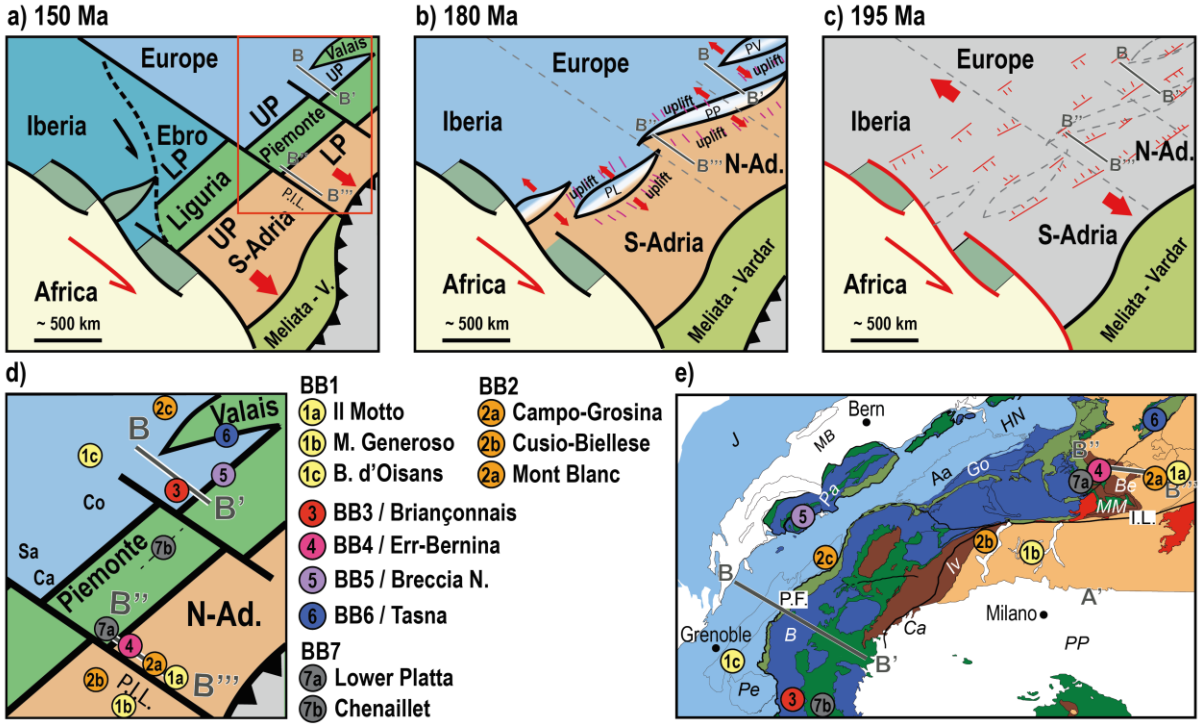


Fig. 4: Schematic maps showing the paleogeographic evolution of the Alpine Tethys at: (a) Late Jurassic (150 Ma; assumed end of rifting/spreading in the Alpine Tethys); (b) Late Pliensbachian (180 Ma; end of necking phase); (c) Early Jurassic (195 Ma; stretching phase). Interpretation based on Decarlis et al., 2018). The interpretation assumes that individual basins formed as segmented en-echelon rift segments separated by accommodation/transfer zones. (d) Zoom on (a) showing the locations of the BBs described in this study at Late Jurassic time, and (e) location of the BBs on the present-day structural map shown in Fig. 1c. Abbreviations: P.I.L.: Paleo Insubric Line; PL: Proto Liguria basin; PP: Proto Piemonte basin; PV: Proto Valais basin; LP: Lower Plate; UP: Upper Plate. Transects B-B' and B''-B''' (for position see also Fig. 1).

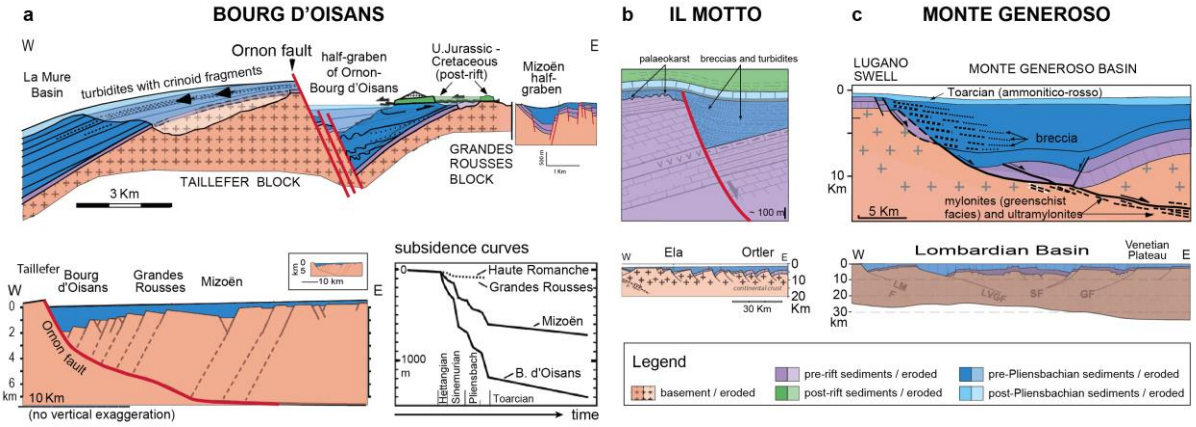


Fig. 5: Examples of BB1 exposed in the Alps documenting the stretching stage observed in the proximal Alpine Tethys margins: (a) the Bourg d'Oisans Basin in the proximal European margin (modified after Chevalier, 2002 and De Graciansky et al., 2012); (b) Il Motto Basin in the Upper Austroalpine Ortler Nappe near Livigno in northern Italy belonging to the former northern Adria proximal margin (modified after Eberli, 1988 and De Graciansky et al., 2012); and (c) the Monte Generoso Basin in the Southern Alps belonging to the former southern Adria margin (modified after Bertotti et al., 1993 and De Graciansky et al., 2012).

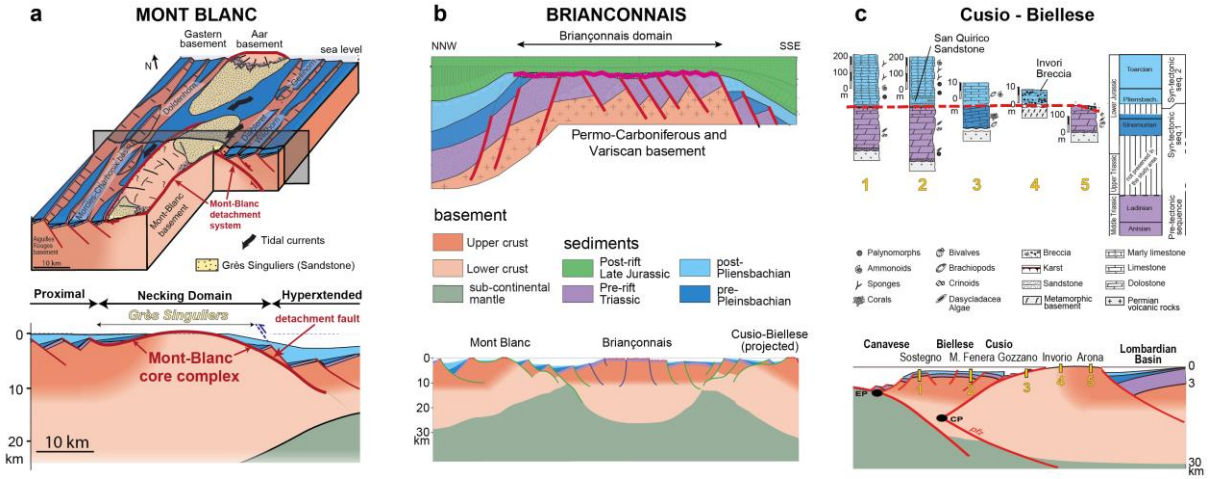


Fig. 6: Examples of BB2 and BB3 exposed in the Alps documenting the necking stage observed at the transition between the proximal and distal Alpine Tethys margins and the future distal part before onset of hyperextension: (a) Mont Blanc core complex representing a remnant of the European necking domain (modified after Ribes et al., 2020a); (b) the Briançonnais domain representing the future distal European margin characterized by a major necking unconformity (modified after De Graciansky et al., 2012); (c) The Cusio – Biellese domain showing the stratigraphic record of the southern Adria necking domain (modified after Beltrando et al., 2015 and Decarlis et al., 2018).

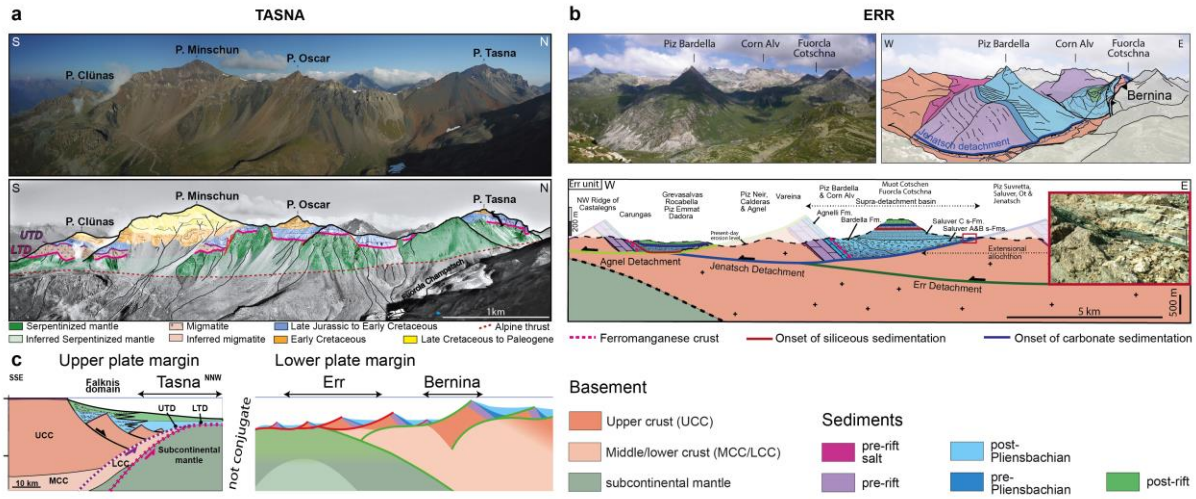


Fig. 7: Examples of BB4, BB5 and BB6 exposed in the Alps documenting the hyperextension and early mantle exhumation stage observed in the distal Alpine Tethys margins: (a) Tasna exposed in the Tasna Nappe in the Engadin Window north of Scuol (SE Switzerland) and representing the most distal European/Briançonnais margin (modified after Ribes et al., 2020b) (UTD: Upper Tasna Detachment; LTD: Lower Tasna Detachment); (b) Err exposed in the Lower Austroalpine Err Nappe in SE Switzerland showing the Bardella extensional allochthon at the Julier Pass; photograph on the lower right corner shows the onlap of syn-tectonic sandstones onlapping onto the detachment surface indicated by the black colored fault gouges; modified after Epin & Manatschal (2018) and Ribes et al. (2019a).

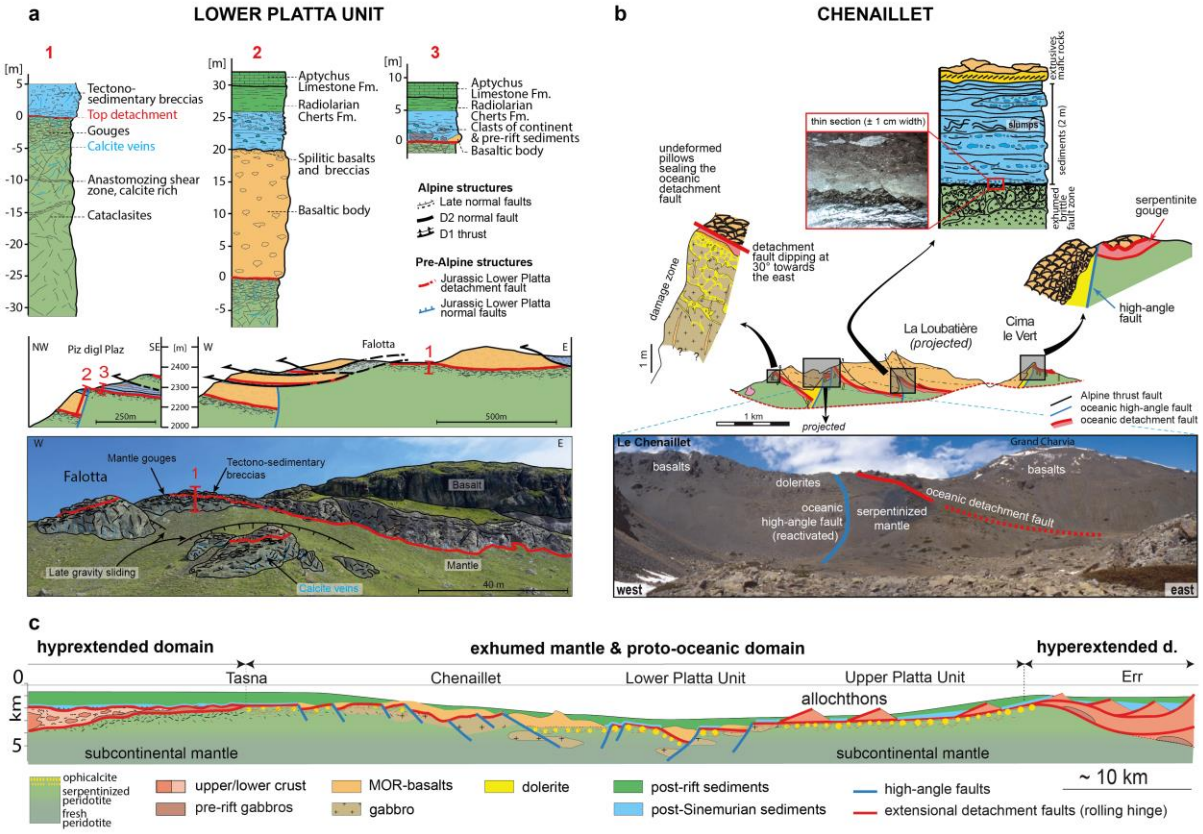


Fig. 8: Examples of BB7 exposed in the Alpes documenting early seafloor spreading (proto-oceanic crust) of the Alpine Tethys: (a) the Lower Platta Unit exposed in the Val Surses in SE Switzerland (modified after Epin et al., 2019); (b) Chanaillet Ophiolite exposed near Briançon along the French/Italian border in the Western Alps (modified after Manatschal et al., 2011); (c) section across the Ocean Continent Transition of the Alpine Tethys showing the transition from hyperextended crust to exhumed mantle and then to proto-oceanic crust (modified after Manatschal & Müntener, 2009). Section (c) shows localities in (a) and (b).

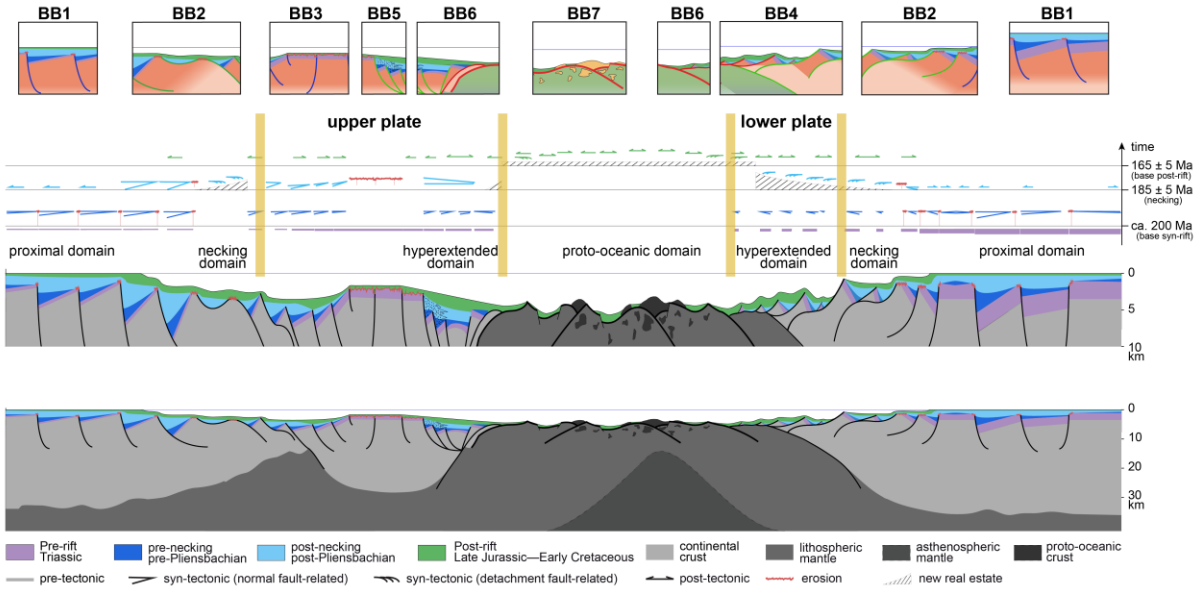


Fig. 9: Section across the Alpine Tethys corresponding to transects introduced in Fig. 3 (for location see Figs. 1 and 4). The section highlights the stratigraphic architecture of the Alpine Tethys margins across the central Piemonte segment and document the syn-tectonic evolution in the overlying Wheeler diagram (for details see text).

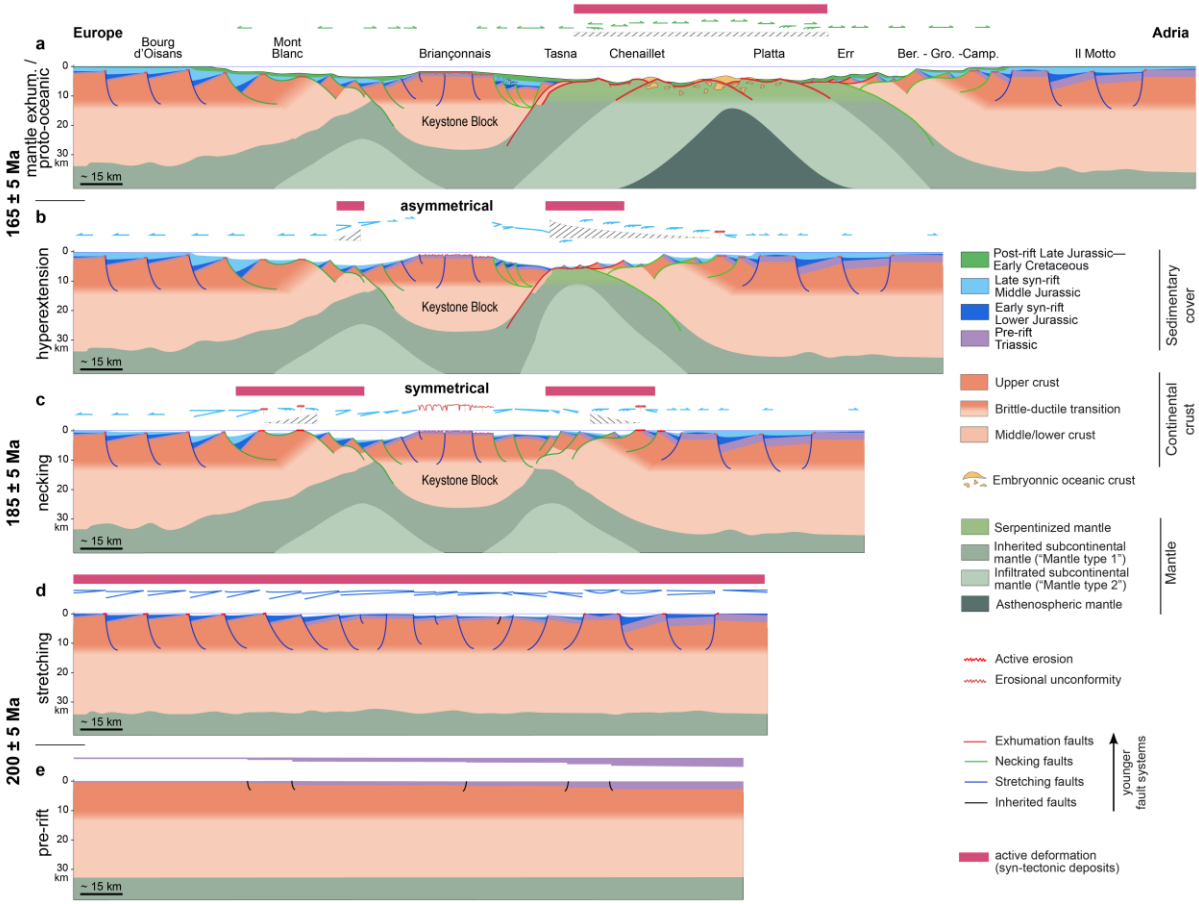


Fig. 10: Main phases of the Alpine Tethys rift evolution: (a) mantle exhumation phase and embryonic seafloor spreading (formation of proto-oceanic crust); (b) hyperextension phase; (c) necking phase; (d) stretching phase; (e) initial stage. See text for a detailed description of the evolution.

	BB1	BB2	BB3	BB4	BB5	BB6	BB7
rift domain	proximal (stretching)	necking	necking (residual keystone)	hyperextended (lower plate)	hyperextended (upper plate)	exhumed	proto-oceanic
type basement	upper continental crust	upper/middle continental crust	upper continental crust	upper/lower continental crust	upper/lower continental crust	exhumed mantle	exhumed mantle/magma
fault-types	high-angle faults	high/low-angle faults	high-angle faults	high/low-angle faults	high/low-angle faults	high/low-angle faults	high/low-angle faults
bathymetry (during formation)	shallow/subareal	shallow/subareal	shallow/subareal	deep/subsiding	deep/subsiding	deep/subsiding	deep/subsiding
type locality (see Fig. 4d & e)	Il Motto / Generoso / Bourg d'Oisans)	Campo-Grosina/ Mont Blanc/Cusio-Biellese	Fond Froid – Lac de l'Ascension (Briançonnais)	Err & Bernina	Breccia Nappe	Tasna OCT	Lower Platta / Chenaillet
key reference	Eberli 1988 Ribes et al. 2019a	Mohn et al. 2012 Ribes et al. 2020a	Claudel & Dumont, 1999	Masini et al., 2012 Epin & Manatschal, 2018	Escher et al. 1993 Steffen et al. 1993	Ribes et al. 2020b	Epin et al. 2019, Manatschal et al. 2011

Table 1: Overview of Building Blocks defined for the Alpine Tethys

References:

Amann, M., Ulrich, M., Manatschal, G., Pelt, E., Epin, M.E., Autin, J., Sauter, D., 2020. Geochemical characteristics of basalts related to incipient oceanization: The example from the Alpine-Tethys OCTs. Terra Nov. 32, 75–88. https://doi.org/10.1111/ter.12438

Angrand, P., Mouthereau, F., Masini, E., Asti, R., 2020. A reconstruction of Iberia accounting for Western Tethys-North Atlantic kinematics since the late-Permian-Triassic. Solid Earth 11, 1313–1332. https://doi.org/10.5194/se-11-1313-2020

Argand, E., 1916. Sur l'arc des Alpes occidentales. Bridel, G.

Badoux, H., & Mercanton, C. H. (1962). Essai sur l'évolution tectonique des Préalpes médianes du Chablais. Birkhäuser.

Barboza, S.A., Bergantz, G.W., Brown, M., 1999. Regional granulite facies metamorphism in the Ivrea zone: Is the Mafic Complex the smoking gun or a red herring? Geology 27, 447–450. https://doi.org/10.1130/0091-7613(1999)027<0447:rgfmit>2.3.co;2

Barfety, J. C. (1985). Le Jurassique dauphinois entre Durance et Rhône: étude stratigraphique et géodynamique; évolution d'une portion de la marge nord téthysienne (Alpes occidentales françaises) (Doctoral dissertation, Université Scientifique et Médicale de Grenoble).

Barnett-Moore, N., Hosseinpour, M., Maus, S., 2016. Assessing discrepancies between previous plate kinematic models of Mesozoic Iberia and their constraints. Tectonics 35, 1843–1862. https://doi.org/10.1002/2015TC004019

Baumgartner, P.O., 2013. Mesozoic radiolarites - accumulation as a function of sea surface fertility on Tethyan margins and in ocean basins. Sedimentology 60, 292–318. https://doi.org/10.1111/sed.12022

Beltrando, M., Compagnoni, R., Ferrando, S., Mohn, G., Frasca, G., Odasso, N., ... & Beltrando, M. (2014). Crustal thinning and mantle exhumation in the Levone area (Southern Canavese Zone, Western Alps). A Field Guide Across the Margins of Alpine Tethys, Journal of the Virtual Explorer, Electronic Edition, 48.

Beltrando, M., Stockli, D.F., Decarlis, A., Manatschal, G., 2015. A crustal-scale view at rift localization along the fossil Adriatic margin of the Alpine Tethys preserved in NW Italy. Tectonics 34, 1927–1951. https://doi.org/10.1002/2015TC003973

Bernoulli, D., 1964. Zur Geologie des Monte Generoso (Lombardische Alpen): ein Beitrag zur Kenntnis der südalpinen Sedimente.

Berra, F., Galli, M. T., Reghellin, F., Torricelli, S., & Fantoni, R. (2009). Stratigraphic evolution of the Triassic–Jurassic succession in the Western Southern Alps (Italy): the record of the two-stage

1341 rifting on the distal passive margin of Adria. Basin Research, 21(3), 335-353.

1342 Bertotti, G., 1991. Early Mesozoic extension and Alpine shortening in the western Southern Alps: The
1343 geology of the area between Lugano and Menaggio (Lombardy, Northern Italy). Mem. Soc. Geol.
1344 Padova 43, 17–123.

1345 Bertotti, G., Picotti, V., Bernoulli, D., & Castellarin, A. (1993). From rifting to drifting: tectonic evolution
1346 of the South-Alpine upper crust from the Triassic to the Early Cretaceous. Sedimentary Geology,
1347 86(1-2), 53-76.

1348 Bertrand, M., 1884. Rapports de structure des Alpes de Glaris et du bassin houiller du Nord. Bull. la
1349 Société Géologique Fr. 3, 318–330.

1350 Bill, M., O'Dogherty, L., Guex, J., Baumgartner, P. O., & Masson, H. (2001). Radiolarite ages in
1351 Alpine-Mediterranean ophiolites: Constraints on the oceanic spreading and the Tethys-Atlantic
1352 connection. GSA Bulletin, 113(1), 129-143.

1353 Boillot, G., Recq, M., Winterer, E.L., Meyer, A.W., Applegate, J., Baltuck, M., Bergen, J.A., Comas,
1354 M.C., Davies, T.A., Dunham, K., Evans, C.A., Girardeau, J., Goldberg, G., Haggerty, J., Jansa,
1355 L.F., Johnson, J.A., Kasahara, J., Loreau, J.P., Luna-Sierra, E., Moullade, M., Ogg, J., Sarti, M.,
1356 Thurow, J., Williamson, M., 1987. Tectonic denudation of the upper mantle along passive
1357 margins: a model based on drilling results (ODP leg 103, western Galicia margin, Spain).
1358 Tectonophysics 132, 335–342. https://doi.org/10.1016/0040-1951(87)90352-0

1359 Bonin, B., Azzouni-Sekkal, A., Bussy, F., Ferrag, S., 1998. Alkali-calcic and alkaline post-orogenic
1360 (PO) granite magmatism: Petrologic constraints and geodynamic settings. Lithos 45, 45–70.
1361 https://doi.org/10.1016/S0024-4937(98)00025-5

1362 Cannat, M., Sauter, D., Lavier, L., Bickert, M., Momoh, E., Leroy, S., 2019. On spreading modes and
1363 magma supply at slow and ultraslow mid-ocean ridges. Earth Planet. Sci. Lett. 519, 223–233.
1364 https://doi.org/10.1016/j.epsl.2019.05.012

1365 Chenin, P., Manatschal, G., Decarlis, A., Schmalholz, S.M., Duretz, T., Beltrando, M., 2019. Emersion
1366 of distal domains in advanced stages of continental rifting explained by asynchronous crust and
1367 mantle necking. Geochemistry, Geophys. Geosystems 2019GC008357.
1368 https://doi.org/10.1029/2019GC008357

1369 Chenin, P., Manatschal, G., Picazo, S., Müntener, O., Karner, G.D., Johnson, C., Ulrich, M., 2017.
1370 Influence of the architecture of magma-poor hyperextended rifted margins on orogens produced
1371 by the closure of narrow versus wide oceans. Geosphere 13, 1–18.
1372 https://doi.org/10.1130/GES01363.1

1373 Chenin, P., Picazo, S., Jammes, S., Manatschal, G., Müntener, O., Karner, G., 2018a. Potential role of
1374 lithospheric mantle composition in the Wilson cycle: a North Atlantic perspective, in: WILSON,
1375 R.W., HOUSEMAN, G.A., MCCAFFREY, K.J.W., DORÉ, A.G., BUITER, S.J.H. (Eds.), Fifty
1376 Years of the Wilson Cycle Concept in Plate Tectonics. Geological Society, London, Special
1377 Publications, 470. https://doi.org/10.1144/SP470.10

Chenin, P., Schmalholz, S.M., Manatschal, G., Duretz, T., 2020. Impact of crust–mantle mechanical coupling on the topographic and thermal evolutions during the necking phase of 'magma-poor' and 'sediment-starved' rift systems: A numerical modeling study. Tectonophysics 228472. https://doi.org/10.1016/j.tecto.2020.228472

Chenin, P., Schmalholz, S.M., Manatschal, G., Karner, G.D., 2018b. Necking of the lithosphere: A reappraisal of basic concepts with thermo-mechanical numerical modeling. J. Geophys. Res. Solid Earth 123, 5279–5299. https://doi.org/10.1029/2017JB014155

Chessex, R.: La g6ologie de la haute vallée d'Abondance, Haute-Savoie, France. -- Ecl. Geol. Helv., 52, p. 295, 1959.

Chevalier, F. (2002). Vitesse et cyclicité de fonctionnement des failles normales de rift: implication sur le remplissage stratigraphique des bassins et sur les modalités d'extension d'une marge passive fossile: aplication au demi-graben liasique de Bourg-d'Oisans (Alpes occidentales, France) (Doctoral dissertation, Université de Bourgogne).

Chevalier, F., Guiraud, M., Garcia, J. P., Dommergues, J. L., Quesne, D., Allemand, P., & Dumont, T. (2003). Calculating the long-term displacement rates of a normal fault from the high-resolution stratigraphic record (early Tethyan rifting, French Alps). Terra Nova, 15(6), 410-416.

Claudel, M.E., Dumont, T., 1999. A record of multistage continental break-up on the Briançonnais marginal plateau (Western Alps): Early and Middle-Late Jurassic rifting. Eclogae Geol. Helv. 92, 45–61.

Coleman, R.G., 1977. Ophiolites. Ancient oceanic lithosphere. Springer-Verlag, Berlin, Heidelberg, New York.Coltat, R., Branquet, Y., Gautier, P., Campos Rodriguez, H., Poujol, M., Pelleter, E., ... & Boulvais, P. (2019a). Unravelling the root zone of ultramafic-hosted black smokers-like hydrothermalism from an Alpine analog. Terra Nova, 31(6), 549-561.

Coltat, R., Boulvais, P., Branquet, Y., Collot, J., Epin, M. E., & Manatschal, G. (2019b). Syntectonic carbonation during synmagmatic mantle exhumation at an ocean-continent transition. Geology, 47(2), 183-186.

Coltat, R., Branquet, Y., Gautier, P., Boulvais, P., & 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.

Conti, P., Manatschal, G., & Pfister, M. (1994). Synrift sedimentation, Jurassic and Alpine tectonics in the central Ortler nappe (Eastern Alps, Italy). Eclogae Geologicae Helvetiae, 87(1), 63-90.

Costamagna, L. G. (2016). The Middle Jurassic Alpine Tethyan unconformity and the Eastern Sardinia–Corsica Jurassic high: A sedimentary and regional analysis. Journal of Iberian Geology, 42(3), 311–334.Debelmas, J., 1955. Les zones subbriançonnaise et brianconnaise occidentale entre Vallouise et Guillestre (Hautes-Alpes).

Decandia, F.A., Elter, P., 1969. Riflessioni sul problema delle ofioliti nell'Appennino settentrionale (nota preliminare). Atti della Soc. Toscana di Sci. Nat.

1415 Decandia, F. A., & Elter, P. (1972). La" zona" ofiolitifera del Bracco nel settore compreso fra Levanto e
1416 la Val Gravena (Apennino ligure). Società Geologica Italiana Bulletin, 11, 37-64.

1417 Decarlis, A., & Lualdi, A. (2008). Late Triassic-early Jurassic paleokarst from the Ligurian Alps and its
1418 geological significance (Siderolitico Auct., Ligurian Briançonnais domain). Swiss Journal of
1419 Geosciences, 101(3), 579-593.

1420 Decarlis, A., Manatschal, G., Haupert, I., & Masini, E. (2015). The tectono-stratigraphic evolution of
1421 distal, hyper-extended magma-poor conjugate rifted margins: Examples from the Alpine Tethys
1422 and Newfoundland–Iberia. Marine and Petroleum Geology, 68, 54-72.

1423 Decarlis, A., Beltrando, M., Manatschal, G., Ferrando, S., Carosi, R., 2017. Architecture of the Distal
1424 Piedmont-Ligurian Rifted Margin in NW Italy: Hints for a Flip of the Rift System Polarity.
1425 Tectonics 36, 2388–2406. https://doi.org/10.1002/2017TC004561

1426 Decarlis, A., Gillard, M., Tribuzio, R., Epin, M.E., Manatschal, G., 2018. Breaking up continents at
1427 magma-poor rifted margins: a seismic vs. outcrop perspective. J. Geol. Soc. London. jgs2018-
1428 041.

1429 De Graciansky, P. C., Roberts, D. G., & Tricart, P. (2011). The Western Alps, from rift to passive
1430 margin to orogenic belt: an integrated geoscience overview. Elsevier.

1431 Desmurs, L., Manatschal, G., & Bernoulli, D. (2001). The Steinmann Trinity revisited: mantle
1432 exhumation and magmatism along an ocean-continent transition: the Platta nappe, eastern
1433 Switzerland. Geological Society, London, Special Publications, 187(1), 235-266.

1434 Desmurs, L., Müntener, O., & Manatschal, G. (2002). Onset of magmatic accretion within a magma-
1435 poor rifted margin: a case study from the Platta ocean-continent transition, eastern Switzerland.
1436 Contributions to Mineralogy and Petrology, 144(3), 365-382.

1437 Dietrich, V. J. (1969). Die Ophiolithe des Oberhalbsteins (Graubünden) und das Ophiolithmaterial der
1438 ostschweizerischen Molasseablagerungen: ein petrographischer Vergleich (Doctoral dissertation,
1439 ETH Zurich).

1440 Dietrich, V., 1970. Die Stratigraphie der Platta-Decke: Fazielle Zusammenhänge zwischen
1441 Oberpenninikum und Unterostalpin. Geologisches Institut der Eidg. Technischen Hochschule
1442 und der Universität Zürich.

1443 Eberli G. P. (1985) Die jurassischen Sedimente in den ostalpinen Decken Graubündens. Dissertation.
1444 ETH Zurich, Zurich

1445 Eberli, G. P. (1987). Carbonate turbidite sequences deposited in rift-basins of the Jurassic Tethys
1446 Ocean (eastern Alps, Switzerland). Sedimentology, 34(3), 363-388.

1447 Eberli, G.P., 1988. The evolution of the southern continental margin of the Jurassic Tethys Ocen as
1448 recorded in the Allgäu Formation of the Austroalpine Nappes of Graubünden (Switzerland).
1449 Eclogae Geol. Helv. 81, 175--214.

Epin, M.-E., Manatschal, G., Amann, M., Ribes, C., Clausse, A., Guffon, T., 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. Int. J. Earth Sci. https://doi.org/10.1007/s00531-019-01772-0

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., Amann, M., 2017. Defining diagnostic criteria to describe the role of rift inheritance in collisional orogens: the case of the Err-Platta nappes (Switzerland). Swiss J. Geosci. 110, 419–438. https://doi.org/10.1007/s00015-017-0271-6

Escher, A., Masson, H., & Steck, A. (1993). Nappe geometry in the western Swiss Alps. Journal of structural Geology, 15(3-5), 501-509.

Ferrando, S., Bernoulli, D., & Compagnoni, R. (2004). The Canavese zone (internal Western Alps): a distal margin of Adria. Schweizerische Mineralogische und Petrographische Mitteilungen, 84(1-20).

Finger, W. (1978). Die zone von Samaden (unterostalpine Decken, Graubünden) und ihre jurassischen Brekzien (Doctoral dissertation, ETH Zurich).

Flament, N; Gurnis, M., and Muller, R.D, (2013). A review of observations and models of dynamic topography. Lithosphere 2013;; 5 (2): 189–210. doi: https://doi.org/10.1130/L245.1

Florineth, D., Froitzheim, N., 1994. Transition from continental to oceanic basement in the Tasna Nappe: evidence for Early Cretaceous opening of the Valais Ocean. Schweiz. Miner. Petrogr. Mitt. 74, 437–448.

Frisch, W., 1979. Tectonic progradation and plate tectonic evolution of the Alps. Tectonophysics 60, 121–139. https://doi.org/10.1016/0040-1951(79)90155-0

Frizon de Lamotte, D., Fourdan, B., Leleu, S., Leparmentier, F., Clarens, P., 2015. Style of rifting and the stages of Pangea breakup. Tectonics 34, 1–21. https://doi.org/10.1002/2014TC003760.Received

Froitzheim, N. (1988). Synsedimentary and synorogenic normal faults within a thrust sheet of the Eastern Alps (Ortler zone, Graubünden, Switzerland). Eclogae Geologicae Helvetiae, 81(3), 593-610.

Froitzheim, N., Eberli, G.P., 1990. Extensional detachment faulting in the evolution of a Tethys passive continental margin, Eastern Alps, Switzerland. Geol. Soc. Am. Bull. 102, 1297–1308. https://doi.org/10.1130/0016-7606(1990)102

Froitzheim, N., Manatschal, G., 1996. Kinematics of Jurassic rifting, mantle exhumation, and passive-

margin formation in the Austroalpine and Penninic nappes (eastern Switzerland). Bull. Geol. Soc. Am. 108, 1120–1133. https://doi.org/10.1130/0016-7606(1996)108<1120:KOJRME>2.3.CO;2

Furrer H (1985) Field Workshop on Triassic and Jurassic Sediments in the Eastern Alps of Switzerland: 25th.-29th. August 1985: Guide Book. Geologisches Institut ETH-Zürich, Zurich

Gawthorpe, R.L., Leeder, M.R., 2000. Tectono-sedimentary evolution of active extensional basins. Basin Res. 12, 195–218. https://doi.org/10.1111/j.1365-2117.2000.00121.xGupta, S., Cowie, P. A., Dawers, N. H., Underhill, J. R. (1998); A mechanism to explain rift-basin subsidence and stratigraphic patterns through fault-array evolution. Geology 26 (7): 595–598. doi: https://doi.org/10.1130/0091-7613(1998)026<0595:AMTERB>2.3.CO;2Handy, M.R., M. Schmid, S., Bousquet, R., Kissling, E., Bernoulli, D., 2010. Reconciling plate-tectonic reconstructions of Alpine Tethys with the geological-geophysical record of spreading and subduction in the Alps. Earth-Science Rev. 102, 121–158. https://doi.org/10.1016/j.earscirev.2010.06.002

Haug, E. (1892). Sur la continuation vers le sud des plis de la Dent du Midi. Bull. Soc. géol. Fr., (3), 20, p. CLXXXIV-CLXXXIX, séance du 19 décembre 1892, avec remarque de M. Bertrand.

Haug, E., 1909. Les géosynclinaux de la chaîne des Alpes pendant les temps secondaires. Gauthier-Villars.

Haupert, I., Manatschal, G., Decarlis, A., Unternehr, P., 2016. Upper-plate magma-poor rifted margins: stratigraphic architecture and structural evolution. Mar. Pet. Geol. 69, 241–261. https://doi.org/10.1016/j.marpetgeo.2015.10.020

Hendry, H. E. (1972). Breccias deposited by mass flow in the Breccia Nappe of the French pre-Alps. Sedimentology, 18(3-4), 277-292.

Hermann, J., Müntener, O., Trommsdorff, V., Hansmann, W., Piccardo, G.B., 1997. Fossil crust-to-mantle transition, Val Malenco (Italian Alps). J. Geophys. Res. 102, 20123. https://doi.org/10.1029/97JB01510

Hsü, K.J., Briegel, U., 1991. Geologie der Schweiz. Switzerland.

Incerpi, N., Martire, L., Manatschal, G., Bernasconi, S.M., 2017. Evidence of hydrothermal fluid flow in a hyperextended rifted margin: the case study of the Err nappe (SE Switzerland). Swiss J. Geosci. 110, 439–456. https://doi.org/10.1007/s00015-016-0235-2

Incerpi, N., Martire, L., Manatschal, G., Bernasconi, S.M., Gerdes, A., Czuppon, G., Palcsu, L., Karner, G.D., Johnson, C.A., 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 Italy). Basin Res. 32, 91–115. https://doi.org/10.1111/bre.12370

Jagoutz, O., Müntener, O., Manatschal, G., Rubatto, D., Péron-Pinvidic, G., Turrin, B.D., Villa, I.M., 2007. The rift-to-drift transition in the North Atlantic: A stuttering start of the MORB machine? Geology 35, 1087–1090. https://doi.org/10.1130/G23613A.1

Kaczmarek, M.-A., Müntener, O., 2008. Juxtaposition of Melt Impregnation and High-Temperature Shear Zones in the Upper Mantle; Field and Petrological Constraints from the Lanzo Peridotite (Northern Italy). J. Petrol. 49, 2187–2220. https://doi.org/10.1093/petrology/egn065

Kilian, W., 1891. Sur quelques Céphalopodes nouveaux ou peu connus de la période secondaire.

Lagabrielle, Y., & Cannat, M. (1990). Alpine Jurassic ophiolites resemble the modern central Atlantic basement. Geology, 18(4), 319-322.

Lagabrielle, Y., 1994. Ophiolites of the southwestern Alps and the structure of the Tethyan oceanic lithosphere. Ofioliti 19, 413–434.

Lagabrielle, Y., Vitale Brovarone, A., Ildefonse, B., 2015. Fossil oceanic core complexes recognized in the blueschist metaophiolites of Western Alps and Corsica. Earth-Science Rev. https://doi.org/10.1016/j.earscirev.2014.11.004

Landry ,P. (1978): Données nouvelles sur la couverture sédimentaire des massifs cristallins externes au Sud du Mont-Blanc. -Géol. alp. (Grenoble) 54, 83-112.

Lavier, L.L., Manatschal, G., 2006. A mechanism to thin the continental lithosphere at magma-poor margins. Nature 440, 324–328. https://doi.org/10.1038/nature04608

Le Breton, E., Brune, S., Ustaszewski, K., Zahirovic, S., Seton, M., & Müller, R. D. (2020). Kinematics and extent of the Piemont-Liguria Basin–implications for subduction processes in the Alps. Solid Earth Discussions, 1-42.

Lemoine, M., 1961. La marge externe de la fosse piémontaise dans les Alpes occidentales. Rev. Géogr. phys. Géol. dyn 2, 163–180.

Lemoine, M. (1967). Brèches sédimentaires marines à la frontière entre les domaines briançonnais et piémontais dans les Alpes occidentales. Geologische Rundschau, 56(1), 320-335.

Lemoine, M., Bas, T., Arnaud-Vanneau, A., Arnaud, H., Dumont, T., Gidon, M., Bourbon, M., de Graciansky, P.C., Rudkiewicz, J.L., Megard-Galli, J., Tricart, P., 1986. The continental margin of the Mesozoic Tethys in the Western Alps. Mar. Pet. Geol. 3, 179–199. https://doi.org/10.1016/0264-8172(86)90044-9

Lemoine, M., Tricart, P., Boillot, G., 1987. Ultramafic and gabbroic ocean floor of the Ligurian Tethys (Alps, Corsica, Apennines): In search of a genetic imodel. Geology 15, 622–625. https://doi.org/10.1130/0091-7613(1987)15

Lescoutre, R., Manatschal, G., 2020. Role of rift-inheritance and segmentation for orogenic evolution: example from the Pyrenean-Cantabrian system. Tectonics.

Li, X.-H.H., Faure, M., Lin, W., Manatschal, G., 2013. New isotopic constraints on age and magma genesis of an embryonic oceanic crust: The Chenaillet Ophiolite in the Western Alps. Lithos 160–

161, 283–291. https://doi.org/10.1016/j.lithos.2012.12.016

Lory, C., 1866. Sur le gisement de la Terebratula diphya dans les calcaires de la Porte-de-France, aux environs de Grenoble et de Chambéry. Bull. la Soc. Geol. Fr. 2, 516–521.

Lory, C., 1860. Description géologique du Dauphiné pour servir d'explication à la carte géologique de cette province.

MacLeod, C. J., Searle, R. C., Murton, B. J., Casey, J. F., Mallows, C., Unsworth, S. C., ... & Harris, M. (2009). Life cycle of oceanic core complexes. Earth and Planetary Science Letters, 287(3-4), 333-344.

Manatschal, G. (1999). Fluid-and reaction-assisted low-angle normal faulting: evidence from rift-related brittle fault rocks in the Alps (Err Nappe, eastern Switzerland). Journal of Structural Geology, 21(7), 777-793.

Manatschal, G., Engström, A., Desmurs, L., Schaltegger, U., Cosca, M., Müntener, O., 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., 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

Manatschal, G., Nievergelt, P., 1997. A continent-ocean transition recorded in the Err and Platta nappes (Eastern Switzerland). Eclogae Geol. Helv. 90, 3–27.

Manatschal, G., Sauter, D., Karpoff, A.M., Masini, E., Mohn, G., Lagabrielle, Y., 2011. The Chenaillet Ophiolite in the French/Italian Alps: An ancient analogue for an Oceanic Core Complex? Lithos 124, 169–184. https://doi.org/10.1016/j.lithos.2010.10.017

Manatschal, G., Chenin, P., Lescoutre, R., Miró, J., Cadenas, P., Saspiturry, N., Masini, E., Chevrot, S., Ford, M., Jolivet, L., Mouthereau, F., Thinon, I., Issautier, B., and Calassou, S. (2021). The role of inheritance in forming rifts and rifted margins and building collisional orogens: a Biscay-Pyrenean perspective; BSGF, DOI: https://doi.org/10.1051/bsgf/2021042 Marroni, M., Feroni, A.C., Di Biase, D., Ottria, G., Pandolfi, L., Taini, A., 2002. Polyphase folding at upper structural levels in the Borbera Valley (northern Apennines, Italy): Implications for the tectonic evolution of the linkage area between Alps and Apennines. Comptes Rendus - Geosci. 334, 565–572. https://doi.org/10.1016/S1631-0713(02)01784-4

Masini, E., Manatschal, G., Mohn, G., Ghienne, J. F., & Lafont, F. (2011). The tectono-sedimentary evolution of a supra-detachment rift basin at a deep-water magma-poor rifted margin: The example of the Samedan Basin preserved in the Err nappe in SE Switzerland. *Basin Research*, *23*(6), 652-677.

Masini, E., Manatschal, G., 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

1590 Masini, E., Manatschal, G., Mohn, G., Unternehr, P., 2012. Anatomy and tectono-sedimentary
1591 evolution of a rift-related detachment system: The example of the Err detachment (central Alps,
1592 SE Switzerland). Bull. Geol. Soc. Am. 124, 1535–1551. https://doi.org/10.1130/B30557.1

1593 McCarthy, A., Müntener, O., 2015. Ancient depletion and mantle heterogeneity: Revisiting the
1594 Permian-Jurassic paradox of Alpine peridotites. Geology 43, 255–258.
1595 https://doi.org/10.1130/G36340.1

1596 McCarthy, A., Tugend, J., Mohn, G., Candioti, L., Chelle-Michou, C., Arculus, R., Schmalholz, S.M.,
1597 Müntener, O., 2020. A case of Ampferer-type subduction and consequences for the Alps and the
1598 Pyrenees. Am. J. Sci. 320, 313–372. https://doi.org/10.2475/04.2020.01

1599 McKenzie, D. (1978). Some remarks on the development of sedimentary basins. Earth and Planetary
1600 science letters, 40(1), 25-32.

1601 Mohn, G., Manatschal, G., Beltrando, M., Haupert, I., 2014. The role of rift-inherited hyper-extension in
1602 Alpine-type orogens. Terra Nov. 26, 347–353. https://doi.org/10.1111/ter.12104

1603 Mohn, G., Manatschal, G., Beltrando, M., Masini, E., Kusznir, N., 2012. Necking of continental crust in
1604 magma-poor rifted margins: Evidence from the fossil Alpine Tethys margins. Tectonics 31,
1605 TC1012. https://doi.org/10.1029/2011TC002961

1606 Mohn, G., Manatschal, G., Masini, E., Müntener, O., 2011. Rift-related inheritance in orogens: a case
1607 study from the Austroalpine nappes in Central Alps (SE-Switzerland and N-Italy). Int. J. Earth
1608 Sci. 100, 937–961. https://doi.org/10.1007/s00531-010-0630-2

1609 Mohn, G., Manatschal, G., Müntener, O., Beltrando, M., Masini, E., 2010. Unravelling the interaction
1610 between tectonic and sedimentary processes during lithospheric thinning in the Alpine Tethys
1611 margins. Int. J. Earth Sci. 99, 75–101. https://doi.org/10.1007/s00531-010-0566-6

1612 Montadert, L., de Charpal, O., Roberts, D., Guennoc, P., Sibuet, J.-C., 1979. Northeast Atlantic
1613 passive continental margins: Rifting and subsidence processes, in: Talwani, M., Hay, W., Ryan,
1614 W.B.F. (Eds.), Deep Drilling Results in the Atlantic Ocean: Continental Margins and
1615 Paleoenvironment, Volume 3. American Geophysical Union (AGU), pp. 154–186.
1616 https://doi.org/10.1029/me003p0154

1617 Müntener, O., Manatschal, G., Desmurs, L., Pettke, T., 2010. Plagioclase peridotites in ocean-
1618 continent transitions: Refertilized mantle domains generated by melt stagnation in the shallow
1619 mantle lithosphere. J. Petrol. 51, 255–294. https://doi.org/10.1093/petrology/egp087

1620 Müntener, O., Pettke, T., Desmurs, L., Meier, M., Schaltegger, U., 2004. Refertilization of mantle
1621 peridotite in embryonic ocean basins: trace element and Nd isotopic evidence and implications
1622 for crust-mantle relationships. Earth Planet. Sci. Lett. 221, 293–308.
1623 https://doi.org/10.1016/S0012-821X(04)00073-1

1624 Müntener, O., Piccardo, G.B., 2003. Melt migration in ophiolitic peridotites: the message from Alpine-
1625 Apennine peridotites and implications for embryonic ocean basins. Geol. Soc. London, Spec.
1626 Publ. 218, 69–89. https://doi.org/10.1144/GSL.SP.2003.218.01.05

Nirrengarten, M., Manatschal, G., Tugend, J., Kusznir, N., Sauter, D., 2018. Kinematic Evolution of the Southern North Atlantic: Implications for the Formation of Hyperextended Rift Systems. Tectonics 37, 89–118. https://doi.org/10.1002/2017TC004495

Nirrengarten, M., Manatschal, G., Tugend, J., Kusznir, N.J., Sauter, D., 2017. Nature and origin of the J-magnetic anomaly offshore Iberia – Newfoundland: implications for plate reconstructions. Terra Nov. 29, 20–28. https://doi.org/10.1111/ter.12240

Nirrengarten, M., Manatschal, G., Yuan, X. P., Kusznir, N. J., & Maillot, B. (2016). Application of the critical Coulomb wedge theory to hyper-extended, magma-poor rifted margins. Earth and Planetary Science Letters, 442, 121-132.

Péron-Pinvidic, G., & Manatschal, G. (2019). Rifted margins: state of the art and future challenges. Frontiers in Earth Science, 7, 218.Petri, B., Duretz, T., Mohn, G., Schmalholz, S.M., Karner, G.D., Müntener, O., 2019. Thinning mechanisms of heterogeneous continental lithosphere. Earth Planet. Sci. Lett. 512, 147–162. https://doi.org/10.1016/J.EPSL.2019.02.007

Petri, B., Mohn, G., Štípská, P., Schulmann, K., Manatschal, G., 2016. The Sondalo gabbro contact aureole (Campo unit, Eastern Alps): implications for mid-crustal mafic magma emplacement. Contrib. to Mineral. Petrol. 171, 52. https://doi.org/10.1007/s00410-016-1263-7

Petri, B., Skrzypek, E., Mohn, G., Mateeva, T., Galster, F., 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. https://doi.org/10.1007/s00531-017-1465-x

Picazo, S., Müntener, O., Manatschal, G., Bauville, A., Karner, G.D., 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. https://doi.org/10.1016/j.lithos.2016.08.02

Piccardo, G.B., Müntener, O., Zanetti, A., Romairone, A., Bruzzone, S., Poggi, E., Spagnolo, G., 2004. The Lanzo South peridotite: melt/peridotite interaction in the mantle lithosphere of the Jurassic Ligurian Tethys. Ofioliti 29, 37–62. https://doi.org/10.4454/OFIOLITI.V29I1.205

Piccardo, G.B., Rampone, E., Vannucci, R., 1990. Upper mantle evolution during continental rifting and ocean formation: evidences from peridotite bodies of the western Alpine-northern Apennine system. Mémoires la Société géologique Fr. 156, 323–333.

Piccardo, G.B., Zanetti, A., Müntener, O., 2007. Melt/peridotite interaction in the Southern Lanzo peridotite: Field, textural and geochemical evidence. Lithos 94, 181–209. https://doi.org/10.1016/j.lithos.2006.07.002

Pinto, V.H.G., Manatschal, G., Karpoff, A.-M., Viana, A., 2015. Tracing mantle-reacted fluids in magma-poor rifted margins: The example of Alpine Tethyan rifted margins. Geochemistry, Geophys. Geosystems 16, 3271–3308. https://doi.org/10.1002/2015GC005830

Pinto, V. H. G., Manatschal, G., Karpoff, A. M., Ulrich, M., & Viana, A. R. (2017). Seawater storage and element transfer associated with mantle serpentinization in magma-poor rifted margins: A

quantitative approach. Earth and Planetary Science Letters, 459, 227-237.Quick, J.E., Sinigoi, S., Negrini, L., Demarchi, G., Mayer, A., 1992. Synmagmatic deformation in the underplated igneous complex of the Ivrea-Verbano zone. Geology 20, 613–616. https://doi.org/10.1130/0091-7613(1992)020<0613:sditui>2.3.co;2

Rampone, E., Borghini, G., Basch, V., 2020. Melt migration and melt-rock reaction in the Alpine-Apennine peridotites: Insights on mantle dynamics in extending lithosphere. Geosci. Front. 11, 151–166. https://doi.org/10.1016/j.gsf.2018.11.001

Rampone, E., Hofmann, A.W., Piccardo, G.B., Vannucci, R., Bottazzi, P., Ottolini, L., 1995. Petrology, mineral and isotope geochemistry of the external liguride peridotites (Northern Apennines, Italy). J. Petrol. 36, 81–105. https://doi.org/10.1093/petrology/36.1.81

Rampone, E., Hofmann, A.W., 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

Rampone, E., Piccardo, G.B., Vannucci, R., Bottazzi, P., 1997. Chemistry and origin of trapped melts in ophiolitic peridotites. Geochim. Cosmochim. Acta 61, 4557–4569. https://doi.org/10.1016/s0016-7037(97)00260-3

Renna, M.R., Tribuzio, R., Sanfilippo, A., Thirlwall, M., 2018. Role of melting process and melt–rock reaction in the formation of Jurassic MORB-type basalts (Alpine ophiolites). Contrib. to Mineral. Petrol. 173, 1–21. https://doi.org/10.1007/s00410-018-1456-3

Ribes, C., Ghienne, J.F., Manatschal, G., Dall'Asta, N., Stockli, D.F., Galster, F., Gillard, M., Karner, G.D., 2020a. The Grès Singuliers of the Mont Blanc region (France and Switzerland): stratigraphic response to rifting and crustal necking in the Alpine Tethys. Int. J. Earth Sci. 109, 2325–2352. https://doi.org/10.1007/s00531-020-01902-z

Ribes, C., Ghienne, J. F., Manatschal, G., Decarlis, A., Karner, G. D., Figueredo, P. H., & Johnson, C. A. (2019b). Long-lived mega fault-scarps and related breccias at distal rifted margins: insights from present-day and fossil analogues. Journal of the Geological Society, 176(5), 801-816.

Ribes, C., Manatschal, G., Ghienne, J.-F., Karner, G.D., Johnson, C.A., Figueredo, P.H., Incerpi, N.N., Epin, M., 2019a. 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. 108, 2071–2095. https://doi.org/DOI: 10.1007/s00531-019-01750-6

Ribes, C., Petri, B., Ghienne, J., Manatschal, G., Galster, F., Karner, G.D., Figueredo, P.H., Johnson, C.A., Karpoff, A., 2020b. Tectono-sedimentary evolution of a fossil ocean-continent transition: Tasna nappe, central Alps (SE Switzerland). Geol. Soc. Am. Bull. 1–20. https://doi.org/10.1130/B35310.1/4863878/b35310.pdf

Robertson, A. H. F., & Searle, M. P. (1990). The northern Oman Tethyan continental margin: stratigraphy, structure, concepts and controversies. Geological Society, London, Special Publications, 49(1), 3-25.

Rosenbaum, G., Lister, G.S., Duboz, C., 2002. Relative motions of Africa, Iberia and Europe during

Alpine orogeny. Tectonophysics 359, 117–129. https://doi.org/10.1016/S0040-1951(02)00442-0

Sanfilippo, A., Salters, V., Tribuzio, R., Zanetti, A., 2019. Role of ancient, ultra-depleted mantle in Mid-Ocean-Ridge magmatism. Earth Planet. Sci. Lett. 511, 89–98. https://doi.org/10.1016/j.epsl.2019.01.018

Sauter, D., Cannat, M., Rouméjon, S., Andreani, M., Birot, D., Bronner, A., Brunelli, D., Carlut, J., Delacour, A., Guyader, V., MacLeod, C.J., Manatschal, G., Mendel, V., Ménez, B., Pasini, V., Ruellan, E., Searle, R., 2013. Continuous exhumation of mantle-derived rocks at the Southwest Indian Ridge for 11 million years. Nat. Geosci. 6, 314–320. https://doi.org/10.1038/ngeo1771

Schaltegger, U., Desmurs, L., Manatschal, G., Müntener, O., Meier, M., Frank, M., & Bernoulli, D. (2002). The transition from rifting to sea-floor spreading within a magma-poor rifted margin: Field and isotopic constraints. Terra Nova, 14(3), 156-162.

Schettino, A., & Turco, E. (2011). Tectonic history of the western Tethys since the Late Triassic. Bulletin, 123(1-2), 89-105.Schmid, S.M., Fgenschuh, B., Kissling, E., Schuster, R., Fügenschuh, B., 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

Schmid, S.M., Pfiffner, O.A., Froitzheim, N., Schönborn, G., Kissling, E., 1996. Geophysical-geological transect and tectonic evolution of the Swiss-Italian Alps. Tectonics 15, 1036–1064. https://doi.org/10.1029/96TC00433

Şengör, A.M.C., 2014. Eduard Suess and Global Tectonics: an Illustrated `Short Guide'. Austrian J. Earth Sci. 107, 6–82.

Speranza, F., Minelli, L., Pignatelli, A., Chiappini, M., 2012. The Ionian Sea: The oldest in situ ocean fragment of the world? J. Geophys. Res. B Solid Earth 117. https://doi.org/10.1029/2012JB009475

Stampfli, G. M., 1993, Le Briançonnais, terrain exotique dans les Alpes?: Eclogae Geologicae Helvetiae, v. 86,p. 1–45.

Stampfli, G. M. (2000). Tethyan oceans. Geological society, london, special publications, 173(1), 1-23.Steffen, D., Jaques, C., Nydegger, T. H., Petroons, D., & Wildi, W. (1993). La Brèche du Chablais à son extrémité occidentale (Hte Savoie, France): Sédimentologie, éléments stratigraphiques et interprétation paléogéographique. Eclogae Geologicae Helvetiae, 86(2), 543-568.

Steinmann, G., 1905. Geologische Beobachtungen in den Alpen. Wagners Universitäts-Buchdruckerei.

Suess, E., 1875. Die Entstehung der Alpen. Braumüller. Wien.

Suess, E., 1883. Das Antlitz der Erde, Ia (Erste Abtheilung). F. Tempsky, Prag G. Freytag, Leipzig 310.

1737 Sutra, E., Manatschal, G., Mohn, G., & Unternehr, P. (2013). Quantification and restoration of
1738 extensional deformation along the Western Iberia and Newfoundland rifted margins.
1739 Geochemistry, Geophysics, Geosystems, 14(8), 2575-2597.

1740 Szameitat, L. S., Manatschal, G., Nirrengarten, M., Ferreira, F. J., & Heilbron, M. (2020). Magnetic
1741 characterization of the zigzag shaped J-anomaly: Implications for kinematics and breakup
1742 processes at the Iberia–Newfoundland margins. Terra Nova, 32(5), 369-380.

1743 Tavani, S., Bertok, C., Granado, P., Piana, F., Salas, R., Vigna, B., Muñoz, J.A., 2018. The Iberia-
1744 Eurasia plate boundary east of the Pyrenees. Earth-Science Rev.
1745 https://doi.org/10.1016/j.earscirev.2018.10.008

1746 Termier, P. (1899). Les nappes de recouvrement du Briançonnais. Bull. Soc. géol. France, (3),27, p.
1747 47-84

1748 Tribuzio, R., Thirlwall, M.F., Vannucci, R., 2004. Origin of the Gabbro–Peridotite Association from the
1749 Northern Apennine Ophiolites (Italy). J. Petrol. 45, 1109–1124.
1750 https://doi.org/10.1093/petrology/egh006

1751 Tricart, P., & Lemoine, M. (1988). A l'origine de la structure des Schistes lustrés à ophiolites du
1752 Queyras (Alpes françaises): un mode atypique d'obduction, conséquence de la structure
1753 particulière de la croûte océanique ligure. Comptes rendus de l'Académie des sciences. Série 2,
1754 Mécanique, Physique, Chimie, Sciences de l'univers, Sciences de la Terre, 306(4), 301-306.

1755 Trümpy, R. (1971) Stratigraphy in mountain belts. Quart J Geol SocLond 126:293–318

1756 Trümpy, R., 1975. Penninic-Austroalpine boundary in the Swiss Alps: a presumed former continental
1757 margins and its problems. Am. J. Sci. 275, 209–238.

1758 Trümpy, R. 1980: Geology of Switzerland. schweizerische Geologische Kom-mission, Wepf & co,
1759 basel.

1760 Tugend, J., Manatschal, G., Kusznir, N.J., Masini, E., 2014. Characterizing and identifying structural
1761 domains at rifted continental margins: application to the Bay of Biscay margins and its Western
1762 Pyrenean fossil remnants. Geol. Soc. London Spec. Publ. 413, SP413--3.
1763 https://doi.org/10.1002/2014TC003529

1764 van Hinsbergen, D. J., Vissers, R. L., & Spakman, W. (2014). Origin and consequences of western
1765 Mediterranean subduction, rollback, and slab segmentation. Tectonics, 33(4), 393-419.

1766 Van Hinsbergen, D. J., Torsvik, T. H., Schmid, S. M., Maţenco, L. C., Maffione, M., Vissers, R. L., ... &
1767 Spakman, W. (2020). Orogenic architecture of the Mediterranean region and kinematic
1768 reconstruction of its tectonic evolution since the Triassic. Gondwana Research, 81, 79-229.
1769 Vissers, R.L.M., Meijer, P.T., 2012. Mesozoic rotation of Iberia: Subduction in the Pyrenees?
1770 Earth-Science Rev. 110, 93–110. https://doi.org/10.1016/j.earscirev.2011.11.001

1771 Weissert, H. J., & Bernoulli, D. (1985). A transform margin in the Mesozoic Tethys: evidence from the

Swiss Alps. Geologische rundschau, 74(3), 665-679.

Weidman, M. 1972. Le front de la Breche du Chablais dans le secteur de Saint-Jean-d'Aulph (Haute-Savoie). Géologie Alpine, 48, 229–246.

Wernicke, B., 1985. Uniform-sense normal simple shear of the continental lithosphere. Can. J. Earth Sci. 22, 108–125. https://doi.org/10.1139/e85-009

Whitmarsh, R.B., Manatschal, G., Minshull, T. a, 2001. Evolution of magma-poor continental margins from rifting to seafloor spreading. Nature 413, 150–154. https://doi.org/10.1038/35093085

Wilson, R. C. L., Manatschal, G., & Wise, S. (2001). Rifting along non-volcanic passive margins: stratigraphic and seismic evidence from the Mesozoic successions of the Alps and western Iberia. Geological Society, London, Special Publications, 187(1), 429-452.

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