Tectonophysics 473 (2009) 4–19

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

A type sequence across an ancient magma-poor ocean–continent transition: the example of the western Alpine Tethys ophiolites

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ARTICLE INFO

Article history:
Received 16 February 2008
Received in revised form 11 July 2008
Accepted 19 July 2008
Available online 5 August 2008

Keywords:
Alps
Ophiolites
Ocean–continent transitions
Detachment faults
Tethys

ABSTRACT

The ophiolites from the Alpine Tethys are incompatible with the definition of the classical 3-layered Penrose ophiolite sequence, but they also show features that are inconsistent with ultraslow-spreading ridge sequences or transform settings. The existence of pre-rift contacts between subcontinental mantle and continental crust, the association of top-basement detachment faults with continent-derived blocks (extensional allochthons) and tectono-sedimentary breccias overlying subcontinental mantle, and a post-rift sedimentary evolution identical to that of the adjacent distal margin enable to characterize some of the Alpine Tethys ophiolites as remnants of a former *O*cean *C*ontinent *T*ransition (OCT). Therefore, we propose that at least some of the Alpine Tethys ophiolites are formed by remnants of an ancient *M*agma-*P*oor-*O*cean *C*ontinent *T*ransition, referred to as a MP-OCT sequence. The type sequence consists of the Platta, Tasna and Chenaillet ophiolite units, the former two representing the OCT of the ancient Adriatic and European/Briançonnais conjugate rifted margins, the latter representing a more developed “oceanic” domain. All three units escaped Alpine subduction and preserve pre-Alpine contacts between exhumed basement and a volcano-sedimentary cover sequence. These units preserve the structural, magmatic, hydrothermal and sedimentary record of continental breakup and early seafloor spreading. The observations compare well with those made along the magma-poor Iberia–Newfoundland rifted margins, which are the only example in an OCT where drill holes penetrated into basement. At present, magma-poor rifted margins form up to 50% of all rifted margins worldwide. We argue that MP-OCT sequences are more common in the geological record but were, in part mistaken as either Mid Ocean Ridge or tectonically dismembered Penrose-type ophiolite sections.

1. Introduction

Since the establishment of the new paradigm of plate tectonics in the late sixties of the last century, ophiolites in Alpine-type collisional mountain belts were often equated with former oceanic crust. At present it is generally accepted that the classical ophiolite stratigraphy as conceived by the Penrose conference definition (Anonymous, 1972) is just one among various types. Ophiolites may derive from back-arc, fore-arc or mid-ocean ridge settings, the latter showing a large variability ranging from fast to slow to ultraslow-spreading environments. In this paper, we describe ophiolites that record the final stage of rifting and incipient seafloor spreading in magma-poor rift systems based on observations made in the Platta, Tasna and Chenaillet ophiolites. These ophiolite units are quite distinct from the “classical” ophiolite sequence observed in the Semail ophiolite in Oman (Glennie et al., 1974; Nicolas and Boudier, 1995) or Troodos in Cyprus (Moores and Vine, 1971). In contrast to these “magma-rich” ophiolites, the *M*agma-*P*oor-*O*cean *C*ontinent *T*ransition (MP-OCT) ophiolites are distinguished by the scarcity of mafic plutonic rocks, the absence of a sheeted dike complex, the occurrence of exhumed, ancient subcontinental mantle capped by top-basement detachment faults and overlain by extensional allochthons, tectono-sedimentary breccias and a post-rift sedimentary sequence similar to that of the adjacent distal margin. Along present-day rifted margins, the OCT is covered by a thick pile of sediments at abyssal depth. A ‘complete’ OCT sequence across a magma-poor rift system has only been drilled across the Iberia–Newfoundland rifted margins. However, drilling along these margins is limited to basement highs. This, and the fact that geophysical imaging has very low resolution at deep margins, makes that at present very little is known about the nature of rock types and structures in present-day OCT. Therefore, the sequence described in

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doi:10.1016/j.tecto.2008.07.021

this paper is not only of interest for the study of ophiolites, but also represents a unique natural laboratory that documents continental breakup and the formation of oceanic crust in a magma-poor rift system.

2. Historical perspective

The concept and definition of ophiolites as remnants of former oceanic domains is of first order importance to interpret paleogeographic domains and their evolution during continental collision. With the advent of plate tectonics, many observations made previously in orogens were ignored and replaced by simple concepts that came along with the new ideas of plate tectonics. Examples for such simple concepts are the homogeneous, 3-layered oceanic crust, as defined by the Penrose conference (Anonymous, 1972), or the idea that the transition from rifting to drifting is abrupt, implying that the transition from continental to oceanic crust is a sharp and well defined boundary. Although these simple concepts might explain in a general way continental breakup in magma-rich systems, they are insufficient to explain magma-poor systems presently observed at ultraslow to slow-spreading ridges or in MP-OCT. Thus, despite the undisputed success of plate tectonics, in the case of the ophiolite research, this theory had the side effect that many detailed observations were overlooked and/or ignored in more recent literature. This can be well demonstrated with the history of the Alpine Tethys ophiolites.

Gustav Steinmann was not the first to use the term ophiolite (see Bernoulli et al., 2003 for a review), but he was the first who noted the close association of serpentinites, diabase and radiolarian cherts along the western boundary of the Austroalpine nappes in eastern Switzerland and to interpret this "rock association", later referred to as "Steinmann Trinity", in geodynamic terms. In his view, the "consanguineous" association of ultramafic and mafic material was characteristic for the axial part of the "geosyncline" and the deep ocean floor (Steinmann, 1905). Steinmann interpreted the diabase, spilite, and variolite (variolitic pillow lavas) as intrusive rocks distinctly younger than the associated sediments, and he stressed their characteristic association with deep-sea sediments, notably radiolarian cherts and deep-water limestones of Maiolica facies (Steinmann, 1925, 1927). Argand (1924, p. 299) noted that "A geosyncline will result, in general, from horizontal extension which stretches the raft of sal [continental crust] … This explains the frequent association of greenstones with bathyal or abyssal sediments. … If extension continues, … the geosyncline makes place to an ocean". Until the late sixties, this classic interpretation did not change fundamentally.

The major revolution in the interpretation of the Alpine Tethys ophiolites occurred in the late sixties and early seventies, when Italian geologists showed evidence for stratigraphic contacts between all the individual terms of the ophiolite suite (basalts, gabbros and mantle rocks) and pelagic sediments in the Apennines (Passerini, 1965; Decandia and Elter, 1969; Elter, 1971, 1972; Decandia and Elter, 1972). In the benchmark paper by Decandia and Elter (1972) on the "zona ofiolitifera del Bracco" in the area between Levanto and Val Graveglia in the Ligurian Apennines, these authors concluded that mantle rocks were exhumed tectonically and overlain by Jurassic pelagic sediments (Fig. 1). They described a major unconformity between mantle rocks and overlying basalts and sediments and recognized that the basement was capped by tectono-sedimentary breccias (e.g. ophicalcites). They were also the first who interpreted mantle exhumation as related to a tectonic process and proposed that mantle exhumation

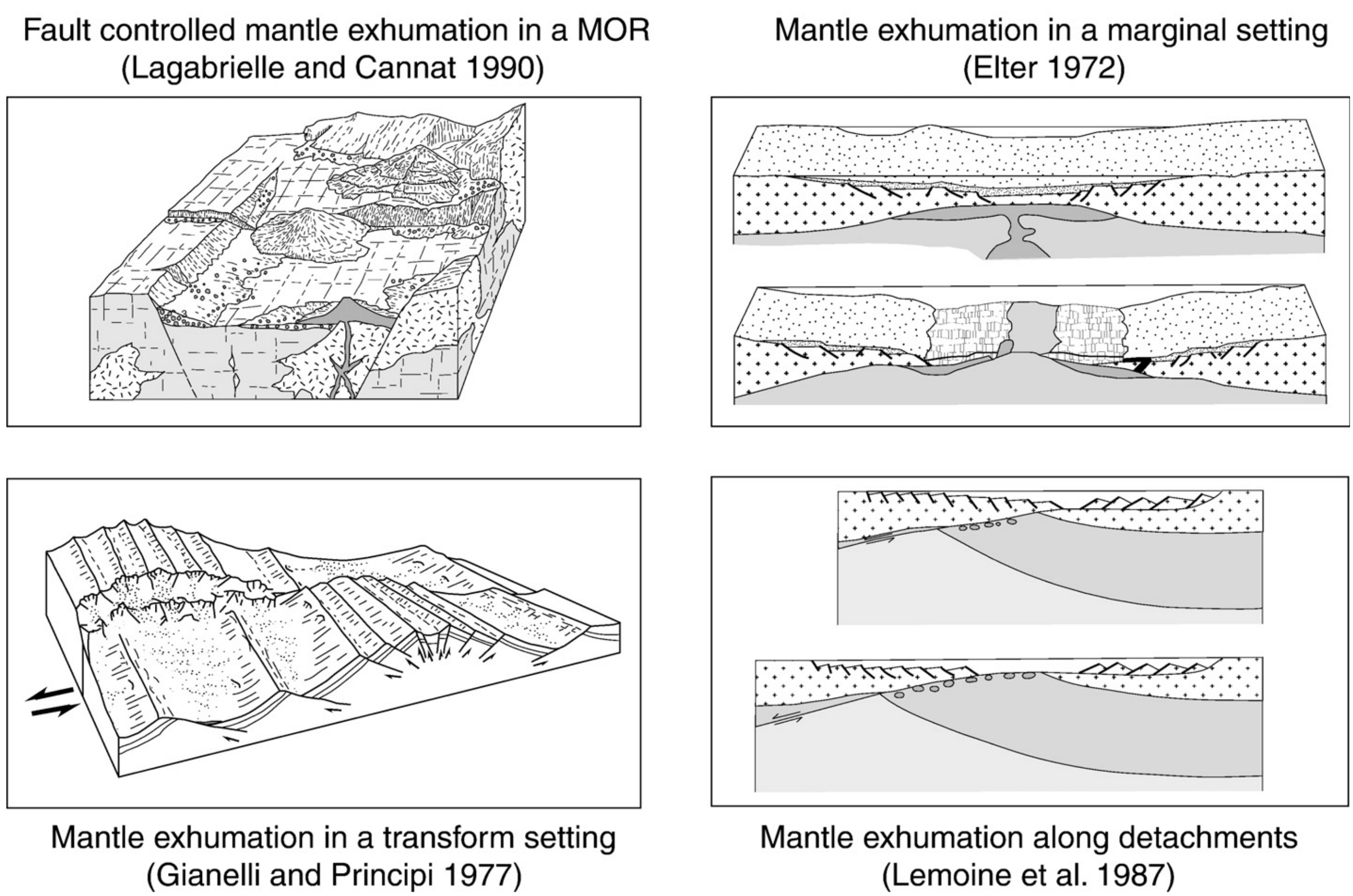

Fig. 1. The four classical models proposed to explain mantle exhumation in the Alpine ophiolites.

had to predate the emplacement of basalts. This interpretation anticipated the discovery of mantle rocks during ODP Leg 103 along the Galicia margin (Boillot et al., 1987) and was at the forefront of concepts that are today proposed to understand continental breakup at magma-poor rifted margins. However, the pioneering work of the Apennine geologists remained largely ignored. The major reason was that studies of the Troodos ophiolites in Cyprus (Moores and Vine, 1971) or the Semail ophiolites in Oman (Glennie et al., 1974) came to completely different conclusions. Since the observations made in these magma-rich ophiolites matched better the first available geophysical data from fast spreading ridges in the Pacific, the 3-layered crust observed in the Troodos and Oman ophiolites was codified during a Penrose Conference in 1972 (Anonymous, 1972) as the type section across an oceanic crust. As a consequence, the observations in the Apennines were either ignored or the ophiolites were re-interpreted as Penrose-type ophiolites, dismembered during Alpine orogeny.

In the seventies and eighties of the last century exhumed mantle rocks were discovered along Transform Zones (Bonatti and Honnorez, 1976) and Slow Spreading Ridges (Karson, 1990; Lagabrielle and Cannat, 1990), and first dredged and then drilled during ODP Leg 103 off Galicia in a marginal setting (Boillot et al., 1980, 1987). In the Alps and Apennines, the evidence for exhumed mantle and gabbroic intrusions that are unconformably overlain by breccias, basalts and pelagic sediments (e.g. Decandia and Elter, 1972) were confirmed in many different places. The geodynamic setting in which mantle exhumation occurred, remained disputed. Gianelli and Principi (1977) and Weissert and Bernoulli (1985) favored a transform setting, Barrett and Spooner (1977), Lagabrielle and Cannat (1990) and Lagabrielle and Lemoine (1997) suggested a slow-spreading system, while Lemoine et al. (1987) proposed, influenced by Wernicke (1981) and the results of the Iberia margin, a simple shear detachment model to explain the asymmetry and in particular the subsidence history of the two Alpine margins (Fig. 1). The discovery of subcontinental mantle in direct contact with marginal sequences in the Tasna (Florineth and Froitzheim, 1994) and Err-Platta (Manatschal and Nievergelt, 1997) and Malenco nappes (Hermann and Müntener, 1996), in the Ligurian domain (Molli, 1996; Marroni et al., 1998; Marroni and Pandolfi, 2007) and in the Pyrenees (Lagabrielle and Bodinier, 2008) supports the idea that at least some of the ophiolites in the Alps, Apennines and Pyrenees are derived from ancient OCTs.

However, the discovery of detachment faults (Karson, 1990), oceanic core complexes (mega-mullion of Tucholke et al., 1998), and various types of crust at ultraslow-spreading systems (e.g. the SW Indian ridge: Dick et al., 2003; Cannat et al., 2006; and the Gakkel ridge: Michael et al., 2003) entirely changed the way of thinking about oceanic crust. The idea of a more or less homogeneous 3-layered crust seems to remain valid only for magma-rich systems. Magma-poor systems are much more heterogeneous and complex. Thus, the description of rock types and structures alone is not sufficient to distinguish between different geodynamic settings in magma-poor systems. This is particularly important when one tries to interpret the geodynamic setting of magma-poor systems.

3. Slow-spreading MOR vs. MP-OCT systems

A prerequisite to distinguish between ophiolite sequences derived from former slow-spreading MOR or MP-OCT settings is to understand the differences between these two settings in present-day oceans. Mid Ocean Ridges might be interpreted as the places on earth where localized tectonic and magmatic accretion occurs, coupled with hydrothermal and seismic activity. The fact that Mid Ocean Ridges are not covered by sediments makes sampling of these zones 'easily' possible. The study of an OCT is in contrast more complex. They are at

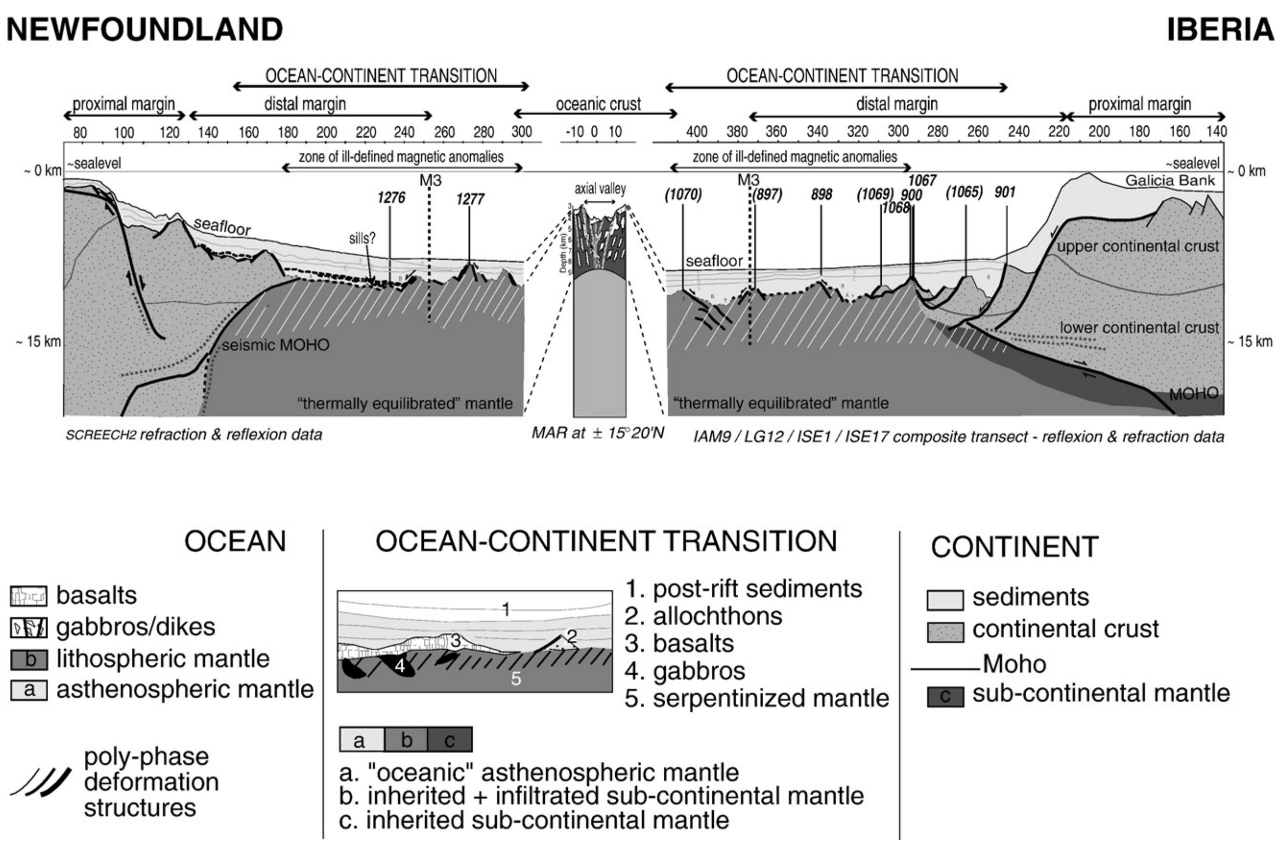

Fig. 2. Cross section across the Iberia–Newfoundland rifted margins (modified after Péron-Pinvidic and Manatschal, in press) and the Mid Atlantic Ridge (modified after Lagabrielle et al., 1998). Note that the ridge and the adjacent conjugate margins are drawn at the same scale.

abyssal depth and covered by kilometers of sediments. A major inconvenience is that present-day examples of places where OCTs form are rare. One site may be the northern Red Sea. Sites like the Woodlark basin, the Gulf of California, or the Tyrrhenian Sea, corresponding to places where oceans are actually forming, are either in back-arc settings or affect thick orogenic crust. Thus, they are not analogues sensu stricto to Atlantic-type OCT discussed here. As a consequence, the relations between the thermal structure, hydrothermal systems, magma distribution and tectonic processes in such systems are poorly understood. OCTs along rifted margins show, like MOR systems, magma-rich and magma-poor end-members. In this paper, we focus on magma-poor systems, which are characterized by fault controlled mantle exhumation, the rare occurrence of magmatic rocks and a complex sedimentary cover. A complete data set from a present-day OCT, including geophysical and drill hole data, is only available from the Iberia–Newfoundland rift system. Therefore, this margin system is referred to as the type margin for MP-OCT (Fig. 2).

Geophysical and drill hole data from the Iberia–Newfoundland OCT show a set of key observations that enable to distinguish between an OCT and a normal oceanic crust (for a more detailed discussion and references see Tucholke and Sibuet (2007), Péron-Pinvidic et al. (2007), Robertson (2007)). OCT at magma-poor rifted margins are characterized by a gradual transition of crustal seismic velocities ranging from 4 to 8 km/s within the uppermost 6 km of the basement, the occurrence of weak and poorly-defined magnetic anomalies and a basement topography formed by ridges and domes (Fig. 2). Drill holes that penetrated and recovered mantle rocks show that these rocks are heterogeneous. On the Iberia margin they are infiltrated and enriched by percolating magmas while on the conjugate margin they are strongly depleted (Müntener and Manatschal, 2006). All drill holes recovered tectono-sedimentary breccias. They cap exhumed and strongly tectonized subcontinental mantle rocks. On the continentward part of the OCT, these breccias contain clasts derived from the adjacent continental crust (ODP Site 1068) while in the holes further oceanwards (Sites 898, 897, 1070) continent-derived clasts were not observed (Fig. 2). They are made of mantle and rare mafic rocks, often impregnated by calcite, which make them indistinguishable from breccias recovered from present-day MOR (ODP Sites 556 and 558). What is important is the discovery of an extensional allochthon formed by continental crust (see ODP Site 1069; Fig. 2). Péron-Pinvidic et al. (2007) showed that this block is separated from the continental crust by a mantle window that has been drilled at ODP Site 1068 (Fig. 2). Both drill hole and geophysical data show that there is, on the scale of the margin, no sharp limit but rather a transition between the OCT and the adjacent first oceanic crust (Péron-Pinvidic et al., 2007). This implies that in order to distinguish between slow-spreading MOR and MP-OCT ophiolites, a range of criteria need to be used, keeping in mind that transitional sequences might be the rule rather than the exception.

4. Time–space relationships in MP-OCT sequences

The discovery of symmetric seafloor spreading recorded by magnetic anomalies in oceanic basins results in a simple time–space relationship, which enables to determine the location of crust as a function of distance from the MOR and its spreading rate. This concept allows the relative position of an ophiolite within a former oceanic basin to be determined, assuming the age of accretion and continental breakup are known and off-axis magmatic accretion can be excluded. However, a prerequisite to use this concept is symmetric seafloor spreading. Péron-Pinvidic et al. (2007) showed that the evolution of an OCT is complex and polyphase and that breakup and onset of seafloor spreading follow a stage of asymmetric mantle exhumation that lasts, in the case of the Iberia–Newfoundland rift system, over tens of millions of years. Thus, OCT are not necessarily symmetric and neither is the processes controlling their formation (Fig. 3).

In a MOR sequence, the age of crustal accretion is either determined by isotopic ages (cooling or crystallization ages), magnetic anomalies, or by the age of the first sediments overlying basement. This is based on the assumption that all magmatic/exhumation processes are localized at the ridge and that the first sediments onlap onto a flat basement next to the ridge. ODP drilling along the Iberia–Newfoundland rifted margins showed that these concepts cannot universally be applied to OCTs. In OCTs, post-rift sediments onlap onto basement highs (Fig. 2) suggesting a major hiatus between basement and the first post-rift sediments. The existence of a hiatus has also been shown in drill holes. For several sites in the OCT, the difference between the basement age (age of exhumation of the basement at the seafloor) and the age of the first sediments can be more than 60 myr (Wilson et al., 2001). This clearly shows that exhumation and accretion of crust in the OCT can at most be approximately dated by the age of the fist sediments overlying basement.

Another important result obtained from the Iberia–Newfoundland rifted margins concerns the age of magmatic rocks in the OCT. Drilling of basement highs located near magnetic anomaly M1 (ODP Sites 1070 and 1277; see Fig. 2) shows that magmatic rocks are made of MORB and alkaline rocks with ages of emplacement that can last over 15 myr (Jagoutz et al., 2007). This means that the ages of magmatic rocks cannot be used per se to determine the age of accretion. The data from the Iberia–Newfoundland rifted margins show that U/Pb ages on

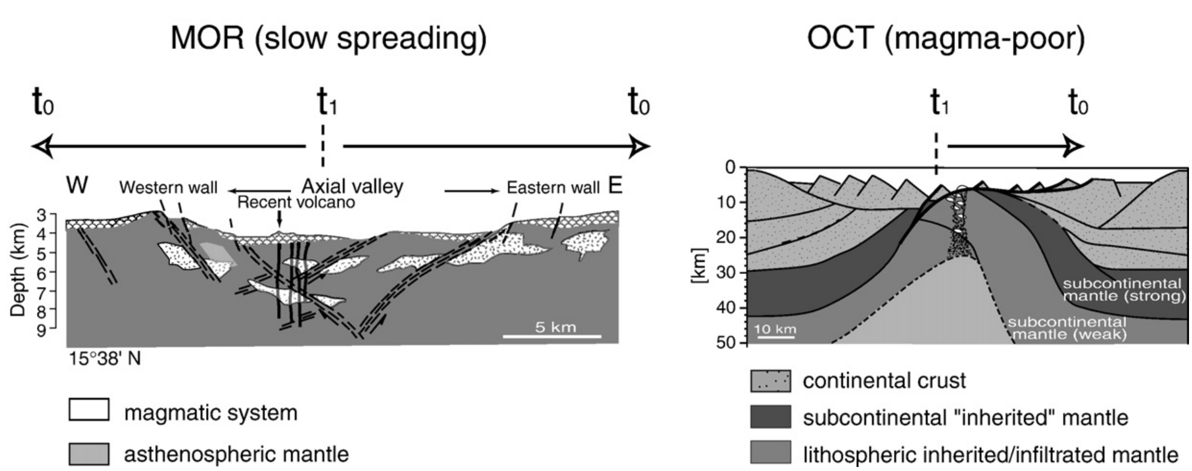

Fig. 3. OCT vs. MOR domains; a simple and first order description of the tectono-magmatic and kinematic evolution of these two domains. Note that the scale of the two systems is very different. The MOR system has been drawn after Lagabrielle et al. (1998) and the OCT system has been modified after Manatschal et al. (2007). Key differences between the two systems are the scale of asymmetry, the proximity to continental crust and the time–space relationships.

zircon and Ar/Ar ages on amphiboles from MOR gabbros only partially correspond with the age of the local corresponding magnetic anomaly. In addition there are intrusive events that are younger than magnetic anomalies, and Ar/Ar ages obtained from plagioclase may be reset and reflect post-accretion hydrothermal processes. As a consequence, they do not date accretion of the crust. Applying these results to ophiolite sequences means that only U/Pb ages on zircon and Ar/Ar ages on hornblende from MOR gabbros may be used to determine the age of accretion of a given piece of oceanic crust. The oldest sediments overlying basement give a minimum age, however, they can be several tens of million years younger than mantle exhumation; alkaline rocks might be younger than breakup, and first mantle exhumation can be expected to occur before the breakup and result in very asymmetric OCT on each side of the ocean (Figs. 2 and 3).

5. From seafloor sequences to ophiolites: emplacement mechanisms

The classical ophiolite concept implies that ophiolites in mountain belts were tectonically emplaced onto continental margins ("obducted") and that they are part of oceanic basement nappes or of tectonic melanges associated with subduction complexes (e.g. Laubscher, 1969; Dewey and Bird, 1970; Coleman, 1971; Gansser, 1974). However, comparing the ophiolites from the Alpine Tethys with respect to ophiolites such as the Oman ophiolite, not only the nature of the ophiolite, but also the emplacement mechanism is different. The Alpine ophiolites do not have a metamorphic sole and the ophiolite bodies are small and are aligned along the mountain chain. This leads to the suggestion that there might be a relation between the geodynamic setting (back-arc, MOR, OCT) and the volume of magma (magma-poor vs. magma-rich) on the one hand and the emplacement mechanism on the other. It is interesting to note that examples of magma-rich OCT sequences, characterized by thick trap basalts, dyke complexes and massive seaward dipping flows are very rare or absent in collisional orogens. This is even more surprising considering that this type of OCT forms at present about 50% of the OCT along rifted margins world wide. Thus, understanding the circumstances under which ophiolite emplacement occurred is important for the interpretation of ophiolite sequences.

In the case of the Alps, the ophiolites were emplaced by different processes and at different stages of the orogenic evolution (Fig. 4). The OCT in the northern Alpine Tethys basin was sampled, together with the units of the northern Adriatic margin, within a Late Cretaceous transpressive fold and thrust belt. The relics of the oceanic crust, the

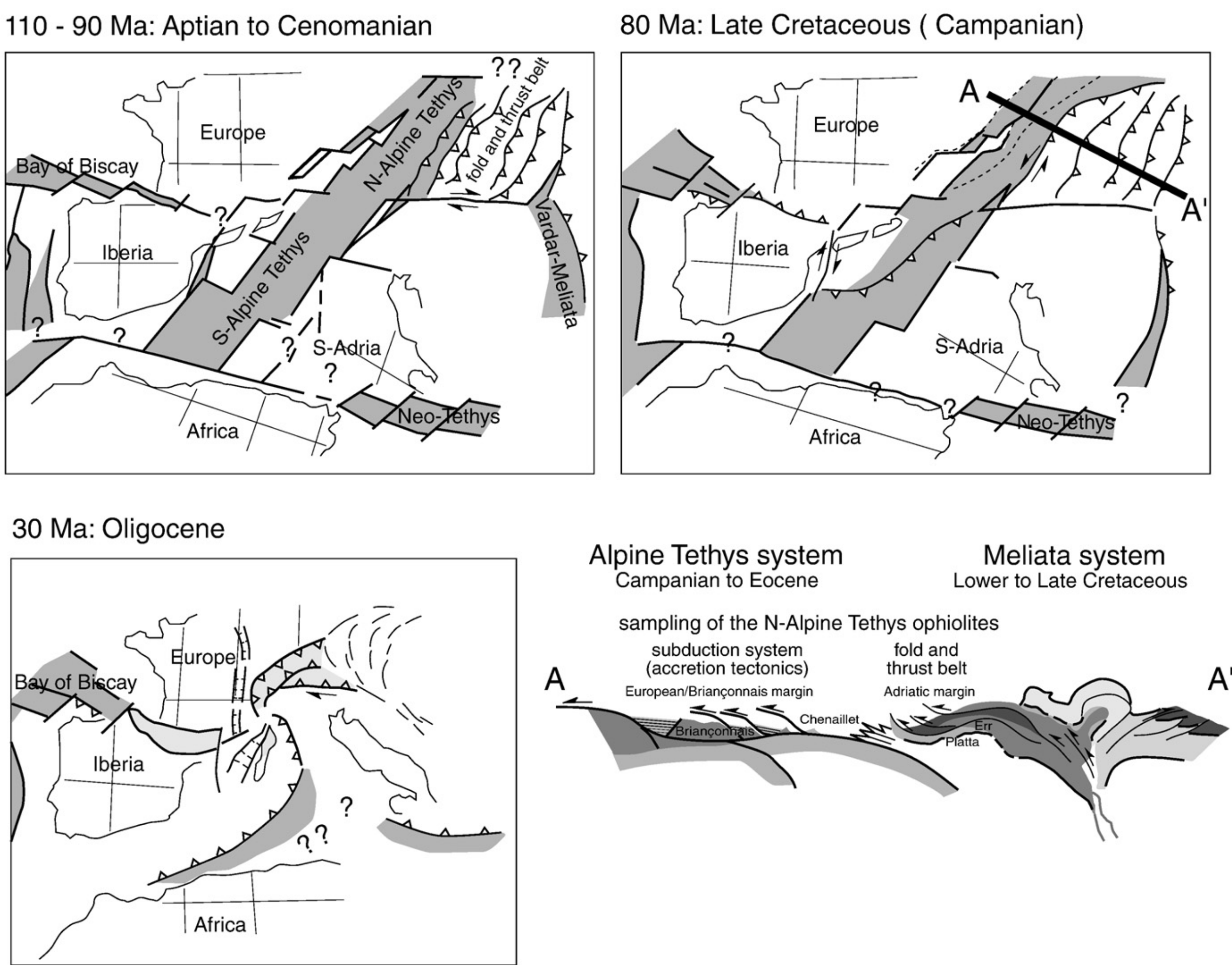

Fig. 4. Paleogeographic maps for the Alpine realm for the Early Cretaceous, the Late Cretaceous and the Oligocene. The section shows the Adriatic-European margins during Late Cretaceous convergence. The sampling of ophiolites derived from the Alpine Tethys basin occurred during three major events: A first one is associated with the closuring of the Meliata-Vardar ocean. During this event, the OCT of the NE-Alpine Tethys was sampled in a fold and thrust belt together with units from the adjacent distal margin. A second event is associated with the subduction and later collision in the north Alpine Tethys realm. During this stage, the ophiolites were either accreted and remain in the accretionary prism (e.g. Chenaillet) or were subducted and exhumed. In a last stage, the ophiolites of the southern Alpine Tethys are sampled in an accretionary prism and thrusted over the Adriatic margin (for more details see text).

OCT and the conjugate European/Briançonnais margin were subducted or accreted during the Late Cretaceous to Eocene subduction (Fig. 4). Thus, only few remnants of these domains are sampled in the mountain chain, either due to accretion in the accretionary prism (e.g. Tasna and Chenaillet) or due to exhumation following subduction (e.g. all units bearing high-pressure metamorphism). In the southern Alpine Tethys basin, subduction initiated, like in the northern basin, in Late Cretaceous time (Molli, 2008) within the oceanic domain. The

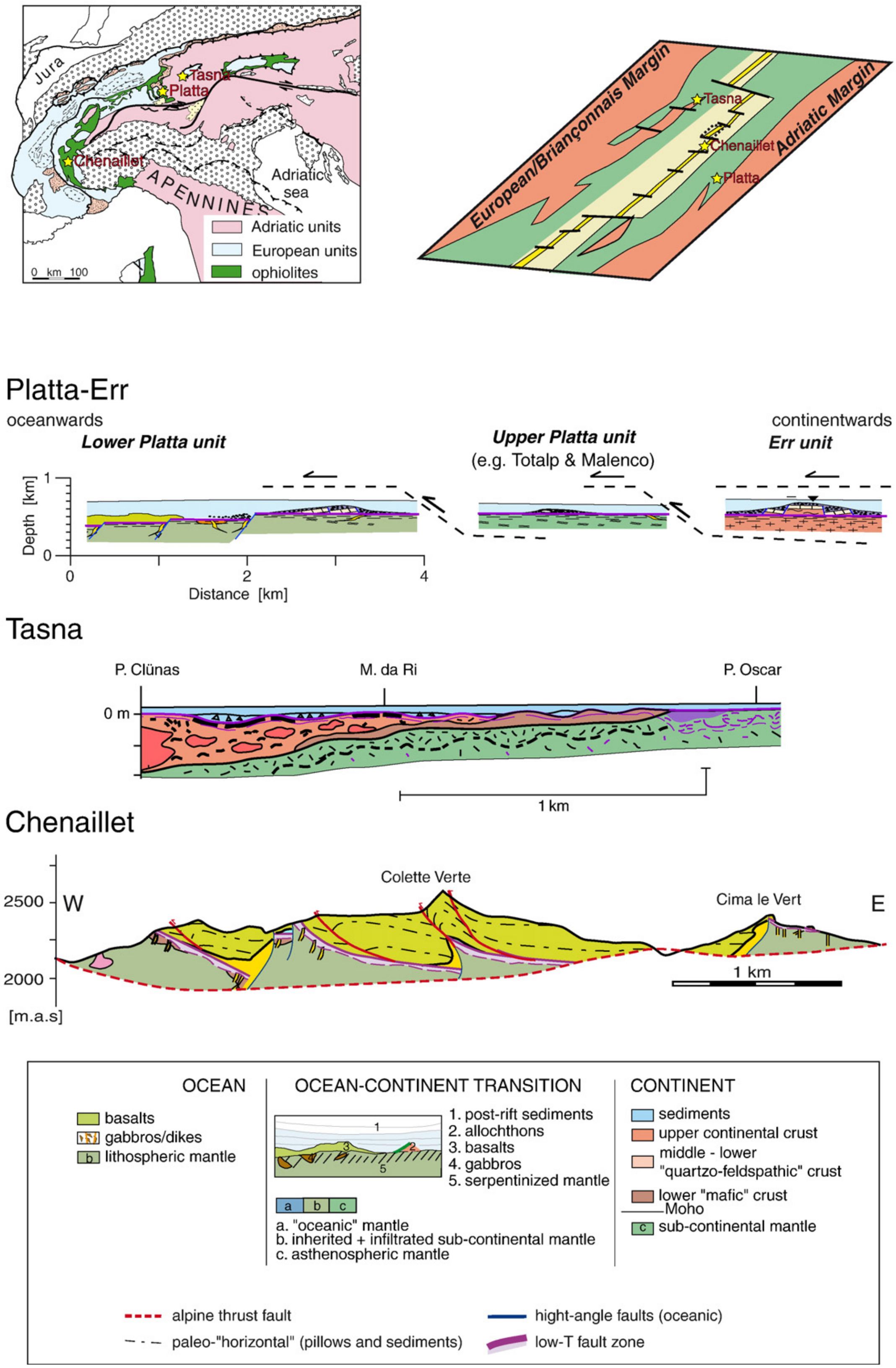

Fig. 5. Sections across the Platta-Err, Tasna and Chenaillet ophiolite units. The maps show the present-day position of these units in the Alps as well as their paleogeographic position in the northern Alpine Tethys basin. The Platta-Err section is modified after Manatschal et al. (2003) and the Tasna section after Manatschal et al. (2006).

final closure of this basin and the final emplacement of the Ligurian ophiolites in the Apennines occurred during Oligocene to Miocene time (Molli, 2008). There, most ophiolites are preserved in huge olistolite blocks and/or tectonic slices, which makes that the reconstruction of a former OCT is less straightforward.

The Alpine Tethys ophiolites are consequently sampled in different ways: (i) either by thrusting in a fold and thrust belt during Late Cretaceous, or (ii) by accretion, subduction and exhumation in an active margin during the latest Cretaceous to Miocene or (iii) were emplaced as olistolites in Cretaceous sediments, before they were accreted and thrusted over the Adriatic margin in the Tertiary (Fig. 4). This explains the different preservation of the former oceanic structures in the ophiolite units. Primary stratigraphic contacts that are not obliterated by pervasive Alpine deformation are only observed in the units that escaped subduction; i.e. in olistolites that were emplaced in sediments during early convergence (Ligurian ophiolites, e.g. Marroni et al., 1998), or in tectonic units that were accreted and remained in the accretionary prism. However, for these examples, the reconstruction of the pre-Alpine position remains difficult. The only remnant of the Alpine Tethys that can be reconstructed with some confidence is the NE part of the northern Alpine Tethys basin. This part was sampled together with the NW Adriatic distal (Err/Bernina) and proximal margin (Upper Austroalpine) within a fold and thrust belt during the collision of the eastern part of Adria with Tisia following the subduction of ocean domains further to the east (e.g. Meliata-Vardar ocean; Froitzheim et al., 1996). In the following, we will focus to the northern Alpine Tethys basin.

6. Tentative reconstruction of a section across a nascent ocean

Paleogeographic reconstructions of orogenic domains are usually obtained by unfolding the orogenic nappe stack (Pleuger et al., 2005). This approach may be justified for units emplaced in fold and thrust belts but much more difficult for units that underwent subduction and subsequent exhumation, or, as shown in the case of the Alps, polyphase convergence linked with multiple subduction zones (Fig. 4). The reconstruction presented here is based therefore on a different approach and considers only units that were not subducted and were not overprinted by pervasive Alpine deformation or metamorphism. Such units, in particular the Platta, Tasna and Chenaillet units, preserve pre-Alpine structures and basement–cover relationships, and most important, two of them preserve the relationship to marginal sequences of the former rifted margin (Fig. 5). Based on these observations, as well as U/Pb ages obtained from zircons from MOR gabbros (see Fig. 6), we propose a paleogeographic reconstruction for these three units in the Alps.

U/Pb ages on zircon from MOR-type gabbros from the ophiolites of the northern Alpine Tethys fall into a narrow age range 166 ± 1 to 155.2 ± 1.2 Ma (Fig. 6). Younger ages for plagiogranites are found in the Chenaillet and Central Alps (Fig. 6). Apart from the Balma and Chiavenna units, where U/Pb ages of about 93 Ma were obtained (Liati and Froitzheim, 2006), all other ages overlap with the age of deposition of radiolarian cherts. These sediments are the first sediments overlying distal continental and oceanic sequences and are therefore the first pelagic post-rift sediments in the OCT dating continental breakup (Decandia and Elter, 1972; Lagabrielle et al., 1984; Bernoulli and Weissert, 1985; Weissert and Bernoulli, 1985; Bill et al., 2001; Lombardo et al., 2002). If one assumes that the U/Pb ages on zircon from MOR gabbros date the accretion of the underlying crust and plate separation rates of ± 2 cm/yr, compatible with the magma-poor nature of the ophiolites, the Alpine ophiolites were sampled within a zone about 200 km wide, which corresponds approximately to the width of the OCT in the Iberia–Newfoundland margins.

The Tasna and Upper Platta units preserve pre-Alpine relationships with marginal sequences of the former continental margin, which makes a strong case for a position near the continent within the OCT (Fig. 5). The reconstruction of units that were located further oceanwards is more difficult and depends mainly on the question whether the accreted, subducted and exhumed units derive from the upper or lower plate of the presumed subduction zone. In the case that the units derived from the lower plate (European plate), all ophiolites in the Western Alps show high pressure, including Lanzo and Sesia, the latter representing a crustal unit, would derive from the European/Briançonnais side. However, we cannot exclude that these units primarily derive from the upper plate, which would put these units on the Adriatic margin (see therefore the two possible paleogeographic positions for Lanzo in Fig. 6). Leaving aside the eternal discussion about the paleogeographic position of the other West-Alpine units, we will focus on the upper Chenaillet unit. This unit was not affected by high-pressure metamorphism, and the U/Pb dating on zircons from MOR-type leucodiorites gives an age of 156 ± 3 Ma (Late Jurassic; Costa and Caby, 2001), which we interpret, as previously discussed, as the accretion age of this crust. Our reconstruction shown in Fig. 7 coincides with the time when the gabbros today exposed in the Chenaillet ophiolite were accreted.

After the examination of most Alpine ophiolites, we propose that the Platta, Tasna and Chenaillet units encompass virtually all elements that are characteristic for a type section across a MP-OCT (Fig. 7). This section illustrates the evolution from initial mantle exhumation (Tasna and Upper Platta), to the activity of a magmatic system (Lower Platta) to the early (?) stages of seafloor spreading (Chenaillet). Although our reconstruction is a simplified 2-D section, we are aware that the units represented here did not derive from a former E–W section across the Late Jurassic Alpine Tethys basin, but rather sampled domains situated at different latitudes in the basin (Fig. 6). However, the observation that MOR gabbros provide similar ages all along the basin and correlate well with the first pelagic sediments suggests that lateral correlations are reasonable. This is also supported by the observation that the adjacent most distal continental domains (Briançonnais and the Lower Austroalpine) can be correlated over hundreds of kilometers along the Alpine chain. We therefore define 3 domains within the northern Alpine Tethys basin; the Adriatic and European/Briançonnais OCT, and a more oceanic unit of largely unknown extent.

7. Remnants of ancient OCTs preserved in the Alps

7.1. Remnants of the Adriatic OCT

The Totalp-Platta-Malenco units are derived from the SE margin of the Alpine Tethys. This domain was sampled in a fold and thrust belt within an external part of a Late Cretaceous orogen that was situated on the northwestern border of Adria (Fig. 4). The southern (Malenco) and northern (Totalp) units were more affected by later Tertiary N–S directed deformation, that makes that paleogeographic reconstructions are better constrained for the northern Platta domain. In a section across the present Platta nappe, two units can be distinguished, an Upper and a Lower Platta Unit (Fig. 5; Desmurs et al., 2001; Schaltegger et al., 2002). These units are separated by a thrust. Major changes in the mantle composition and the volume and type of magma can be observed between these two units (Desmurs et al., 2002; Müntener et al., 2004). Of particular importance is that the two units observed in the Platta nappe occur in the same nappe stack together with units of the adjacent distal and proximal margins (Manatschal and Nievergelt, 1997) (Fig. 4). It is also important to note that in the Malenco unit, representing the southern continuation of the Upper Platta unit, a Permian gabbro body (Hansmann et al., 2001) is found to be intrusive in lower crustal and mantle rocks, indicating that the contact between mantle and lower continental crust has to be Permian or older (Trommsdorff et al., 1993; Müntener and Hermann, 1996). As a consequence, the mantle rocks of the Malenco unit represent the pre-rift subcontinental mantle. This underscores the

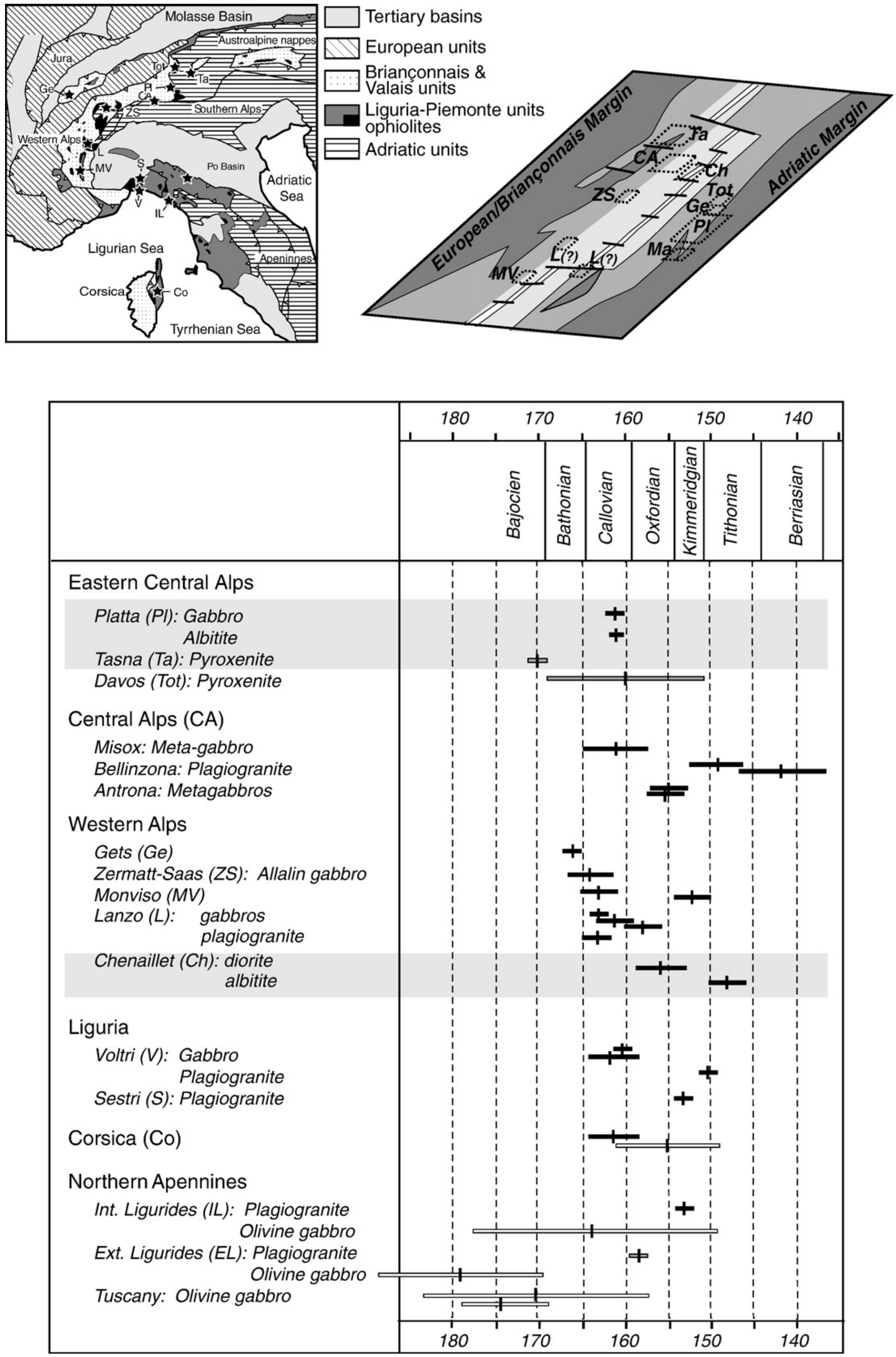

Fig. 6. Compiled age determinations of mafic rocks from the Piemont-Ligurian ocean. U–Pb on zircons: black bars, Ar–Ar on amphiboles: grey bars, Sm–Nd mineral isochrones: white bars. Data sources: Ohnenstetter et al. (1981), Peters and Stettler (1987), Borsi et al. (1996), Bill et al. (1997), Rampone et al. (1998), Rubatto et al. (1998), Costa and Caby (2001), Lombardo et al. (2002), Schaltegger et al., (2002), Rubatto and Hermann (2003), Rubatto and Scambelluri (2003), Stucki et al. (2003), Rampone (2004), Tribuzio et al. (2004), Liati et al. (2005), Manatschal et al. (2006), Kaczmarek et al. (2008), Rubatto et al. (2008), and Villa, personal communication. The maps show the present-day distribution of the units in the Alps and their interpreted position in the ancient Alpine Tethys ocean. (Ca: Central Alps; Ch: Chenaillet; Ge: Gets; L: Lanzo; Ma: Malenco; MV: Monviso; Pl: Platta; Ta: Tasna; Tot: Totalp; ZS; Zermatt-Saas).

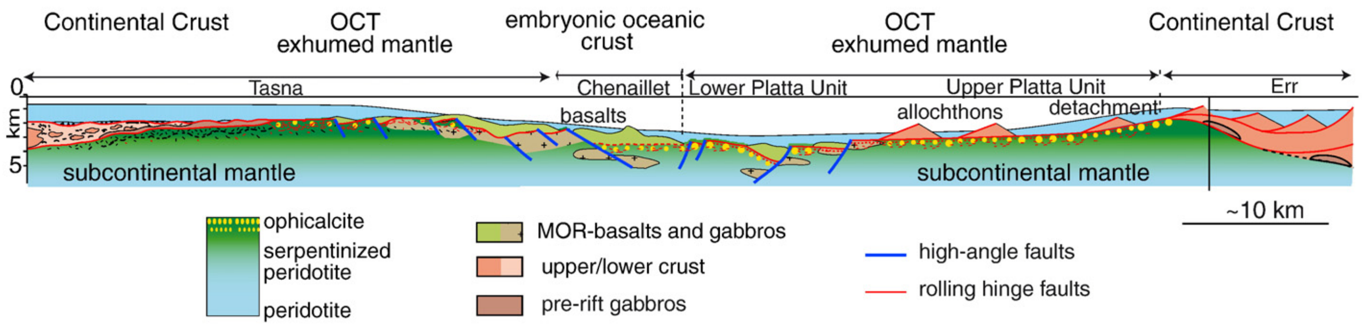

Fig. 7. Tentative palinspastic reconstruction of a section across a nascent ocean based on the observations made in the Tasna, Chenaillet and Platta units. The section shows the observed relationships between detachment structures, associated sediments, exhumed mantle rocks, and intrusive and extrusive magmatic rocks and may be considered as a type section across a magma-poor ocean–continent transition.

close relationship between mantle and continental units and is also important for the following discussion concerning the origin and nature of the mantle found in the OCT. Remnants of the most distal Adriatic margin are also exposed and described from the Canavese und Ivrea units in the S-Alps (Ferrando et al., 2004) and the External Ligurides (Marroni et al., 1998; Montanini and Tribuzio, 2001; Marroni and Pandolfi, 2007).

7.2. Remnants of the Briançonnais/European OCT

The conjugate margin of the Adriatic margin was subducted together with the oceanic crust. Some remnants were exhumed and are today preserved in the western Alps. These units are metamorphosed under blueschist to eclogite facies conditions and are strongly deformed, which makes accurate reconstructions of their paleogeographic position rather speculative. This explains the debates concerning the paleogeographic position of units such as the Sesia-Lanzo zone (Lagabrielle and Cannat 1990; Froitzheim and Manatschal, 1996) or the opening of an Early Cretaceous ocean in the Alps (Valais ocean) (Liati et al., 2005), which in our opinion is poorly supported by the existing data (e.g. Masson, 2002; Manatschal et al., 2006; Beltrando et al., 2007; Masson et al., 2008), and age determinations on oceanic mafic rocks display large variations for units that are associated to the Valais basin (e.g. Liati et al., 2005; Liati and Froitzheim, 2006). Although for most ophiolites exposed in the western Alps a confident kinematic reconstruction is not possible, the occurrence of continent-derived detritus and allochthons, radiolarian cherts of late Middle Jurassic age, and U/Pb ages on zircons from MOR gabbros ranging between 166 and 155 Ma suggests that all these units derived from the vicinity of continental units. As outlined above, a conclusive interpretation of the paleogeographic position of high-pressure ophiolites is not possible, however, we prefer that all those units that record a high-pressure imprint were part of the subducting plate rather than of the upper plate. This is mainly because remnants of the Adriatic OCT are preserved in a thrust stack that was already formed when subduction started in the northern Alpine Tethys basin (see above). If this interpretation is correct, it would suggest that all units exposed in the most internal parts of the Alps, i.e. Zermatt, Lanzo, Viso, probably also Corsica, are derived from the European/Briançonnais OCT (Fig. 6; remark two possible positions for Lanzo and Sesia). Units of the Briançonnais/European margin that escaped subduction, occur throughout the Alps. These are the Briançonnais units that carry very characteristic Middle Jurassic shallow marine sediments (Lemoine et al., 1987; Borel, 1995). A well-preserved example is the Tasna unit in the Engiadina window in SE Switzerland. The Tasna unit consists of a wedge of continental crust that is separated from the underlying mantle by a detachment fault (Fig. 5). Both mantle and continental rocks are capped by a brittle, top-basement detachment fault that is sealed by Lower Cretaceous sediments that are characteristic for the Briançonnais/European domain (Florineth and Froitzheim, 1994; Manatschal et al., 2006). The paleogeographic position of Tasna has therefore to be located on the European/Briançonnais margin. Florineth and Froitzheim (1994) originally suggested that Tasna formed during the opening of an Early Cretaceous ocean separating the Briançonnais from the European margin. On the basis of new field observations and radiometric dating, Manatschal et al. (2006) re-interpreted the position of the Tasna OCT and suggested that it formed during the opening of the Alpine Tethys in Jurassic time (for a more detailed discussion of the paleogeographic position of Tasna, see Manatschal et al. (2006), and for a general discussion of 'the Valais problem' see Masson (2002) and Masson et al. (2008)).

8. Remnants of oceanic lithosphere in the Alps

In the Alps evidence for true oceanic lithosphere, i.e. units in which mantle and magmatic sequences are genetically linked, are not observed. The one possible exception is the Monte Maggiore unit in Corsica, although this unit does not include a cover unit (Rampone, 2004). The ophiolite that shows the closest affinity to what one may call "oceanic crust" in a loose sense in the Alps is the Chenaillet ophiolite (Fig. 5). This ophiolite is exposed in the Franco–Italian Alps. It is, in contrast to the lower Lago Nero unit, only weakly affected by Alpine deformation (e.g. Bertrand et al., 1987) and it represents a well-preserved ocean-floor sequence that yields U/Pb ages on zircons from MOR diorites that are 5–10 myr younger than the oldest ages observed in the Alps. Assuming accretion rates of ± 5 to 10 mm/yr half rate, which are characteristic for magma-poor systems, the Chenaillet ophiolite can be considered to have formed at about 50 to 100 km away from the location of breakup.

9. Characterization of an OCT seafloor sequence

In the following sections we describe the structures and lithologies observed in a section across the former OCT of the Alpine Tethys (Fig. 7). Because the Platta, Chenaillet and Tasna units capture all key features observed in Alpine ophiolites, we rely on the assumption that these 3 units are representative, and might be used as a type section for OCTs of magma-poor rift systems. Although tectonic, magmatic, hydrothermal and sedimentary processes are intimately related and cannot be separated from each other, we summarize the most pertinent features in a topological description.

10. Structures in the OCT

The most prominent structures observed in a OCT are top-basement detachment faults. Top-basement detachment faults are characterized by a specific assemblage of rocks, including cataclasites (e.g. damage zone) and gouges (core zones), the latter two often "impregnated" by calcite near the top of the basement (ophicalcite), and overlain by tectono-sedimentary breccias that grade into sedimentary breccias and post-rift sediments (Fig. 8). These detachment faults overprint mylonitic shear zones in peridotites and gabbros in the footwall and are overprinted further oceanwards by syn-magmatic high-angle normal faults.

10.1. Top-basement detachment faults

Top-basement detachment faults are fault zones that are exhumed at the seafloor as a consequence of ongoing extension. It took a long time to recognize these structures as faults. Certainly the most simple reason is that in contrast to habitual faults, defined as the interface between a hanging wall and a footwall block, these faults do not carry any longer their original hanging wall. Because these faults are at low angles and the exhumed brittle fault rocks are often reworked and re-deposited along the exhumed fault surface, many geologists interpreted these contacts as either sedimentary or reactivated Alpine tectonic contacts. The occurrence of ophicalcites associated with top-

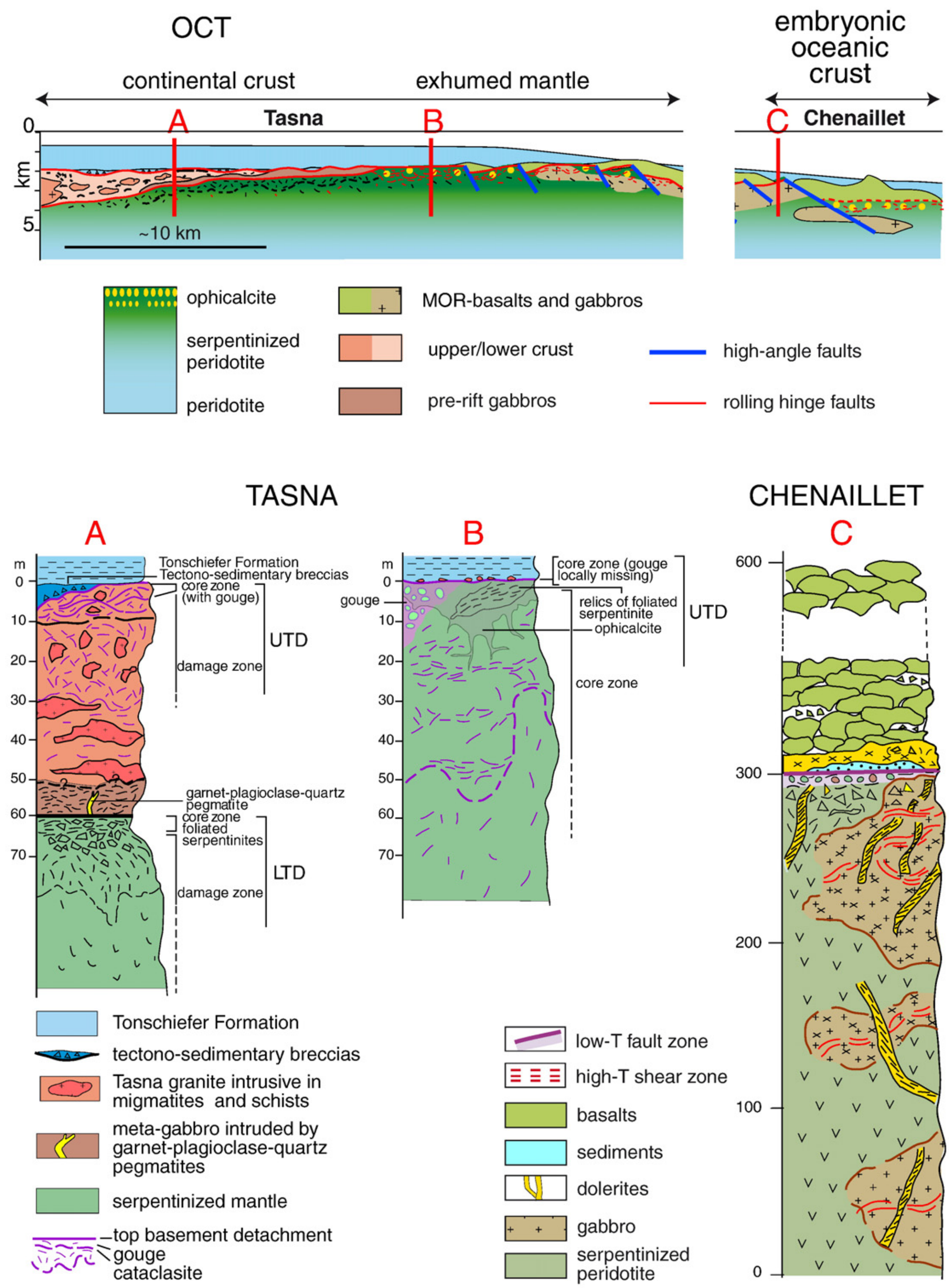

Fig. 8. Lithologies and deformation structures in an ocean–continent transition as seen in the Tasna and Chenaillet units. Sections A, B and C show vertical sections across the most distal margin, the exhumed mantle and a more developed oceanic domain. Observations from the Tasna are modified after Manatschal et al. (2006).

basement detachment faults made that these contacts were interpreted as weathering (calcrete) crusts on subaerially exposed mantle (Folk and McBride, 1976), as magmatic carbonatites (Bailey and McCallien, 1960) or metamorphic contacts similar to metamorphic soles (Cornelius, 1935; Peters, 1963). The first who interpreted ophicalcites as the result of tectonic processes were Decandia and Elter (1972), Bonatti et al. (1974) and Bernoulli and Jenkyns (1974). Today, brittle fault rocks, i.e. cataclasites and gouges associated with ophicalcites and tectono-sedimentary breccias are widely recognized from mid-ocean ridges (e.g. Escartin et al., 2003; Boschi et al., 2006) and have been drilled along the Iberia–Newfoundland margins. Indeed, all drill sites that penetrated basement along the Iberia–Newfoundland margins sampled sedimentary breccias that pass down-hole into tectono-sedimentary breccias that overlie brittle fault rocks. Often these rocks are impregnated near the seafloor by calcite (Manatschal et al., 2001; Robertson, 2007). Similar rock associations but of different composition, are also described from low-angle detachment faults in continental crust (Florineth and Froitzheim, 1994; Manatschal et al., 2006, 2007).

An idealized section across a top-basement detachment fault starts, some tens to some hundred meters below the top of the basement, with a protolith: often a foliated, massive serpentinized peridotite or a gabbro (Fig. 8). Up-section, fractures and veins filled by chlorite and serpentine minerals mark the transition into serpentinite or gabbro cataclasites. Locally, bands of localized deformation occur, that are formed by foliated serpentinite cataclasites. The intensity of the brittle deformation increases up-section and develops into a core zone, which is formed by serpentinite gouges. Although it looks as if the gouges are the result of extreme cataclastic deformation (therefore the term ultra-cataclasite is often used), the contact between gouges and cataclasites is sharp (Fig. 8). In many places it can be observed that the gouges are injected into the surrounding cataclasites. The gouges are characterized by rounded or elongated clasts, the latter defining a lineation. In the matrix, a foliation is also observed and defined by serpentine minerals. Petro-structural investigations of the fault rocks reveal a syn-tectonic retrograde metamorphic evolution. Clasts of dolerite within the fault zone suggest that detachment faulting was accompanied by magmatic activity. Hydrothermal alteration is indicated by strong mineralogical and chemical modifications. A penetrative impregnation/replacement by calcite is observed near the seafloor, which forms the characteristic “ophicalcites”. Locally the sections are incomplete, which might be due to seafloor erosion or gravitational processes that remove, rework and redeposit the fault rocks along the exhumed fault surface leading to tectono-sedimentary breccias.

Very similar rock associations are also observed on oceanic and metamorphic core complexes in oceanic and continental domains. Thus, this rock association is characteristic for top-basement detachment faults rather than an OCT setting. However, the occurrence of continent-derived clasts in tectono-sedimentary breccias overlying exhumed subcontinental mantle, observed in the Tasna and Platta units (Fig. 5) as well as drilled off Iberia (ODP Site 1068; Fig. 2), might represent a good fingerprint for an OCT. Another important observation is that all the deformation that is related to top-basement detachment faults occurs in the “brittle” field and affects an already serpentinized mantle.

10.1.1. Mylonitic shear zones

Mylonitic shear zones are observed in mantle and gabbros throughout the OCT. They are truncated by top-basement detachment faults. Where shear sense criteria are available, the mylonitic shear zones often show a sense of shear opposite to that of the top-basement detachment faults. Therefore, it is still unclear whether the peridotite mylonites are related to detachment faulting or if they are much older. Based on the kinematics and their relationship to the brittle fault zone, it can be excluded that the mylonites form the prolongation of the brittle detachment faults at depth. In the Chenaillet ophiolite, gabbro mylonites associated with leucodiorites (U/Pb- on zircon: 156 ± 3 Ma; Costa and Caby, 2001) are likely to be related to the exhumation history of these rocks to the seafloor. Mével et al. (1978), Caby (1995) and Costa and Caby (2001) showed that these mylonites formed in the presence of magma and/or high-temperature fluids, as indicated by the crystallization of syn-deformational amphiboles and the occurrence of syn-tectonic emplacement of magmatic veins in the mylonitized gabbros.

10.1.2. High-angle faults

High-angle faults are observed across the whole OCT, but in many cases they were obliterated by Alpine deformation (in particular in the Lower Platta unit). In the continental crust, high-angle faults are cut by top-basement detachment faults (Manatschal, 2004). Further oceanwards high-angle faults cut low-angle detachment faults (Fig. 7). This is particularly well observed in the Chenaillet unit (Fig. 5). In this unit, N–S trending high-angle normal faults can be seen to truncate and displace the top-basement detachment faults, leading to small domino-like structures. The basins, limited by these high-angle faults, are some hundreds to a few kilometers wide and few tens to some hundreds of meters deep. Because the high-angle faults are sealed locally by basalts and masked by volcanic edifices, we interpret them as oceanic structures being active during the emplacement of the basalts. The alignment of porphyritic basaltic dykes parallel to, and their increasing abundance towards the high-angle faults suggests that they may have served as feeder channels for the overlying volcanic rocks.

11. Mantle rocks in the OCT

The petrologic and geochemical study of mantle rocks in the Alps (Piccardo et al., 2004; Müntener et al., 2004) shows a large variability documenting complex and polyphase processes which are comparable to those found in mantle rocks drilled from the present-day OCT in the Iberia–Newfoundland margin (Müntener and Manatschal, 2006). Although in detail the mantle rocks are complex and heterogeneous, they can be grouped in three major types.

A first type is identified in the Upper Platta and Tasna units (Fig. 5), but occurs also in the Totalp, Malenco and the External Ligurides. This mantle type is dominated by spinel lherzolites, rich in pyroxenites. Trace and major element compositions in clinopyroxene show that these rocks equilibrated in the spinel peridotite field in the lithosphere (~800 to 950 °C) (Müntener et al., 2000, Montanini et al., 2006). Because these rocks are welded by Permian gabbros to the lower crust (e.g. Malenco; Müntener and Hermann, 1996; Hermann et al., 1997), the classical interpretation for this type is that it represents the old lithospheric mantle that was beneath the continental crust before onset of rifting.

A second type of mantle can be identified in the Lower Platta unit and the Chenaillet unit (Fig. 5). This mantle type is made of serpentinized lherzolites and subordinate harzburgites and dunites. Microstructures reminiscent of impregnation, and cpx major and trace element chemistry indicate that spinel peridotite is (locally) replaced by plagioclase-bearing assemblages. Pyroxene thermometry on primary minerals indicates high temperatures of equilibration (≥1200 °C) for the mantle rocks. In contrast to the first mantle type, it shows rare pyroxenite dykes and it is equilibrated at higher temperatures under lower pressures in the plagioclase stability field. A Sm–Nd model age obtained from one peridotite from the Platta nappe shows that these rocks were depleted during post-Variscan times (Müntener et al., 2004). In the same outcrop, geochemical data indicate that adjacent peridotites underwent a pervasive impregnation by tholeiitic melts, similar to what has been found in the Apennines (Müntener and Piccardo, 2003; Piccardo et al., 2004) and the Iberian margin (Cornen et al., 1996; Müntener and Manatschal, 2006). Trace and major element compositions from clinopyroxene derived from impregnated peridotite show similar compositions like those from Lanzo Sud, parts of the external Ligurides and Chenaillet. Since magma infiltration/impregnation occurred after depletion, impregnation most likely post-dates Permian partial melting events and may be older than the Middle Jurassic exhumation. Sm–Nd plagioclase–clinopyroxene isochrones on mantle rocks gave 164 ± 20 Ma (Rampone et al., 1995), which suggests that infiltration might be of Jurassic age. Indirect constraints for the age of the infiltration can be obtained from their relation with mylonites and fault zones. In the case of Lanzo, melt migration was contemporaneous with the development of mantle shear zones, that in turn are cut by gabbro dikes dated by U/Pb on zircon at 162 ± 2 Ma (Kaczmarek et al., 2008) (Fig. 6). Thus, magma infiltration has to be older and began prior to mantle exhumation at the seafloor, suggesting that extreme crustal thinning during final rifting was accompanied by melt infiltration at depth.

A third type of mantle rock that is expected to occur in an oceanic domain is a depleted mantle that is genetically linked to the MOR magmatic rocks found in the ophiolite sequence. Such mantle rocks could so far only be found in the Monte Maggiore ophiolite in Corsica (Rampone, 2004). This suggests that true oceanic crust is rarely preserved in the Alpine ophiolites.

12. Magmatic rocks in the OCT

In the Alpine ophiolites, three different types of magmatism related to the transition from late rifting to seafloor spreading could be identified: 1) basaltic magma that was infiltrated in and reacted with mantle rocks, 2) MOR-type magmatic rocks that occur as generally small (<1 km) gabbro bodies and/or basaltic extrusions, 3) alkaline intrusive and extrusive rocks. The volume of magmatic rocks is generally increasing oceanwards. At the zone between continental crust and exhumed mantle (e.g. Tasna, Upper Platta) magmatic rocks are rare or absent. Further oceanwards all three types of magmatism occur. MOR magmatic rocks are gabbros, dolerites and basalts. The gabbros form individual small intrusions and each gabbro body represents a different batch of melt. They intrude mantle peridotites that were previously affected by magma percolation. Locally, there is evidence that they intruded while the surrounding mantle was already serpentinized (Desmurs et al., 2001), suggesting a very shallow depth of intrusion. The gabbros range from troctolite and olivine-gabbros to Fe–Ti gabbros and plagiogranite, and show clear evidence of syn-magmatic deformation, partially obliterated by retrograde amphibolite and low-grade metamorphic processes. The occurrence of syn-magmatic mylonitic shear zones with syn-kinematic amphibole in gabbros (Mével et al., 1978; Costa and Caby, 2001; Desmurs et al., 2001) also suggests that these gabbros were intruding into tectonically active systems with complex relations between magmatism, hydrothermal alteration and deformation. Dolerite dykes are not very common, and where they are observed, they are tectonized at the top of the mantle. The basalts near the continent form isolated volcanoes made up of mainly pillow breccias, further oceanwards they are related to high-angle faulting and form up to 300 m thick layers formed by pillows and massive flows (Fig. 8). Desmurs et al. (2002) discovered that the magma-composition changes from T to N-MORB going oceanwards. Hf isotopic composition and the εNd values document a MORB-type, depleted mantle source of these rocks (Schaltegger et al., 2002).

The relative age relationships between the different types of igneous rocks found in the OCT are, on an outcrop scale, documented by cross cutting relationships and absolute age dating. MOR gabbros from the Lower Platta unit intrude infiltrated mantle rocks. U/Pb ages on zircons from these MOR gabbros gave 161 ± 1 Ma (Schaltegger et al., 2002) indicating that the infiltration had to occur before 161 Ma. Albitites recording the same U/Pb zircon ages are associated with gabbros and interpreted to result from differentiation of the gabbros. Peters and Dietrich (pers. communication) suggested that alkaline basalts were intruding Lower Cretaceous sediments. In the Chenaillet unit, the plagiogranites are about 8 myr younger than the MOR gabbros (Costa and Caby, 2001). Although the absolute age of magma percolation in the mantle is not well constrained, field data and relative age relationships suggest that refertilization preceded the emplacement of the first gabbros and dolerites. The latter are time equivalent to the deposition of the radiolarian cherts, dated as Callovian to Bathonian (167 to 161 Ma; Bill et al., 2001). Because these are the first sediments that cover oceanic rocks as well as the adjacent distal margin, they are assumed to be contemporaneous with continental breakup (Wilson et al., 2001). The alkaline rocks, if present, are post breakup and are emplaced in the OCT. These age relationships are very similar to those described from the Iberia–Newfoundland margins (Jagoutz et al., 2007).

13. Hydrothermal processes

Hydrothermal processes found in the ophiolites of the Alps can be subdivided into three groups: 1) high-temperature hydrothermal processes, 2) serpentinization processes, and 3) formation of ophicalcites. These three processes are observed to occur across the whole OCT.

Remnants of high-temperature hydrothermal processes are mainly observed in mylonitized gabbros. In particular in the Chenaillet example, high-temperature, syn-magmatic mylonites show brown amphibole recrystallizing around pyroxenes (Mével et al., 1978). Evidence for the growth of high-T hydrous minerals is also found in mantle shear zones from the Lanzo massif (Kaczmarek, 2007). However, if this high-temperature hydrothermal event is a penetrative event, or if it occurred only along shear zones (where it is found today) is difficult to determine.

Serpentinization in Alpine mantle rocks is pervasive and often almost complete. Olivine is rare, cpx and opx are preserved only occasionally. In this context it is important to note that most Alpine mantle sections preserve remnants of ophicalcites, sediments or basalts. This indicates that they had reached a very shallow level in the crust, i.e. the uppermost 300 to 500 m in the OCT. This suggests the existence of a major rheological contrast at that depth, which may either correspond to a serpentinization front or magmatic underplating. Velocities obtained from present-day OCT suggest that serpentinization can be complete as far down as 2 km (Chian et al., 1999). A well studied example concerning serpentinization processes is the Tasna OCT (Manatschal et al., 2006). Detailed chemical and isotopic data, and structural studies have been used to constrain serpentinization across a section perpendicular to the seafloor. The results show that serpentinization is a polyphase process that predates, but also post-dates the development of the detachment faults and their exhumation to the seafloor (Manatschal et al., 2006). Thus, serpentinization presumably initiated beneath the thinned continental crust. Evidence for major hydrothermal processes that are linked to mantle exhumation might also explain the enrichment of Cr, Ni and Mg along detachment faults in the overlying continental crust (Manatschal et al., 2000). Although the observations made in the Platta and Chenaillet units and off Iberia suggest that serpentinization is a pervasive process that occurs during mantle exhumation, in the Lanzo peridotite serpentinization was less efficient, despite the evidence of exposure at the seafloor (Pelletier and Müntener, 2006).

"Ophicalcites" are clast- or matrix-supported breccias composed of fragments of ±serpentinized peridotites set in a matrix of red limestone and/or cemented by sparry calcite capping exhumed mantle. These breccias are very common in OCT and are always associated with top-basement detachment faults. Their occurrence could therefore be taken as a fingerprint for detachment faults. Typically, they are either cements of red-stained limestones and/or white sparry calcite in veins, or result from low-temperature alteration by hydrothermal fluids (100–170 °C) that leads to the in situ replacement of serpentine or pyroxene by calcite (Früh-Green et al., 1990). The ophicalcites are therefore interpreted to result from the repeated tectonic and/or hydraulic fracturing of the serpentinized peridotites near the sea floor that is linked with hydrothermal processes.

14. Cover sequences

Top-basement detachment faults are the dominant structural element of OCT sequences. The hanging wall of these structures is formed by extensional allochthons: tectono-sedimentary breccias, post-rift sediments, and, further oceanwards also by basalts.

The extensional allochthons are composed of continent-derived blocks, ranging in size from km down to the deca-meter scale, often associated with tectono-sedimentary breccias. A large allochthon, overlying mantle has been drilled in the Iberia Abyssal Plain (ODP Site 1069; Fig. 2). Péron-Pinvidic et al. (2007) showed that this 'allochthon' joints further to the north the continental margin. This observation suggests that large allochthons (up to 20 km wide, 2 km thick) observed on sections perpendicular to the margin are not necessarily true allochthons and, on a map view, they may be surrounded by mantle windows. The occurrence of such extensional allochthons is probably one of the strongest criteria to define a MP-OCT sequence. On a spreading ridge, the emplacement of continent-derived extensional allochthons is unlikely (but see Bonatti et al., 1996). Thus, the occurrence of extensional allochthons and tectono-sedimentary breccias composed of both mantle- and continent-derived clasts is a valuable criterion to distinguish a MP-OCT sequence from a MOR sequence. Application of this criterion to orogens, however, is not straightforward, and large allochthons might be misinterpreted as true crystalline nappes, or mantle windows as former remnants of small oceanic basins. For smaller allochthons it is difficult to distinguish them from olistolites. However, the basal contact of an allochthon typically is a brittle detachment fault.

Tectono-sedimentary breccias are common in OCT sequences and typically cover tectonic breccias (cataclasites and gouges). They are tectonized at their base and grade upwards, into sedimentary breccias. In some outcrops in the Platta and Totalp units, they also overlie ophicalcites. This is consistent with the observation that ophicalcite clasts are reworked in these breccias. The tectono-sedimentary breccias are complex breccias that are typically clast-supported, poorly organized breccias that are mainly formed by clasts derived from the underlying footwall (e.g. Hobby High; Manatschal et al., 2001; ODP Leg 1277, Robertson, 2007). The observation that these breccias are often tectonized at the base, but show evidence for gravitational processes and infiltration by overlying post-rift sediments, renders recognition of formation processes rather difficult. Manatschal et al. (2001) interpreted these breccias as formed in a conveyor belt type system, where basement rocks are altered, tectonized and exhumed along a detachment fault and reworked and re-deposited along one and the same fault zone.

Basalts become more voluminous oceanwards, and locally, they are observed to cover exhumed mantle rocks. In most of these examples, the basalts are formed by pillow breccias. Well-developed basalt sequences sealing detachment faults can only be observed in the Chenaillet ophiolite (Figs. 5 and 8).

Radiolarian cherts are in most outcrops the oldest sediments, overlying tectono-sedimentary breccias, extensional allochthons, or basalts. However, in some places, Upper Jurassic to Lower Cretaceous Aptychus limestones (e.g. Maiolica) are found to onlap onto basement. The occurrence of breccias and olistholites within the radiolarian cherts and Aptychus limestones, as well as the local thickening of the radiolarian cherts suggests the existence of basement topography in the OCT in the Alps. The hiatus observed in the Tasna OCT and the lack of post-rift sediments in the Chenaillet ophiolite may also suggest that basement highs existed, similar to those observed in OCT in the Iberia–Newfoundland margins. The existence of basement topography is an important feature that needs to be taken into account in unraveling exhumation and sedimentation processes. Péron-Pinvidic et al. (2007) showed that basement morphology is the result of morpho-tectonic events that occur after mantle exhumation during continental breakup, as observed in the Chenaillet unit. This might be related to the occurrence of syn-magmatic high-angle faulting.

15. Discussion and conclusions

The aim of this paper is to describe a type section across an OCT of a magma-poor rift system. In our reconstruction we focused on three ophiolite units that were not affected by major Alpine deformation and metamorphism and from which the paleogeographic position can be reconstructed with some confidence. Similar to "magma-poor" MOR sequences, the MP-OCT sequences are characterized by the scarcity of mafic plutonic rocks and the occurrence of exhumed mantle, the absence of a sheeted dike complex linking the intrusives with the volcanic pillow lavas, and the occurrence of top-basement detachment faults associated with tectono-sedimentary breccias. However, there are a number of characteristics that can be used to characterize MP-OCT sequences and to distinguish them from true seafloor spreading sequences. These are:

- U/Pb ages on zircons from MOR gabbros that are of breakup age.
- Input of continent-derived material and in particular the occurrence of tectono-sedimentary breccias containing clasts of continental crust.
- Preservation of pre-Alpine contacts between mantle rocks and continental crust.
- Occurrence of continent-derived allochthons over exhumed sub-continental mantle.
- Exhumed mantle rocks derived from the subcontinental lithosphere that have no genetic link to the magmatic rocks observed in the OCT.

These are criteria that can be used to recognize a MP-OCT ophiolite and to distinguish it from a MOR sequence. We infer that many MP-OCT sequences in orogens have been described as ridge sequences and we think that MP-OCTs are more common than hitherto recognized. In the Alps it seems that the contact to first oceanic crust is transitional rather than abrupt, and that no sharp limit existed between continental and oceanic crusts. Péron-Pinvidic et al. (2007) showed that this is also true for Iberia. Thus, distinguishing a MP-OCT sequence from a MOR sequence is not trivial and some overlap can be expected. These sequences can therefore not be characterized by one vertical section, but rather by their spatial context in the evolution from the continent towards the oceanic crust. The most prominent structures are top-basement detachment faults that initiate in the continental crust and cut into mantle. They truncate mylonitic shear zones and are overprinted by high- and low-angle faults, which may or may not act as feeder systems for local seafloor volcanic systems. These structures are observed in the Alps, and drilled and seismically imaged off Iberia. They are associated with tectono-sedimentary breccias and continental rocks (extensional allochthons).

Mantle rocks in both the Alpine and Iberia–Newfoundland OCTs are characterized by a large compositional variation that might result from various processes and/or may record different histories. In MP-OCT sequences, two general types of mantle rocks can be distinguished. A first type is exposed near the continent and predominantly made of heterogeneous, enriched and depleted subcontinental mantle. During rifting, this mantle only cooled and hydrated while it was pulled out to the seafloor (cold exhumation of Müntener and Piccardo, 2003). A second type of mantle that is found further oceanwards records impregnation by syn-rift melts and higher temperatures of equilibration before cooling and hydration occurred (hot exhumation of Müntener and Piccardo, 2003). This subdivision has also been emphasized by Piccardo (2008) for the Ligurian Tethys ophiolites. In his model, these ophiolites represent remnants of a former ultraslow-spreading system, suggesting that they formed, like the Chenaillet ophiolite, within a domain further away from the continental margin.

Magmatic rocks in the OCT are more abundant going oceanwards. Although the Alpine Tethys and Iberia–Newfoundland rift system are classically interpreted as non-volcanic or non-magmatic systems, from field observations and drilling it is clear that magma is in the system. Basaltic magma infiltrates mantle rocks, at least locally (Cornen et al., 1996; Müntener and Manatschal, 2006), it is present as MOR gabbros and basalts (Jagoutz et al., 2007; Robertson, 2007), or as alkaline magmas (Jagoutz et al., 2007; Jagoutz and Müntener, unpublished data). The occurrence of different magmatic rocks displaying similar temporal and spatial relationships in the Iberia–Newfoundland margins and the Alpine Tethys ophiolites suggest that in both OCTs the magmatic system developed in a similar way. The occurrence of infiltrated and enriched mantle and the existence of localized alkaline magmas emplaced after breakup might be characteristic for MP-OCT sequences.

On an outcrop scale, it is often difficult to decide whether a sequence formed in a MOR or an OCT setting. There is consensus that MOR sequences are formed by steady state, “symmetric” and localized accretion that can be controlled by either mechanic, magmatic or both processes within a relatively robust and localized spreading system. OCT sequences in contrast can be expected to be more asymmetric and highly heterogeneous systems in which deformation and magmatic processes are not localized, and the magmatic products may be dismembered by detachment faulting (Fig. 3). Moreover, the thermal structure, the morpho-tectonic evolution and the hydrothermal processes are likely to be different and may be used to distinguish between these two systems. However, ultraslow-spreading systems such as Gakkel Ridge or the Southwest Indian Ridge show that spreading is stable and remains localized in the ridge over tens of millions of years. Thus, also the rocks and structures that form in slow to ultraslow-spreading ridges might be similar to those observed in OCT, the overall setting and processes might be different. Therefore, one must be careful in the interpretation of the geodynamic setting of ophiolites. Stand alone criteria such as the occurrence of exhumed mantle, the absence of magma, or the presence of detachment faults are not sufficient. Moreover, it also depends on the definition of what one may call “normal” oceanic crust. With the new observations made at deep margins and mid ocean ridges it is more and more clear that some of the concepts and terms that were created to describe oceanic crust and consequently also ophiolites are inappropriate and need to be scrutinized.

On a global scale, about 50% of the OCT show characteristics of MP-OCTs similar to those observed in the Iberia–Newfoundland margins (Fig. 2), the remainder are volcanic OCTs. Ophiolites derived from volcanic and MP-OCTs are rare comparing to ophiolites derived from back-arc basins or mid-ocean ridges. The recognition of MP-OCT sequences tells us about the nature of the former margin and adjacent oceanic crust. From present-day settings we know that MP-OCT are diagnostic for extremely thinned, magma-poor margins that can extend over hundreds of kilometers (e.g. Iberia–Newfoundland). However, before we start to speculate about the processes it is important to have a catalogue of observations in order to distinguish between ophiolites from different settings. Based on the new criteria established in this paper, it will be possible to revisit some of the ophiolites in the Eastern Tethys in order to find out if MP-OCTs existed in the Eastern Tethys or not. The discovery of MP-OCTs would have major implications for interpreting the overall tectonic evolution from rifting to subsequent collision of the Eastern Tethys and elsewhere.

Acknowledgements

We gratefully acknowledge the support of our research by the GDR Marges and the Swiss National Science Foundation (Grants 20-55284.98 and PP002-102809). We thank Daniel Bernoulli, Marco Beltrando and Gwenn Péron-Pinvidic for comments on an earlier version of this manuscript, and Henri Masson and Giancarlo Molli for constructive reviews. We thank also Annie Bouzeghaia for improving the quality of the figures.

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