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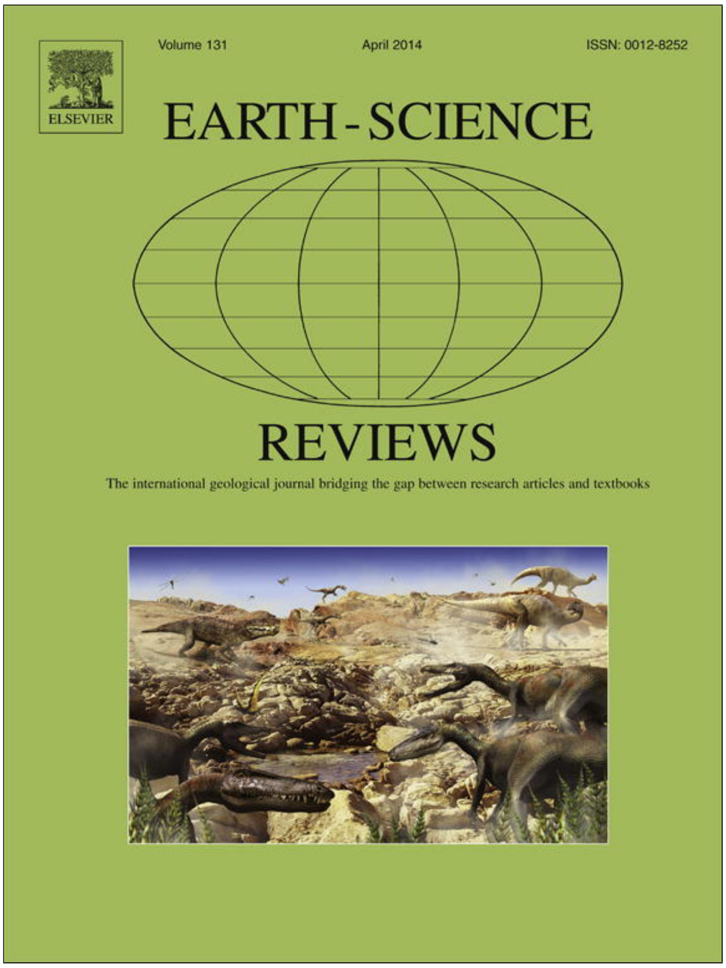
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Recognizing remnants of magma-poor rifted margins in high-pressure orogenic belts: The Alpine case study

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ABSTRACT

Magma-poor rifted margins are being increasingly recognized in present-day Atlantic-type systems. However, findings of fossil areas floored by exhumed mantle or hyper-extended crust are comparatively rare within orogenic belts that were originated through the inversion of pre-existing rifted margins. This discrepancy may be due to the common reactivation of lithological contacts during subduction/orogeny, potentially masking pre-orogenic relationships, and, most importantly, to the frequent lack of a pre-orogenic layer-cake architecture, hindering retro-deformation of multiply deformed tectonic units. This study outlines a methodology to detect sections of magma-poor, hyper-extended rifted margins without a layer-cake architecture in multiply deformed/metamorphosed terrains. This approach is defined by comparison to well studied examples of fossil analogues preserved in weakly deformed parts of Alpine orogens. In the latter domains, continental basement and hydrated peridotites were exhumed at the basin floor during Jurassic rifting along long-offset detachment systems. Extensional geometries locally resulted in tectonic sampling of laterally discontinuous slivers of allochthonous continental basement and pre-rift sediments from the hanging wall blocks. Lithostratigraphic associations consisting of continental basement rocks directly juxtaposed with syn- to post-rift meta-sediments and/or serpentinized subcontinental mantle are widespread within sections of Alpine-type orogenic belts that underwent high- to ultra-high-pressure metamorphism. However, similar associations may arise from a variety of processes other than rift-related lithospheric thinning in magma-poor environments, including subduction mélange dynamics or deposition of sedimentary mélanges along convergent/divergent margins. The partial preservation of rift-related lithostratigraphic associations may still be assessed, despite the lack of biostratigraphic evidence, by (1) the consistency of the lithostratigraphic architecture over large areas, despite pervasive Alpine deformation, which rules out chaotic mixing during subduction/exhumation, (2) the presence of clasts of basement rocks in the neighboring meta-sediments, indicating the original proximity of the different lithologies, (3) evidence of brittle deformation in continental basement and ultramafic rocks pre-dating Alpine metamorphism, indicating that they were juxtaposed by fault activity prior to the deposition of post-rift sediments, and (4) the similar Alpine tectono-metamorphic evolution of ophiolites, continental basement and meta-sediments.

A re-assessment of basement–cover relationships in the North-Western Alps following this approach, combined with published studies on exhumed mantle domains sampled in the rest of the Western Alps, indicates that several tectono-metamorphic units from the most deformed/metamorphosed part of the belt, between the Canavese Line and the Penninic Front, sample hyper-extended lithosphere related to the Jurassic opening of the Western Tethys. Relative plate motion during Cretaceous–Tertiary basin inversion was largely accommodated at the transition between areas floored by hyper-extended crust or hydrated subcontinental mantle and domains consisting of thicker continental crust. As a result, distal margins were preferentially subducted, whereas the proximal domains and the Briançonnais paleo-high underwent relatively minor deformation and metamorphism. The high-pressure Alpine tectono-metamorphic units were probably detached from the downgoing lithosphere along a hydration front that is typically observed in present-day distal margins. The recognition of preserved

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pre-Alpine relationships between continental basement, post-rift sediments and/or serpentinized ultramafic rocks calls for a re-assessment of the relative role of subduction and rifting dynamics in establishing the present-day orogen architecture.

Contents

1. Introduction

The current knowledge of magma-poor rifted margin relies heavily on research carried out in the last 50 years in present-day systems, chiefly along the Atlantic Iberia–Newfoundland margins, and in fossil analogs, mainly within the Alpine Tethys realm of Western Europe (e.g. Elter, 1971, 1972; Lombardo and Pognante, 1982; Lemoine et al., 1987; Lagabrielle and Cannat, 1990; see Bernoulli and Jenkyns, 2009; Lagabrielle, 2009; Manatschal and Müntener, 2009; Péron-Pinvidic and Manatschal, 2009; Mohn et al., 2010 for recent reviews). Studies conducted since the 1960s in little deformed/metamorphosed parts of the Alps–Apennines–Corsica orogenic system provided the earliest accounts of the lithological composition and rift-related architecture of the Jurassic Tethys ocean (see Lagabrielle, 2009 for a historical perspective). Pre-orogenic contacts between exhumed subcontinental mantle or rift-related gabbros and the overlying volcano-sedimentary cover sequences were first detected in the Ligurian units of the northern Apennines (e.g. Passerini, 1965; Elter, 1972b). Documented sedimentary cover sequences typically consisted of pelagic sediments, locally intercalated with ophiolitic breccias hosting clasts originated from the underlying serpentinized peridotites and gabbros. Similar lithostratigraphic associations were later recognized in the Piemonte units of the Western Alps, despite pervasive Alpine deformation and metamorphism at blueschist to eclogite facies conditions (e.g. Bearth, 1967; Dal Piaz, 1969; Lemoine et al., 1970; Dal Piaz, 1971; Elter, 1971; Lagabrielle et al., 1982; Tricart and Lemoine, 1983; Lemoine and Polino, 1984; Deville et al., 1992), indicating that pre-orogenic relationships could be preserved, at least locally, throughout subduction/exhumation.

Subsequent drilling offshore Iberia and field studies in the Eastern Swiss Alps during the 90s helped refining this early picture, showing that rift-related hyper-extension may result in lithostratigraphic associations displaying transitional features between the embryonic oceanic crust previously described from the Alpine Tethys and typical continental crust, where continental basement is directly overlain by pre-, syn- and post-rift sediments (Boillot et al., 1987; Whitmarsh et al., 2001; Wilson et al., 2001; Manatschal, 2004; Tucholke and Sibuet, 2007). These intermediate lithological associations, which are typical of domains floored by severely extended continental crust and subcontinental mantle, can be up to 200 km wide along the Iberia–Newfoundland conjugate margins (e.g. Péron-Pinvidic and Manatschal, 2009; Fig. 1). Hyper-extended crust, located outboard relative to the proximal margin, consists of continental basement with <10 km thick crust, directly onlapped by syn- to post-tectonic sediments or by submarine extrusive magmatic rocks. As the residual continental crust thins out oceanward, the hyper-extended crust grades into a domain where lower crustal rocks and subcontinental mantle can be exhumed at the seafloor by downward-concave long-offset detachment faults. In this area serpentinized mantle is locally overlain by slivers of continent-derived blocks, referred to as ‘extensional allochthons’, often consisting of upper crustal rocks and/or pre-tectonic sediments, originated from the stretched and fragmented hanging wall. This kind of margin architecture is being increasingly recognized in present-day magma-poor rifted margins, including the eastern Indian margin (Nemčok et al., 2012), the South Atlantic (Unternehr et al., 2010), the southern Australian margin (Espurt et al., 2012) and the late Jurassic to lower Cretaceous Møre and Vøring margins, in the North Atlantic (Osmundsen and Ebbing, 2008). Fossil hyper-extended crust and lithosphere characterized by extensional allochthons related to Jurassic rifting have also been extensively detected in sections of Alpine mountain belts that were only marginally affected by orogeny-related deformation and metamorphism (e.g. Froitzheim and Eberli, 1990; Florineth and Froitzheim, 1994; Molli, 1996; Durand-Delga et al., 1997; Manatschal, 2004; Masini et al., 2011; Mohn et al., 2012).

Notably, the high-pressure parts of several Alpine-type orogenic belts also host tectono-metamorphic units with lithological associations consisting of laterally discontinuous slivers of Paleozoic continental basement juxtaposed against Jurassic meta-ophiolites and/or post-rift meta-sedimentary rocks of presumed Jurassic to Cretaceous age. In the North-Western Alps, these lithological associations have been ascribed alternatively to multiple reactivation of subduction/exhumation-related shear zones, juxtaposing continental and oceanic rocks (e.g. Ballèvre and Merle, 1993; Lister and Forster, 2009), to pre-orogenic rift-related extensional tectonics (e.g. Dal Piaz, 1999; Beltrando et al., 2010a, 2012), or to chaotic mixing of originally unrelated rock types within a subduction channel (e.g. Polino et al., 1990; Gerya et al., 2002). According to the latter view, hydration of the mantle wedge lithosphere overlying a subducting plate may feed a buoyancy-driven return flow towards the surface, with different rock types from the downgoing lithosphere being entrained in the newly formed low-viscosity channel (Gerya et al., 2002).

Alternative processes that may lead to similar lithostratigraphic associations include deposition of sedimentary mélanges along convergent or divergent margins. In the Pyrenees, large olistholiths (>1 km^2) of well-preserved peridotites are found alongside conglomerates with clasts of shelf sediments and, more rarely, of Paleozoic continental basement and rift-related gabbros embedded into debris-flow deposits (Lagabrielle and Bodinier, 2008; Jammes et al., 2009; Clerc et al., 2012). These formations are interpreted as Albian post-rift sediments deposited in basins floored by exhumed subcontinental mantle, later inverted during the Pyrenean orogeny (Fig. 2d; e.g. Lagabrielle and Bodinier, 2008; Clerc et al., 2012). In the northern Apennines, large slivers of continental basement, variably serpentinized mantle, gabbro and basalt, locally preserving Middle Jurassic early post-rift sedimentary cover rocks, are also found as slide blocks in Cretaceous sedimentary mélanges of the External Ligurian Units (Molli, 1996; Marroni et al., 1998). These sedimentary units are generally interpreted as syn-orogenic deposits related to transpressional deformation affecting the hyper-extended margin of the Adriatic plate (Fig. 2e; e.g. Marroni et al., 2002).

Deciphering the relative contribution of the different tectono-sedimentary processes listed above to the shaping of (ultra-)high-pressure tectono-metamorphic units has important implications for constraining subduction dynamics and the mechanisms controlling the tectonic sampling of rock units from the downgoing lithosphere and their subsequent exhumation to the surface. This task is complicated by subduction/exhumation processes, generally reworking lithological contacts, masking original rock textures and erasing the biostratigraphic record. Therefore, this paper is devoted to outlining a methodology to detect remnants of magma-poor hyper-extended rifted margins lacking a layer-cake architecture in highly deformed/metamorphosed terrains. The proposed approach is illustrated for the North-Western Alps and Corsica case studies, where both hyper-extended crustal domains (Ferrando et al., 2004; Gasco and Gattiglio, 2010; Beltrando et al., 2013) and areas floored by exhumed mantle (e.g. Lemoine et al., 1987; Dal Piaz, 1999; Beltrando et al., 2010a; Vitale Brovarone et al., 2011a; Beltrando et al., 2012; Meresse et al., 2012; Vitale Brovarone et al., 2013) have been identified. As similar lithostratigraphic associations are being increasingly documented elsewhere (e.g. Andersen et al., 2012; Skrzypek et al., 2012; Van Staal et al., 2013), the methodology outlined here might be applicable to several orogenic belts worldwide, with important implications for the understanding of subduction/orogenic dynamics.

2. Jurassic paleogeography of the Alpine Tethys

Since the early 70s, a large number of studies were devoted to constraining the pre-orogenic paleogeography of the area that was later involved into the Alpine orogeny in Western Europe (see Frisch, 1979; Stampfli, 1993; Martin et al., 1994; Mohn et al., 2010; Masini et al., 2013 for reviews). The resulting picture relies on information combined from different parts of the Alpine belt that underwent relatively minor Cretaceous to Tertiary reactivation. The generally accepted view of the Jurassic paleogeography of this domain consists of two main continental masses, namely the Adriatic/African plate and the European plate, separated by a Mesozoic oceanic basin, labeled Alpine Tethys (Fig. 3). This basin was characterized by a main branch, known as South Penninic (or Piemonte-Ligurian) basin, and a minor northerly branch, the North Penninic (or Valaisan) basin (e.g. Sturani, 1975; Trümpy, 1980; Lemoine, 1985). The two sub-basins, in the area that later became part of the Western and Central Alps, were separated by a continental high, the Briançonnais rise (e.g. Elter, 1972a; Trümpy, 1949; Lemoine, 1985). Several paleogeographic reconstructions suggest that the Western Tethys basin was highly fragmented by regional-scale E–W trending transform faults (e.g. Beccaluva et al., 1984; Lemoine, 1985; Weissert and Bernoulli, 1985).

Subsequent studies have progressively refined this early picture, showing that large areas of the South and North Penninic basins were floored by partly serpentinized subcontinental mantle (e.g. Lemoine et al., 1987; Lagabrielle and Cannat, 1990; Manatschal and Müntener,

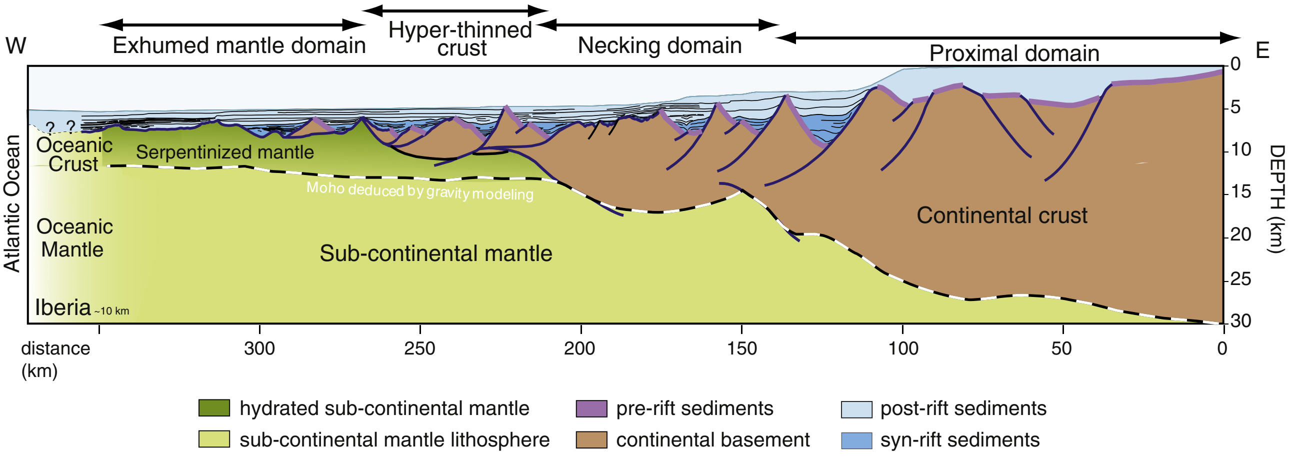

Fig. 1. Interpreted section across the distal Iberian rifted margin along the TGS/Lusigal 12 seismic reflection lines, based on all available geophysical and ODP drill hole data (modified after Sutra et al., 2013).

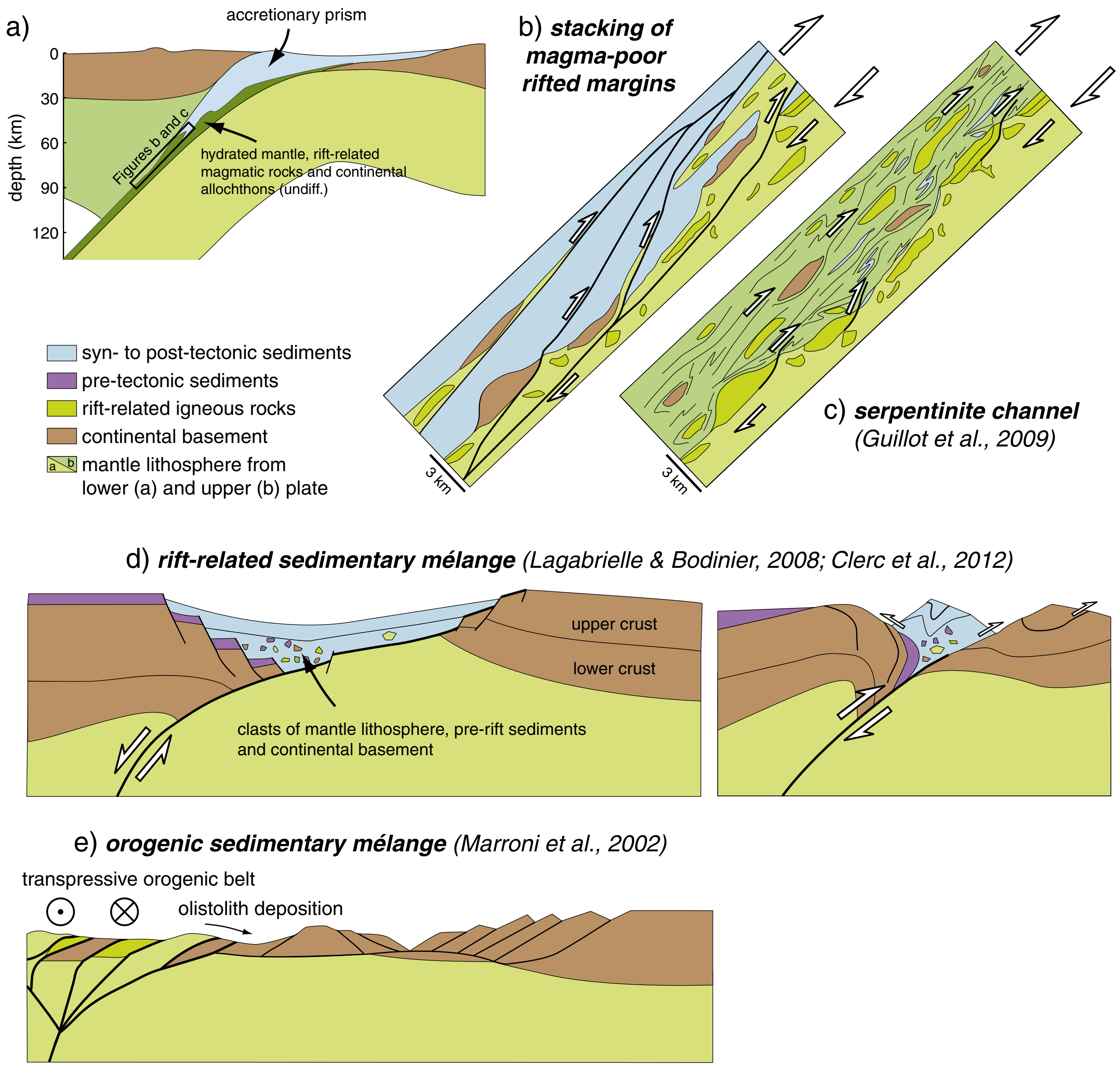

Fig. 2. The juxtaposition of continental basement slivers, serpentinized subcontinental mantle and syn- to post-rift sediments may arise in subduction zones (a), through stacking of slivers of hyper-extended lithosphere (b) or serpentinite channel dynamics (c); modified from Guillot et al., 2009) or through the formation of sedimentary mélanges, either along distal rifted margins (d); modified from Lagabrielle and Bodinier, 2008) or along transpressive margins (e); modified from Marroni et al., 2002).

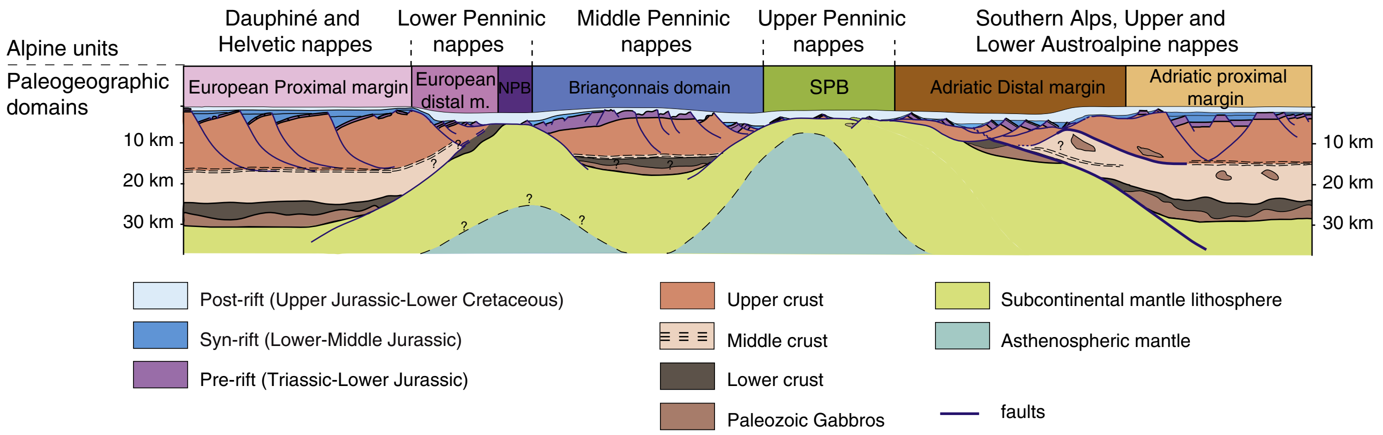

Fig. 3. Paleogeography of the Western Tethys as reconstructed from observations performed in the Central-Eastern Alps and Western Alps (modified after Mohn et al., 2010).

2009) and that thinned continental basement directly overlain by syn- to post-rift sediments marked the transition from the proximal Adriatic margin to the South Penninic basin (Fig. 1; e.g. Froitzheim and Eberli, 1990; Masini et al., 2011). The resulting paleogeography, largely established in the little deformed Eastern Swiss Alps and in the Southern Alps (Figs. 3, 4 and 5), consists of an Adriatic/Apulian proximal margin, preserved in the so-called Upper Autroalpine nappes (e.g. Ortler nappe) and in the Serie dei Laghi, grading outboard (to the west) into a necking zone, preserved in the Middle Austroalpine nappes (Fig. 5; Mohn et al., 2012). This domain was followed to the west by the Adriatic hyper-extended domain, floored locally by exhumed crust and overlain by extensional allochthons, now sampled in the Lower Austroalpine nappes in the Eastern Swiss Alps [Err nappe (Froitzheim and Eberli, 1990; Manatschal and Nievergelt, 1997; Masini et al., 2011, 2013) and Bernina nappe (Mohn et al., 2012)] and in the Canavese Zone in the Southern Alps (Ferrando et al., 2004). The areas floored by exhumed mantle belonging to the South Penninic basin are now best preserved in the Forno/Malenco, Platta and Totalp units in the Eastern Swiss Alps (Figs. 4 and 5). The Briançonnais rise, which separated the South Penninic from the North Penninic basin (Frisch, 1979), is best preserved in the Western Alps (Fig. 4). Remnants of the North Penninic basin are now sampled in the Valaisan units, which locally preserve evidence of rift-related exhumation of subcontinental mantle, as described in the Tasna nappe, which crops out in the Engadine window (Fig. 4; Florineth and Froitzheim, 1994; Manatschal et al., 2006). The proximal European margin can then be seen throughout the Northern Alpine foreland, in the so-called Helvetic–Dauphinois domain. Importantly, the units that are now stacked in the Alpine belt should not be viewed as originally being part of two conjugate margins, due to significant syn-convergent strike slip kinematics, during closure of the Alpine Tethys (e.g. Rosenbaum et al., 2002; Beltrando et al., 2010b).

3. Lithostratigraphic fingerprints of non-layer-cake, hyper-extended crust and mantle in the Eastern Swiss Alps

The lithostratigraphic features and tectono-sedimentary evolution of the areas floored by hyper-extended crust and exhumed mantle have been described in detail in an extensive body of literature (e.g. Decandia and Elter, 1972; Marroni et al., 1998; Mohn et al., 2010; Masini et al., 2011). Only the key aspects that are relevant for the recognition of similar domains in highly deformed/metamorphosed nappe stacks are highlighted here and in Figs. 6 and 7. These aspects involve the assessment of the internal coherence of multiply deformed units, which is unlikely to arise by chaotic sedimentary and tectonic processes, and the stratigraphic evidence suggesting original proximity of different rock types prior to the Alpine orogeny.

3.1. Rift-related geometry: where is the (layer) cake?

The geometry of magma-poor rifted margins is not characterized by a layer-cake configuration, since several lithological bodies terminate laterally (Fig. 6a; see also references on present-day margins listed in

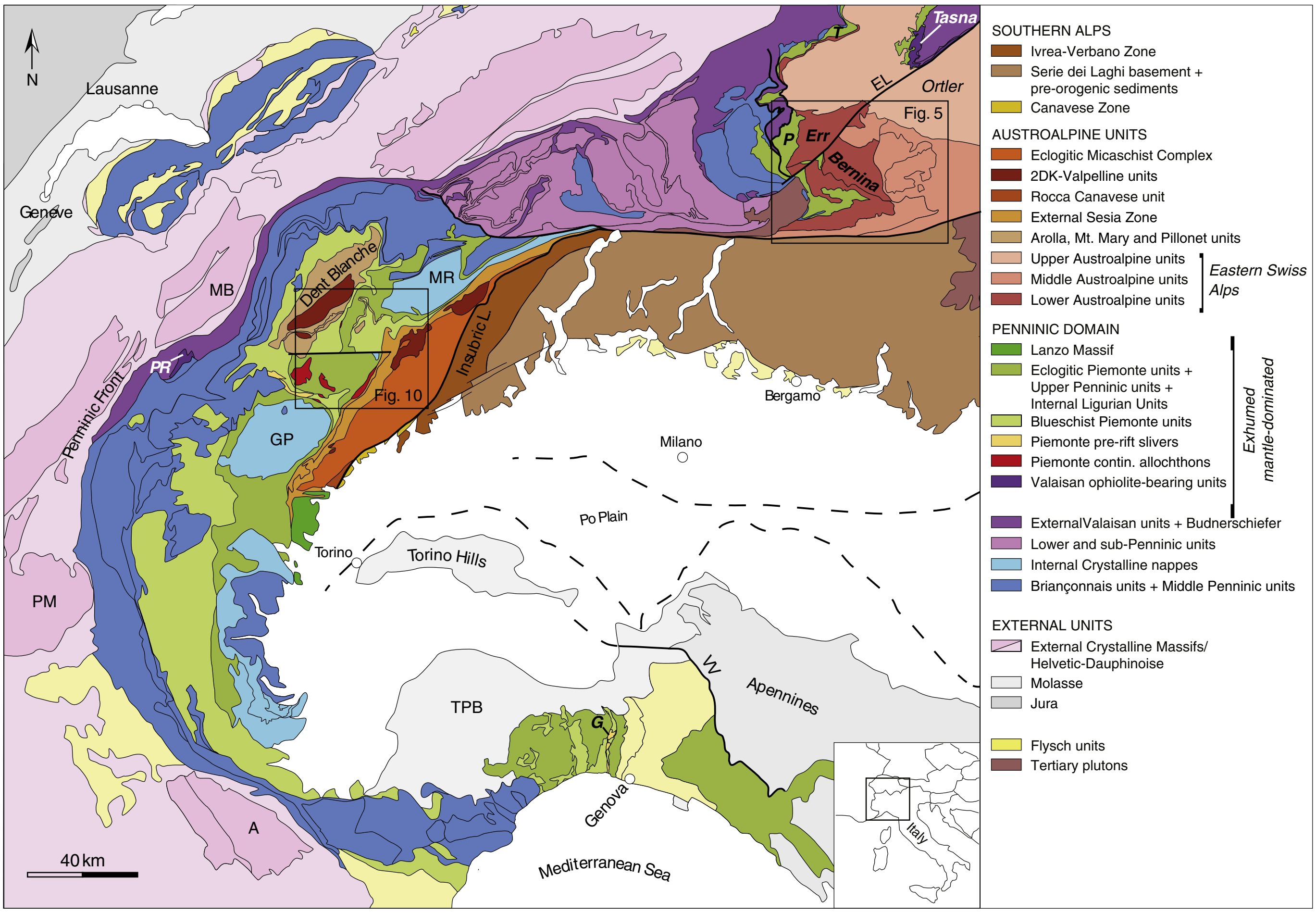

Fig. 4. Tectonic map of the Alps, compiled after Bigi et al., 1990; Handy et al., 1999; Capponi and Crispini, 2008; Bousquet et al., 2008; Molli et al., 2010; Galli et al., 2011; Mohn et al., 2011; Galster et al., 2012 and own observations. A: Argentera massif; G: Gazzo–Isoverde unit; GP: Gran Paradiso unit; MB: Mont Blanc massif; MR: Monte Rosa unit; P: Platta unit; PM: Pelvoux massif; PR: Punta Rossa unit; TPB: Tertiary Piemonte basin; VV: Villavernia–Varzi Line.

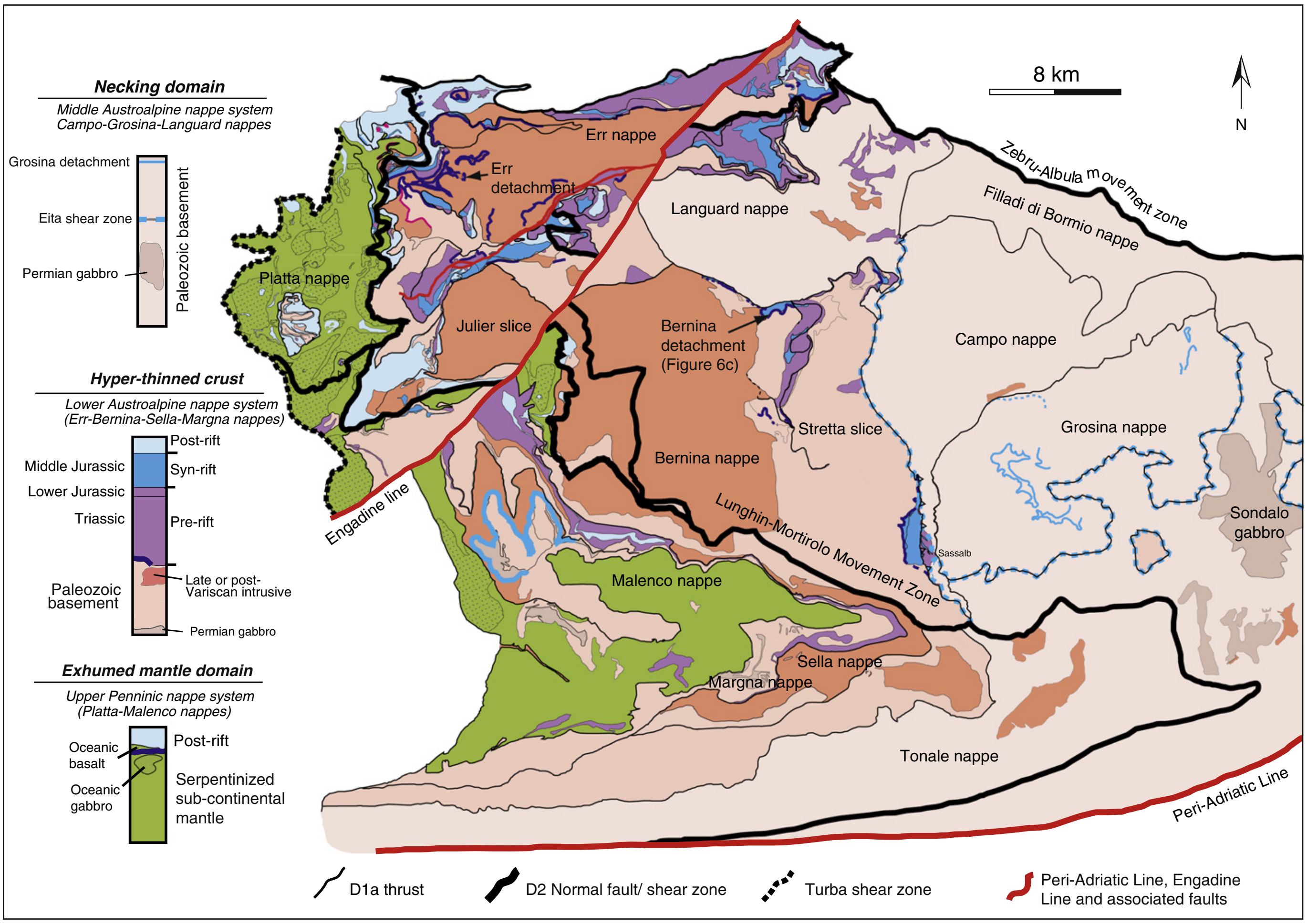

Fig. 5. Geological map of the Austroalpine and Upper Penninic nappes in SE-Switzerland and N-Italy, between Valtellina, Albula, and Julier valleys (modified after Mohn et al., 2011).

section 1). When dealing with multiply deformed metamorphic terrains, this pre-orogenic complexity needs to be taken into account. In the well-exposed Tasna nappe, in the Eastern Swiss Alps (Figs. 4 and 6b), exhumed subcontinental mantle is directly overlain by slivers of continental basement rocks, consisting of Paleozoic continental metagabbros, which are overlain by migmatites intruded by Paleozoic granitoids. Continental basement tapers out laterally, where the footwall of the extensional system is directly onlapped by post-rift sediments, consisting of dark shales (Florineth and Froitzheim, 1994; Manatschal et al., 2006). Similar features are observed in areas floored by hyper-extended crust, where exhumed continental basement can be overlain directly by laterally discontinuous extensional allochthons of pre-rift sediments, continental basement or a combination of the two (Fig. 6a and c; e.g. Iberian rifted margin drilling results in Whitmarsh and Wallace, 2001). The presence of allochthonous slivers may result in local topography, controlling the geometry and lithological composition of locally-sourced coarse-grained syn-tectonic sediments (Masini et al., 2012). As a result, syn-tectonic sedimentary bodies typically display abrupt lateral terminations and marked lithological variations, as clasts may alternatively originate from continental basement or platform sediments (Fig. 6a; Masini et al., 2011). In the Tasna nappe, laterally discontinuous lenses of syn-tectonic breccia, consisting of continental basement clasts in a dark shale matrix, are locally found resting directly onto exhumed continental basement (Manatschal et al., 2006).

These observations indicate that allochthonous material (hanging wall blocks) and syn-tectonic sediments should not be used as reference horizons when trying to assess the coherency of multiply deformed metamorphic terrains, since their abrupt lateral terminations might be erroneously interpreted as resulting from orogeny-related tectonics. In this context, field mapping should rely on the detection of key planar surfaces, which are expected to have been continuous prior to orogeny. In magma-poor rifted margins, these marker horizons correspond to the top of the exhumed basement (red lines in Fig. 6) and the base of the first post-tectonic sediments, either syn- or post-rift in age (blue and orange lines, respectively, in Fig. 6). Therefore, the top of the exhumed serpentinized mantle should be used as reference horizon in domains floored by mantle lithosphere. It should be noted that this surface is not necessarily completely flat, due to the documented presence of post-detachment high-angle normal faults (e.g. Manatschal et al., 2011) and/or corrugations on the detachment surface (e.g. Tucholke et al., 1998; MacLeod et al., 2009; Masini et al., 2012). In the areas floored by hyper-extended crust the basal marker horizon corresponds to the top of the exhumed continental basement.

As mentioned above, a second marker horizon should be chosen within the post-tectonic sedimentary sequence, which seals the allochthons and/or syn-tectonic sediments [note that post-tectonic sediments, in the context of the evolving margin, may be both syn- and post-rift (for terminology see Masini et al., 2013)]. The marker layer should lie as close as possible to the base of the post-tectonic sedimentary sequence. The choice will depend on the availability of lithologically distinctive horizons, which are known to be broadly synchronous over the margin that is being investigated. In the Alpine Tethys realm a good marker layer for the distal Adriatic margin and the South Penninic basin is provided by the early post-rift Mn-rich radiolarian cherts deposited directly on exhumed subcontinental mantle in the late Middle to early Late Jurassic (Figs. 7a and b; Weissert and Bernoulli, 1985). In case of marked rift-

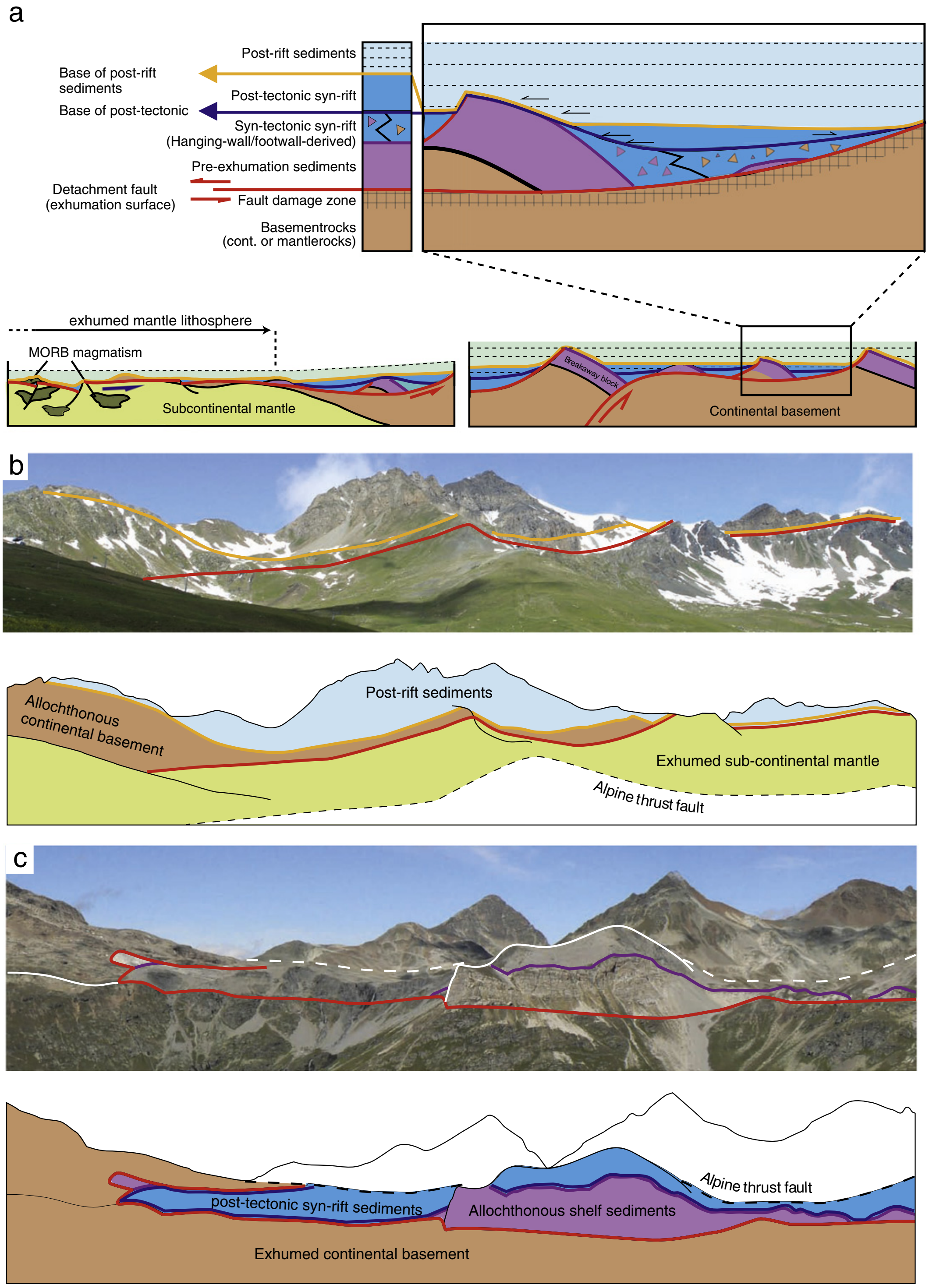

Fig. 6. (a) Key lithostratigraphic features of hyper-extended domains as determined from studies of present-day margins and fossil examples cropping out in Eastern Switzerland. Note that basement-cover relationships depicted in detail in the upper diagram apply to domains floored by hyper-extended crust and mantle lithosphere alike. Field examples are shown in (b) and (c). An allochthonous sliver of Paleozoic basement resting above serpentinized sub-continental mantle is well preserved in the Tasna nappe, in the Engadine window (b). Note the post-tectonic sediments sealing the exhumation surface and the ultramafics-ultramafic–allochthon pair. In the Bernina unit (Lower Austroalpine units, Swiss Alps) in Val da Fein (b), continental basement is exhumed by a low-angle detachment fault and directly overlain by discontinuous slivers of Triassic dolostone. Late-syn-rift sediments seal the exhumation surface. The marker horizons that should be used as reference horizons for mapping of multiply deformed terrains are indicated.

related topography or sediment-starved environments, younger post-rift sediments can be found onlapping top-basement surfaces or pre- to syn-rift lithologies residing along local highs (Fig. 6a). In this context, the surface of onlap unconformity may be chosen as marker horizon.

Therefore, as apparent from this brief review, the exhumed subcontinental mantle and continental basement can be alternatively overlain by continental allochthons, syn-tectonic sediments, post-tectonic sediments and, further oceanward, also by MOR-type submarine lava flows. The

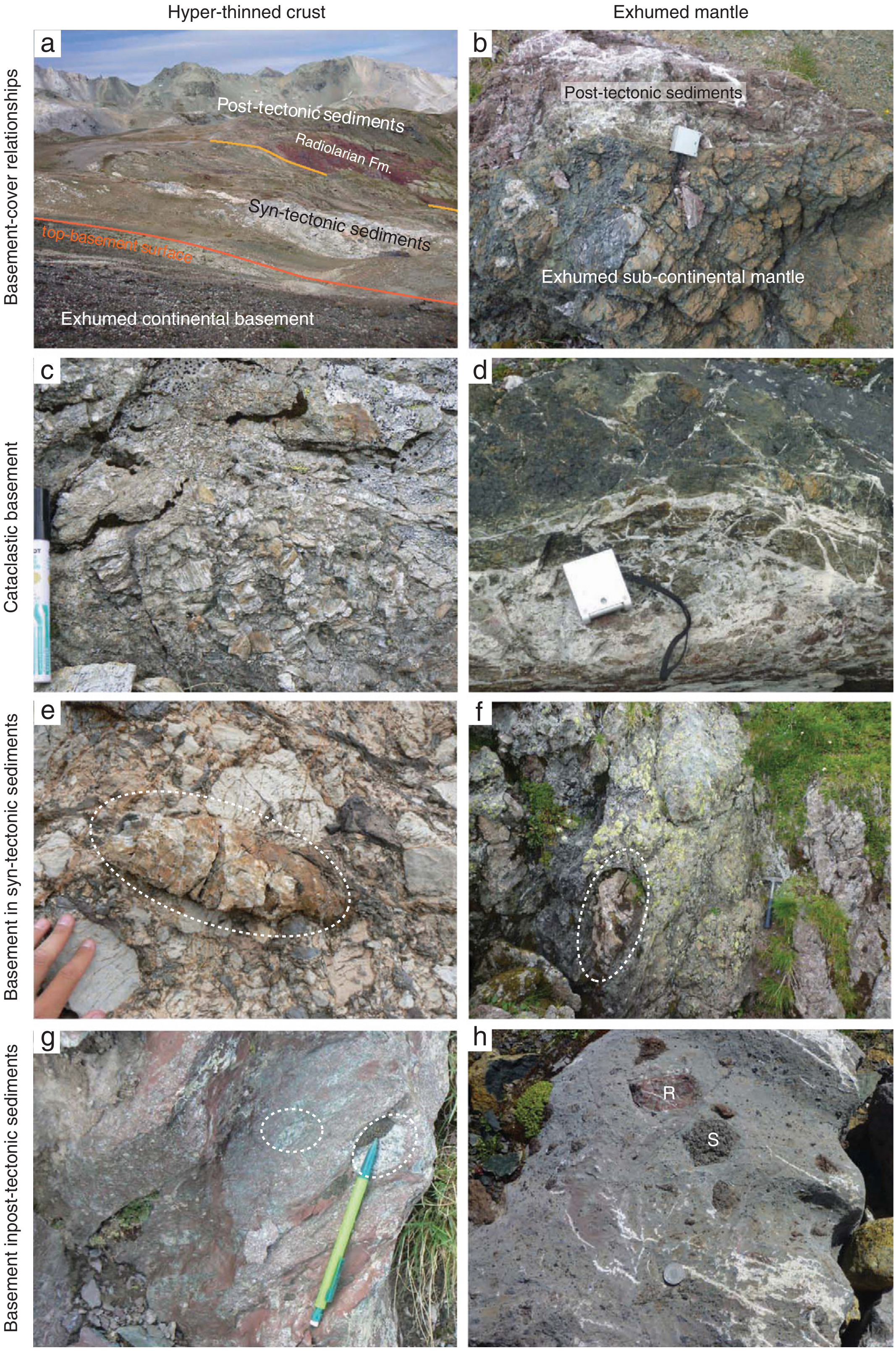

Fig. 7. The Alpine distal margin sedimentary facies preserved in Eastern Switzerland. (a) Stratigraphy of the Lower Austroalpine units, showing exhumed continental basement capped by the Err detachment fault, syn- and post-rift sediments (Fuorcla Cotschna–Spelm Ravulaunas; UTM WGS84 32N: 556046E; 5148971N); (b) contact between exhumed subcontinental serpentinized mantle and post-tectonic sediments consisting of ultramafic ophicalcites (Totalp, Platta nappe; UTM WGS84 32N: 561495E; 5188076N); (c) cataclastic basement below the Err top-basement detachment fault, Err nappe, Lower Austroalpine unit (UTM WGS84 32N: 558997E; 5150144N); (d) cataclastic and foliated serpentinites along top-basement surface (Totalp, Platta nappe; UTM WGS84 32N: 561495E; 5188076N); (e) supra-detachment syn-tectonic clast-supported polymictic breccias with angular clasts of pre-rift carbonates, fault rocks and cataclastically deformed continental basement (circled; Forcla Cotschna; UTM WGS84 32N: 556046E; 5148971N); (f); polymictic breccia reworking pre-rift carbonates (circled) and continental basement rocks above exhumed mantle (Totalp, Platta nappe; UTM WGS84 32N: 562370E; 5188963N); (g) coarse-grained polymictic facies in post-tectonic sediments, with clasts of continental basement (circled; Piz Nair, Lower Austroalpine; UTM WGS84 32N: 560234E; 5150767N); (h) ophicalcitic post-rift sediments with clasts of serpentinites (s) and radiolarian cherts (c; Totalp, Platta nappe; UTM WGS84 32N: 561495E; 5188076N).

most continuous reference layers correspond to the exhumation surface of the lower plate and to the base of the post-tectonic sediments. The distance between the two surfaces, in the Alpine Tethys realm, which was sediment-starved during hyper-thinning and exhumation, may reach up to 1 km, when thick packages of syn-rift sediments or thick allochthons are present (Fig. 7a; Masini et al., 2011). At a regional scale these marker horizons converge oceanwards, until they eventually overlap (Fig. 6). Furthermore, in the absence of interleaving allochthons and syn-tectonic sediments, the two surfaces overlap (Fig. 6a and b; e.g. Molli, 1996).

3.2. Basement reworking into the overlying sediments

Stratigraphic observations from well-preserved hyper-extended margins can further support the original proximity of extensional allocthons in the hanging wall of detachment systems with the associated syn- to post-tectonic sediments. Supra-detachment sedimentary processes commonly result in reworking of all crustal and mantle rocks exposed along detachment systems, as indicated by the occurrence of rock-fall, debris-flow or turbiditic deposits, sealing the top-basement detachment fault plane (e.g. Alps: Masini et al., 2011, 2012; Iberia: ODP Site 1068 in Wilson et al., 2001, see their Fig. 17). The base of these syn-tectonic deposits generally consists of coarse and poorly-sorted breccias. Clasts include fault rocks (cataclastic/altered basement and indurated black gouges), continental basement rocks, pre-rift sediments and, in the areas floored by exhumed mantle lithosphere, even mantle rocks (Figs. 7e and f; Desmurs et al., 2001). Clast composition is generally closely related to the lithological composition of the neighboring exhumed basement. In the proximity of extensional allochthons, clasts of footwall basement are progressively replaced by elements derived from the allochthons, which provide hanging wall derived syn-tectonic deposits (Fig. 6a; e.g. Masini et al., 2011). Further away from the allochthons, clasts are sourced from footwall lithologies including fault rocks (cataclastic basement, black gouges), continental or mantle basement rocks (Figs. 7e and f; Desmurs et al., 2001). Downsection, these breccias become progressively more massive and less polymictic, grading into the so-called “tectono-sedimentary breccia layer” (Manatschal et al., 2006). This layer spans the base of the sedimentary succession and the top of the tectonized, exhumed basement lying directly underneath, corresponding with the damage zone of the detachment fault. Since the base of these syn-tectonic deposits is often deformed, the transition between tectono-sedimentary breccia and the underlying basement, representing the exhumed footwall of the fault (Fig. 7c), is generally rather difficult to locate precisely and is generally better defined as a zone rather than as a plane. Clasts of fault rocks into the syn-tectonic sediments indicate that the fault plane is locally eroded, further hindering the precise recognition of the base of the sedimentary succession overlying exhumed surfaces. Following subduction/orogeny-related deformation and metamorphism, the more oligomict facies of the syn-tectonic sedimentary breccia may be difficult to distinguish from the underlying exhumed basement (e.g. reconstituted granites in Masini et al., 2011; cfr. Fig. 7c and d with Fig. 7e and f). Only the larger clasts (or “exotic” lithologic clasts) can generally be distinguished in these meta-breccias, providing evidence for a sedimentary origin of the deposit (see below).

In the Lower Austroalpine nappes of the Eastern Swiss Alps, syn-tectonic sediments are laterally discontinuous and taper out moving away from their source area. In this domain, coarse breccias grade upsection into finer turbiditic deposits (interbeds of litharenites, siltstones and shales) overlain by pelagic shales. Onlapping relationships with the underlying sedimentary and basement rocks indicate that these pelagic deposits postdate local exhumation and do not show evidence for rift-related deformation. Clasts of exhumed basement and extensional allochthon lithologies can still be found in clastic or pelagic post-tectonic sediments, suggesting episodic sedimentary inputs from local highs (Fig. 7g and h). In the Alps, this latter feature is related to the overall sediment-starved environment that characterized the South Penninic basin until post-rift time (Wilson et al., 2001).

4. The recognition of remnants of rifted margins in highly deformed/metamorphosed terrains: the principles of metamorphic lithostratigraphy

In the high-pressure/low-temperature part of orogenic belts, the assessment of the pre-orogenic relationship between different rock types may be complicated by tectonic reworking of primary lithological contacts and pervasive recrystallization, masking the original rock textures. Furthermore, the unambiguous reconstruction of the pre-metamorphic stratigraphy is often hampered by the lack of preserved fossils within meta-sedimentary rocks, except for some notable exceptions (e.g. Marthaler et al., 1986; Cavargna-Sani et al., 2010; Galster et al., 2010). Techniques from metamorphic petrology and structural geology are inherently inadequate to test whether material points that are now juxtaposed were already located in the same relative position before orogeny. Metamorphic mineral fabrics that can be correlated across lithological boundaries are normally formed at a relatively late stage in the tectono-metamorphic evolution, generally during exhumation (e.g. Reddy et al., 1999, 2003). As a result earlier slip, resulting in the tectonic juxtaposition of originally unrelated rock types, cannot be teased out with structural analysis alone. Such limitations can occasionally be overcome comparing the Pressure–Temperature–time (*PT*t) history of neighboring lithologies, as demonstration of attainment of different *PT* conditions at a given time by different rocks is evidence of juxtaposition by subduction-related dynamics (e.g. Federico et al., 2007) or by later tectonic events. However, these comparisons are normally possible for the high pressure to exhumation path only, since prograde mineral assemblages are only rarely preserved in high-pressure units. Furthermore, metamorphic recrystallization is generally episodic and ithologies with different bulk rock compositions may re-equilibrate at variable stages of a specific *PT* evolution, resulting in seemingly different *PT* histories (e.g. Proyer, 2003).

On the other hand, meta-sedimentary cover sequences are sometimes attributed to the neighboring continental basement exclusively based on their similarities with less deformed/metamorphosed sections or on the lateral continuity and consistency of the meta-sedimentary sequence (e.g. Galster et al., 2012). This approach may also lead to erroneous results in cases when meta-sedimentary sequences are tectonically detached from their substrate along weak layers over large areas (e.g. Sartori and Marthaler, 1994). The pitfalls involved in the techniques outlined above can be overcome with a multi-disciplinary approach, combining lithostratigraphic, sedimentological and (occasionally) paleontological observations, which are typical of classic studies from the Piemonte units of the western Alps (e.g. Lemoine et al., 1970; Lagabrielle et al., 1984; Tricart and Lemoine, 1991), with structural, petrographic and geochronological studies (i.e. Spalla et al., 2005; Forster and Lister, 2008), in the light of the most recent discoveries on the architecture of hyper-extended margins. The pre-subduction/orogeny lithostratigraphy of domains that underwent multiple stages of deformation and metamorphism can be reconstructed provided that:

(1) the tectononometamorphic unit is characterized by coherent lithostratigraphy over a large area. Therefore, key pre-orogenic marker horizons should be traceable continuously across the orogeny-related macro-structures. As shown in the previous section, the choice and recognition of these markers are critical for the evaluation of the internal coherency of units originated from magma-poor rifted margins, where several lithological bodies terminate laterally as a result of rift-related tectonics (Figs. 1b, 3 and 6).
(2) the original proximity of the different rock types can be inferred, mainly based on the presence of clasts comparable to the basement lithologies within the associated meta-sediments.

(3) the different rock types recorded a similar subduction/orogeny-related Pressure–Temperature–time evolution and share the deformation history (*PT*td) starting from the oldest fabric or structure that can be correlated across lithologies.

In many case studies, orogeny-related deformation results in significant reworking of pre-orogenic contacts, disrupting the internal coherence of tectono-metamorphic units. In these circumstances, the *consistency* of the lithostratigraphy (i.e. showing constant patterns over wide areas), combined with (2) and (3) might still allow an origin from hyper-extended margins to be proposed, as shown in Section 6.1.2 for the Piemonte units. Recent applications of this methodology to high-pressure tectono-metamorphic units of the North-Western Alps and Corsica are illustrated in the following sections.

5. Tectono-metamorphic evolution of the Western Alps

The Western Alps formed starting from the Late Cretaceous in response to the northward drift of the Adriatic plate, followed by collision with the European plate in the late Eocene–Oligocene. Extensive reviews of the tectono-metamorphic evolution of the high-pressure part of the belt, between the Insubric Line and the Penninic Front, can be found in Rosenbaum and Lister (2005), Bousquet et al. (2008), Beltrando et al. (2010b) and Dal Piaz (2010). Only the key features are recalled here (Figs. 4, 8).

The Insubric Line separates the Canavese Zone, which was originally part of the distal Adriatic margin (Ferrando et al., 2004) and underwent Alpine metamorphism at anchizonal conditions, from the Sesia Zone. The latter consists largely of Paleozoic continental basement recording Alpine metamorphism at blueschist to eclogite facies conditions (Dal Piaz et al., 1972; Compagnoni et al., 1977). The Sesia Zone is traditionally subdivided into Eclogitic Micaschist Complex, which experienced $P > 1.8$ GPa (Konrad-Schmolke et al., 2011), Second Dioritic–Kinzigitic Zone and Gneiss Minuti Complex, where only blueschist facies metamorphic assemblages have been reported (Fig. 4). The Sesia Zone, together with the more westernly located continental basement units of the Pillonet, Mt. Mary and Dent Blanche nappe system (Fig. 4), occupies the highest structural position within the present-day tectonic pile. The Sesia Zone is bounded to the west and south by the underlying ophiolitic units of the Piemonte zone and Lanzo massif (e.g. Kienast and Pognante, 1988; De Giusti et al., 2004; Bucher et al., 2005; Groppo et al., 2009). Based on Alpine metamorphic grade, the Piemonte units are generally subdivided into eclogitic and blueschist Piemonte units, which in the North-Western Alps are separated by a complex Alpine shear zone (e.g. Reddy et al., 2003), labeled Piemonte Movement Zone (Beltrando

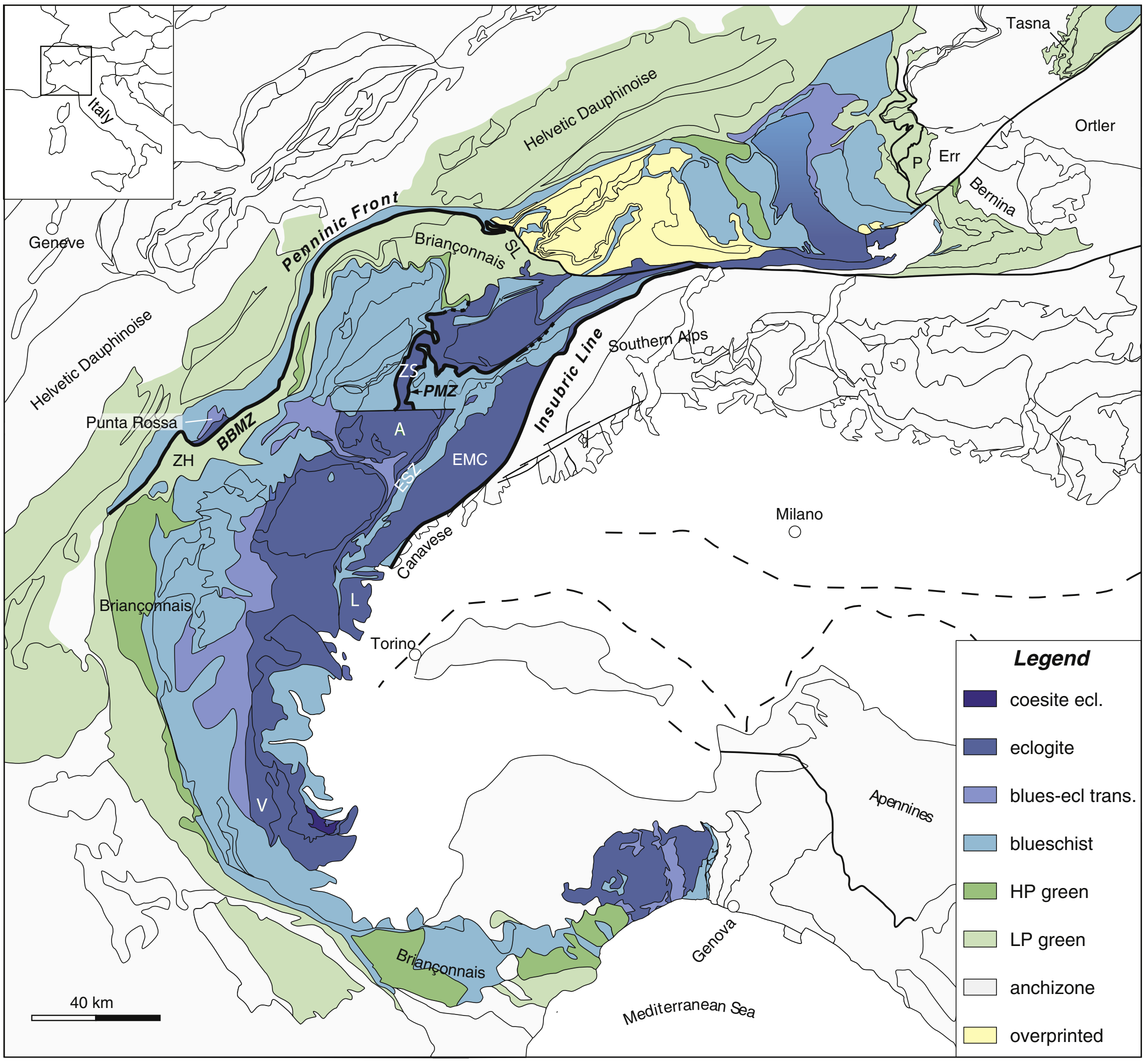

Fig. 8. metamorphic map of the Alps, compiled after Oberhänsli et al., 2004; Bousquet et al., 2008; Beltrando et al., 2010b and own observations. A: Avic massif; BBMZ: Basal Briançonnais Movement Zone; EMC: Eclogitic Micaschist Complex; ESZ: External Sesia Zone; L: Lanzo massif; P: Platta unit; PMZ: Piemonte Movement Zone; V: Monviso unit; ZS: Zermatt–Saas Zone; ZH: Zone Houillèr.

et al., 2010b; Fig. 8). The eclogitic Piemonte units are underlain by the Internal Crystalline nappes (Monte Rosa, Gran Paradiso and Dora Maira), which underwent Alpine metamorphism at eclogite facies conditions (Fig. 8). Further to the west, the Briançonnais nappe system underwent relatively minor Alpine deformation and metamorphism, ranging from blueschist to anchizonal facies conditions (Cigolini, 1992; Desmons et al., 1999; Ganne et al., 2003; Malusà et al., 2005; Sartori et al., 2006). In contrast, the underlying and more north-westernly located ophiolite-bearing Valaisan units preserve local evidence of high-pressure metamorphism at $P \geq 1.5$ GPa (Cannic et al., 1996; Bousquet et al., 2002), prior to a renewed sharp decrease of recorded metamorphic pressure in the Helvetic–Dauphinoise domain (Fig. 8).

An extensive geochronological dataset indicates that the onset of metamorphism and deformation is progressively younger from the more easterly to the more westernly units (e.g. Bocquet, 1974; Frey et al., 1974; Hunziker, 1974; Hunziker et al., 1992; Duchêne et al., 1997; Rubatto et al., 1998; Rosenbaum and Lister, 2005; Beltrando et al., 2010b). The earliest high-pressure metamorphism has been dated at ca. 79 Ma in the Eclogitic Micaschist Complex (U–Pb on zircon and allanite; Rubatto et al., 2011) and at 75–73 Ma in the Pillonet unit (^{40}Ar/^{39}Ar and Rb–Sr on high-Si white micas coexisting with sodic amphiboles; Cortiana et al., 1998). A significant age gap is observed between the latest HP metamorphic stages in the Sesia Zone, at $t > 69$ Ma [U–Pb on zircon (Rubatto et al., 1998, 2011); Rb–Sr on white mica (Babist et al., 2006)], and the recorded onset of HP metamorphism in the underlying eclogitic Piemonte units, at ca. 48–44 Ma (e.g. Duchêne et al., 1997; Rubatto et al., 1998; Dal Piaz et al., 2001; Lapen et al., 2003; Beltrando et al., 2009). Note that intermediate ages in the 62–55 Ma range have locally been estimated from the calcschists belonging to the blueschist Piemonte unit in the south-western Alps [^{40}Ar/^{39}Ar and K/Ar on white mica (Takeshita et al., 1994; Agard et al., 2002)]. These ages might alternatively result from incomplete resetting of pre-Alpine mineral reservoirs (Takeshita et al., 1994) or might be recording Cretaceous accretionary prism dynamics (Agard et al., 2002). A broadly continuous younging towards more westerly (or structurally lower) units is then apparent, from 44 to 35 Ma in the Internal Crystalline nappes (e.g. Tilton et al., 1991; Duchêne et al., 1997; Gebauer et al., 1997; Rubatto and Hermann, 2001; Meffan-Main et al., 2004; Lapen et al., 2007; Gabudianu Radulescu et al., 2009; Rosenbaum et al., 2012) to ca. 42–32 Ma for the eastern edge of the Briançonnais nappe system [^{40}Ar/^{39}Ar on white mica (Ganne, 2003; Strzerzynski et al., 2012)] to ca. 33 Ma for exhumation-related fabrics in the Punta Rossa unit, in the Valaisan nappe system [^{40}Ar/^{39}Ar on white mica (Cannic, 1996)]. Deformation and metamorphism then affected the External Crystalline massifs, in the Helvetic–Dauphinois domain, with ductile shear zone formation at ca. 29.5 ± 0.9 Ma in the Mont Blanc massif (Th–Pb on allanite; Cenki-Tok et al., 2014), ca. 33.6 ± 0.6 in the Argentera massif (^{40}Ar/^{39}Ar on wm; Sanchez et al., 2011) and ca. 34–30 Ma in the Pelvoux massif (^{40}Ar/^{39}Ar on wm; Simon-Labric et al., 2009), recording the early stages of widespread continent–continent collision. The interplay between margin geometry and Adria–Europe relative movement vector was likely responsible for significant variations in the timing of onset of collision in the different parts of the Western Alps.

6. Basement–cover relationships in the Western Alps

A wealth of studies of the different Mesozoic meta-sedimentary cover sequences was carried out in the high-pressure part of the Western Alps (e.g. Ellenberger, 1958; Debenedetti, 1965; Michard and Vialon, 1966; Lemoine et al., 1970; Elter, 1972a; Sturani, 1975; Polino and Dal Piaz, 1978; Dal Piaz et al., 1979a; Bearth and Schwander, 1981; Caby, 1981; De Wever et al., 1987; Sartori, 1987; Gouffon, 1993; Sartori and Marthaler, 1994; Venturini, 1995; Tumiati, 2005). Comparatively less attention has been paid to the relationship between meta-sediments and associated basement rocks, which was alternatively assumed as primary (e.g. Elter, 1971; Deville et al., 1992) or tectonic (e.g. Polino et al., 1990). Despite the important lithostratigraphic studies performed in the Piemonte units of the Cottian Alps in the 70s, 80s and early 90s (e.g. Lemoine et al., 1970; Lagabrielle et al., 1982; Deville et al., 1992), the study of basement–cover relationships was largely abandoned in HP terrains in the 90s, under the assumption that the sedimentary cover would be invariably detached from the underlying basement as a result of multi-stage subduction-related deformation (Polino et al., 1990 and references therein). Therefore, as usual for highly deformed/metamorphosed terrains, a distinction has been drawn traditionally between 'continental' (Sesia Zone, Internal Crystalline nappes and Briançonnais nappe system) and 'oceanic' units (Lanzo massif, Piemonte Zone, Valaisan nappe system). However, as shown in this review, such *a priori* distinction, in the axial zone of the North-Western Alps, resulted in the overlooking of pre-Alpine relationships between rock types that were considered exclusive of 'typical' oceanic or continental origin.

As summarized in this section, the different types of basement–cover relationships observed in the Sesia Zone, Piemonte units and Valaisan units of the North-Western Alps display the typical features of rift-related hyper-extended crust and exhumed mantle. As this contribution is aimed at illustrating the methodology to tackle the study of sections of magma-poor rifted margins lacking a layer-cake starting geometry within orogenic belts, only selected Alpine examples are discussed. Furthermore, a well-studied example from Alpine Corsica will be reviewed. A review of basement–cover relationships of all Alpine nappes is beyond the scope of this contribution. It is also worth noting that the recognition of pre-Alpine basement–cover relationships of the kind described here, in specific parts of the Western Alps, might be beyond the resolution of the methodology proposed here, due to extensive Alpine deformation and relative displacement of different rock types.

In this section, basement–cover relationships within Alpine tectono-metamorphic units are discussed without reference to their pre-orogenic relative position. As field mapping strategies, in deformed magma-poor rifted margins, are dictated by the nature of the lower plate of the detachment system, a distinction has been drawn between areas with 'regionally exhumed continental basement' and areas with 'regionally exhumed serpentinized mantle'. In Section 7, the lithostratigraphic information from the tectono-metamorphic units will be discussed in the context of the pre-Alpine architecture of the Adriatic and European margins.

6.1. Regionally exhumed serpentinized mantle juxtaposed with continental basement in the North-Western Alps

In the North-Western Alps, serpentinized ultramafic rocks crop out extensively in the Lanzo massif (e.g. Boudier, 1978) and in the Piemonte units (e.g. Elter, 1971; De Giusti et al., 2004; Li et al., 2004; Dal Piaz et al., 2010). Relatively minor occurrences are located in the Valaisan units (e.g. Beltrando et al., 2012 and references therein), in the Canavese Zone (Beltrando et al., in press), along the Periadriatic Line (e.g. Ferrando et al., 2004) and in the Sesia Zone [Rocca Canavese Zone (Pognante, 1989); Eclogitic Micaschist Complex (Ferraris and Compagnoni, 2003); Second Dioritic–Kinzigitic Zone (Dal Piaz et al., 1971)]. As shown in the following sections, the majority of these bodies were exhumed at the bottom of the Jurassic Tethys, where it was juxtaposed against slivers of continental basement of variable size by major extensional faults.

6.1.1. Punta Rossa unit (Valaisan units)

The Punta Rossa unit, which is part of the Valaisan units, provides the best-preserved example in the Western Alps of a rift-related lithostratigraphic section typical of a hyper-extended domain floored by exhumed mantle lithosphere (Fig. 9; see Beltrando et al., 2012 for a detailed decription of this domain). This inference is based on lithostratigraphic, structural, petrographic and geochronological

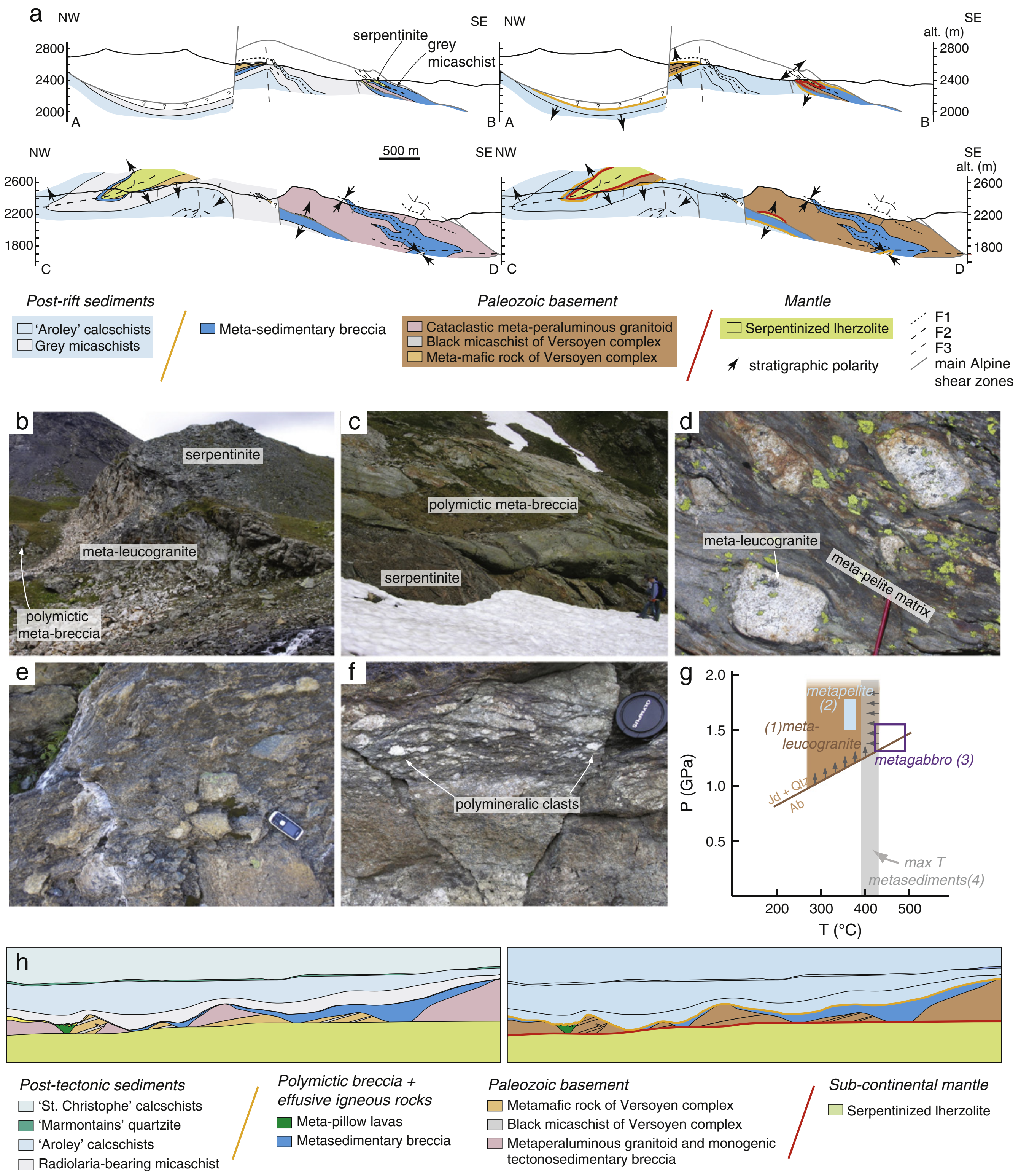

Fig. 9. Punta Rossa unit (Valaisan units). (a) Geological cross sections (modified after Beltrando et al., 2012). Note that basement allochthons consist of different rock types and that allochthons and coarse clastics, of presumed syn-tectonic deposition, are laterally discontinuous. If lithological differences in basement are discarded and key horizons identified, the large scale folds are more easily identified. In the Punta Rossa unit, serpentinized mantle peridotites are directly in contact with Paleozoic basement, including meta-leucogranites (b; UTM WGS84 32N: 332734E; 5064201N) or polymictic breccias (c; UTM WGS84 32N: 333393E; 5062515N). Clasts of leucogranites are found occasionally in the post-tectonic gray micaschists (d; UTM WGS84 32N: 333563E; 5062645N) Monomictic breccias developed at the expense of serpentinized peridotites (e; UTM WGS84 32N: 333324E; 5062516N) and meta-leucogranites (f; note the angular polymineralic clasts; UTM WGS84 32N: 332687E; 5064217N) can be interepreted as pre-metamorphic fault rocks. Estimates of the *PT* evolution of the different lithologies are hampered by extensive late-stage re-equilibration at greenschist facies conditions. Despite these limitations, all lithologies preserve evidence of metamorphic re-equilibration at P > 1.0 GPa (g). The maximum P estimated from meta-gabbros in the neighboring Hermite unit are also indicated. References: 1 = Saliot, 1979; 2 = Bousquet et al., 2002; 3 = Cannic et al., 1996; 4 = Beltrando et al., 2012. All these observations allow retro-deforming the present-day Punta Rossa unit into a pre-orogenic scenario (h). Retro-deformation is performed using the red and orange lines as markers.

evidence combined as outlined in Section 4, indicating original proximity of the different rock types found in the area as well as a common Alpine tectono-metamorphic evolution, preserving the original coherency of this unit. In the heavily folded Punta Rossa unit, serpentinized ultramafic rocks, ranging in size from a few m^2 to nearly 0.5 km^2 are alternatively juxtaposed with thin slivers of continental basement or with clast-supported polymictic meta-breccias (Fig. 9a–c). The clast composition of the meta-breccia mirrors the different types of continental basement found in the area, namely Permian leucogranites (Fig. 9b; Beltrando et al., 2007a) and Carboniferous gabbros and diorites intrusive in micaschists (Masson et al., 2008). Detailed field mapping shows that continental basement slivers and meta-polymictic breccias display marked thickness variations and abrupt lateral terminations (Fig. 9a). The discontinuous distribution of these rock types is at odds with the lateral continuity of top of the ultramafic rocks and the bottom of the pelagic gray micaschists overlying the breccias. These two surfaces can be followed throughout the area, across the observed Alpine structures (Fig. 9a; Beltrando et al., 2012). Lithostratigraphic observations show that the clast composition of the polymictic meta-breccia is largely controlled by the type of basement found directly in contact, indicating original proximity of Paleozoic basement and sediments at the time of deposition. Furthermore, the matrix/clast ratio in the sedimentary meta-breccia increases progressively from the contact with the basement to the overlying gray micaschists, providing a useful indicator of original stratigraphic polarity (Beltrando et al., 2012). Clasts of Permian granitoids are locally found also in the fine-grained gray micaschist overlying the polygenic breccia (Fig. 9d). These observations indicate that Paleozoic continental basement and serpentinized mantle peridotites were both exposed at the bottom of the Valaisan basin, where they underwent partial reworking in the sedimentary cover. The lateral continuity of specific marker horizons across Alpine folds indicates that the Punta Rossa unit preserves a coherent pre-Alpine lithostratigraphic section, despite the lateral discontinuity of Paleozoic basement slivers and meta-breccias (see Beltrando et al., 2012 for details; compare Fig. 9h with Fig. 6b). Furthermore, pre-metamorphic monomictic breccias are occasionally observed along the interface between serpentinized ultramafic rocks and meta-leucogranites (Fig. 9e and f), where sub-cm polymineralic clasts are wrapped around by Alpine fabrics developed within an originally finer-grained matrix. These rock types, which are never observed in the meta-sediments, may be interpreted as resulting from pre-metamorphic cataclastic deformation in the context of rifting.

Studies of the tectono-metamorphic evolution of the different rock types found within the Punta Rossa unit provide further support to this view, showing that ultramafic rocks, Paleozoic continental basement and Mesozoic meta-sediments share the same deformation history, starting from the oldest metamorphic mineral fabric that can be correlated across the different lithologies (Loprieno et al., 2011; Beltrando et al., 2012). This deformation event, which led to isoclinal folding associated with a pervasive axial plane cleavage, was developed relatively late in the tectono-metamorphic evolution of this area, along the exhumation path (Loprieno et al., 2011; Beltrando et al., 2012). $^{40}Ar/^{39}Ar$ geochronology on white mica from meta-granitoids and gray micaschists yielded identical ages of ca. 33–34 Ma for this mineral fabric (samples V93-02 and V94-58 in Cannic, 1996). This deformationf/metamorphic event, followed by multi-stage deformation and metamorphism at greenschist facies conditions, resulted in extensive re-equilibration of the pre-existing high-pressure mineral assemblages (Bousquet et al., 2002; Loprieno et al., 2011;), thus limiting comparisons of the pre-34 Ma metamorphic evolution among the different rock types (Fig. 9g). Rare relict mineral assemblages in meta-pelites consisting of carpholite + phengite + chlorite indicate re-equilibration at $P = 1.5–1.7$ GPa and $T = 350–400$ °C (Bousquet et al., 2002). These conditions are supported by Tmax estimates by Raman Spectroscopy on Carbonaceous Material (RSCM) at ~400 °C (Beltrando et al., 2012). Furthermore, rare relict jadeite has been reported from peraluminous meta-granitoids found in the basement allochthons of the Punta Rossa unit (Saliot, 1979). In Ca-poor meta-granitoids, jadeite stabilization at $T = 400$ °C occurs at $P > 0.8$ GPa through the reaction albite = quartz + jadeite (e.g. Bucher and Frey, 2002), thus providing only a minimum estimate to the actual pressure experienced. Metamafic rocks, instead, are generally pervasively re-equilibrated at greenschist facies conditions during the last stages of deformation and metamorphism and preserve only rare relicts of pre-existing glaucophane. However, metamorphic conditions comparable to those proposed for the meta-pelites of the Punta Rossa unit have been estimated in Carboniferous meta-gabbros belonging to the neighboring Hermite unit (Cannic et al., 1996), which is lithologically similar to the Punta Rossa unit and underwent the same tectono-metamorphic evolution (Beltrando et al., 2012).

The combined lithostratigraphic, structural and petrographic observations summarized here indicate that serpentinized ultramafic rocks, Paleozoic basement and syn- to post-rift sediments were deformed coherently during the Alpine orogeny and that multiple evidence of original proximity of the different rock types are found. While structural analysis shows that the different rock types shared the same deformation history starting from the oldest structure/mineral fabric that can be correlated across lithological boundaries, comparisons of their earlier *PT*t evolution are limited by pervasive recrystallization at greenschists facies conditions and/or poorly diagnostic mineral assemblages.

6.1.2. Piemonte units

The Piemonte units (Fig. 10) provide a vivid illustration of the difficulties related to the recognition of domains floored by hyper-extended lithosphere associated with continent-derived basement and sediments in areas that underwent pervasive deformation, polyphase metamorphism and frequent reactivation of pre-Alpine contacts during subduction/orogeny-related shearing. The presence of hydrated mantle peridotites exhumed at the seafloor has long been recognized within in the high-pressure Piemonte units (Franchi et al., 1908; Bearth, 1967; Dal Piaz, 1969, 1971; Elter, 1971; Bigi et al., 1990; Tartarotti et al., 1998; De Giusti et al., 2004), based on the frequent similarities with the lithostratigraphy of the nearly underformed/unmetamorphosed ophiolitic units found in the Apennines (e.g. Decandia and Elter, 1972; Abbate et al., 1994) and of present-day margins (e.g. Lemoine et al., 1987; see Lagabrielle, 2009 for a review). In the Piemonte units of the North-Western Alps, serpentinized ultramafic rocks, locally preserving evidence of seafloor hydration (e.g. Li et al., 2004; Fontana et al., 2008), may be capped by Mn-rich metacherts (Figs. 10 and 11a; Dal Piaz, 1969; Dal Piaz et al., 1979a; Castello, 1981; Baldelli et al., 1983;) or, more commonly, by fault-related ophicalcites (Fig. 10; e.g. Driesner, 1993; Dal Piaz et al., 2010). Sedimentary ophicalcites and polymictic breccias, with clasts of meta-mafic rocks, ultramafics and rare dolostone also occur (Dal Piaz, 1999 and references therein; Fig. 11b–d). Preserved contacts between metabasalt/serpentinites and metacherts have been documented in several areas, including the part of the eclogitic Piemonte units located in the northernmost-Western Alps, commonly labeled Zermatt–Saas Zone (Bearth, 1967; Dal Piaz et al., 1979a,b; Bearth and Schwander, 1981), in its southern continuation, in the Avic massif (Fig. 10; Dal Piaz and Nervo, 1971; Martin-Vernizzi, 1982; Castelli, 1985; Tartarotti et al., 1998; Martin et al., 2008), and in the overlying blueschist Piemonte units, locally labeled Combin Zone (e.g. Dal Piaz, 1969; Dal Piaz et al., 1979b; Caby, 1981; Baldelli et al., 1983; Dal Piaz, 1999). Metacherts are locally followed upwards by pure marbles and, more commonly, by abundant calcschists, as also documented in the South-Western Alps (e.g. Lemoine et al., 1970; Deville et al., 1992; Fudral, 1998; Tricart and Schwartz, 2006).

In the eclogitic Piemonte units of the North-Western Alps, the lithologies listed above are often juxtaposed with two types of 'exotic' rocks types, consisting either of Paleozoic continental basement or shelf sediments (Figs. 10 and 11e). The continental basement slivers

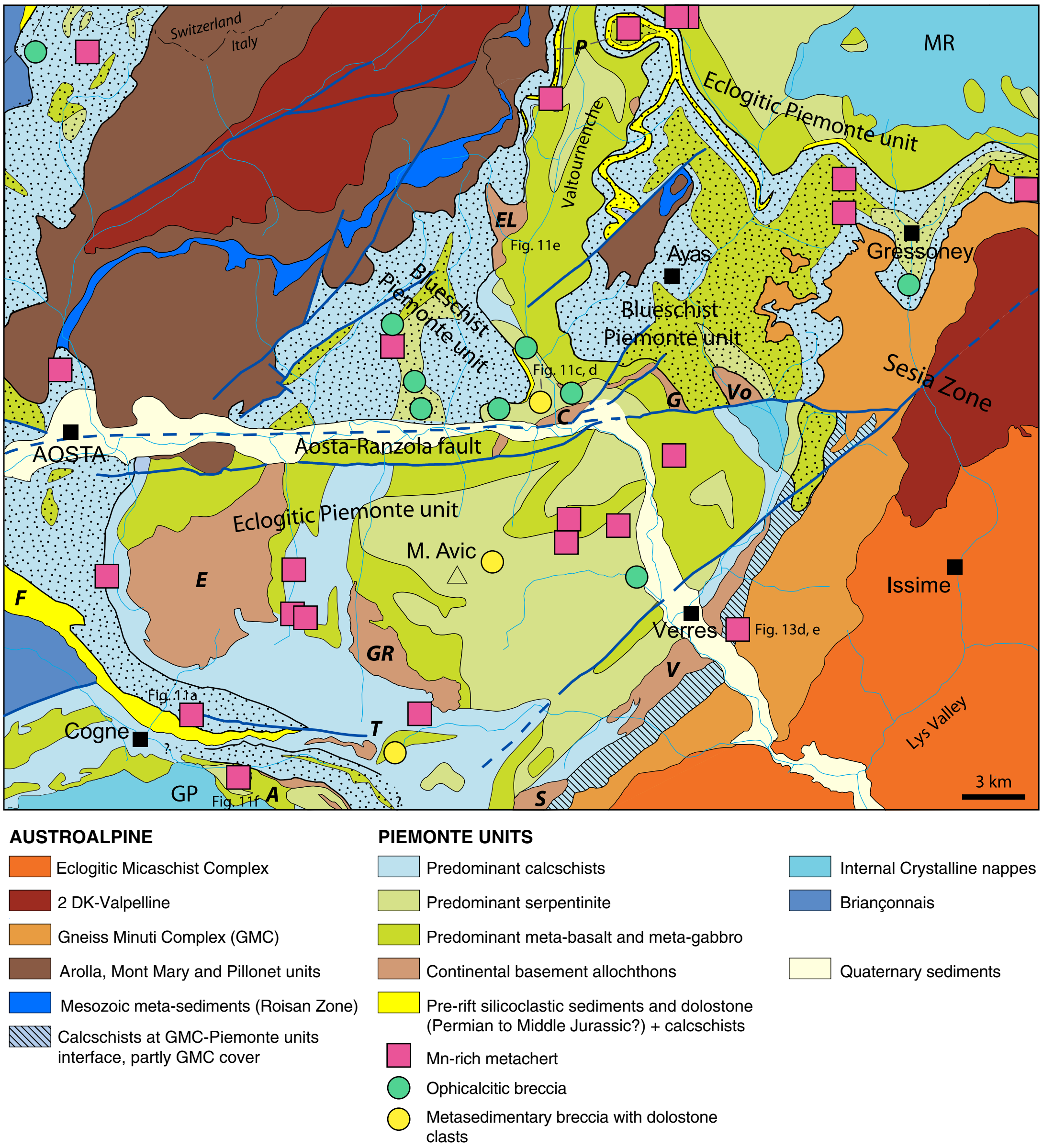

Fig. 10. Lithotectonic map of the lower and central Aosta Valley (see Fig. 4 for map location). Dotted area indicates blueschist Piemonte units (locally referred to as 'Combin Zone'). Main outcrops of Mn-rich metacherts, ophicalcites and dolomite-bearing breccias resting in contact with serpentinites are also indicated. Main continental slices: A = Acque Rosse slice; C = Chatillon slice; E = Monte Emilius slice; EL = Etirol-Levaz slice; G = Grun slice; GR = Glacier-Refray slice; T = Tour Ponton slice; S = Santanel slice; V = Verres slice; Vo: Vollon slice; P = Pancherot–Cime Bianche units; F = Fasceau de Cogne.

consist of high-pressure metamorphic rocks, often preserving evidence of pre-Alpine metamorphism at granulite to amphibolite facies conditions (Etirol-Levaz, Emilius, Verres, Tour Ponton, Glacier-Rafray, Acque Rosse slivers), and of intrusives of mafic and acidic composition (e.g. Dal Piaz and Nervo, 1971; Beltrando et al., 2010a). Details on the lithological composition and tectono-metamorphic evolution of each sliver can be found in an extensive body of literature [Acque Rosse slice (Paganelli et al., 1995; Beltrando, 2007); Tour Ponton (Nervo and Polino, 1976); Glacier-Refray (Dal Piaz and Nervo, 1971; Dal Piaz et al., 1979b); Santanel (Battiston et al., 1987); Verres (Lardeaux and Spalla, 1991; Dal Piaz, 2011); Emilius (e.g. Dal Piaz et al., 1983; Pennacchioni, 1996); Chatillon (Dal Piaz and Martin, 1986; Rolfo et al., 2004); Grun-Vollon (Biino and Compagnoni, 1988; Dal Piaz, 2011); Perriere (Conte et al., 1997); Etirol-Levaz (Ballèvre et al., 1986; Dal Piaz et al., 2001; Beltrando et al., 2010a)]. These slivers were traditionally grouped under the common label of 'Lower Austroalpine units' (Ballèvre et al., 1986) or "eclogitic lower Austroalpine outliers" (Dal Piaz, 1999). They rest along or in close proximity with the contact between the eclogitic Piemonte units and the overlying blueschist Piemonte units. The unexpected juxtaposition of these continent-derived lithologies with typical ophiolitic rocks, already noted by Hermann (1937), was generally ascribed to complex subduction/orogenic dynamics. Processes considered typical of 'subduction channel' or 'serpentinite channel' (Gerya et al., 2002; Bousquet, 2008), or the multi-stage reactivation of the tectonic interface between continent- and ocean-derived nappes (e.g. Gosso et al., 1979; Ballèvre and Merle, 1993; Forster et al., 2004) have been repeatedly proposed. However, Dal Piaz (1999) pointed out the lithostratigraphic similarities between the Platta nappe, in the Eastern Swiss Alps, and the eclogitic Piemonte units. Marked similarities between the Alpine Pressure–Temperature–time–deformation history of several continental slivers and of the neighboring ophiolitic rocks in eclogitic Piemonte units emerged through later studies,

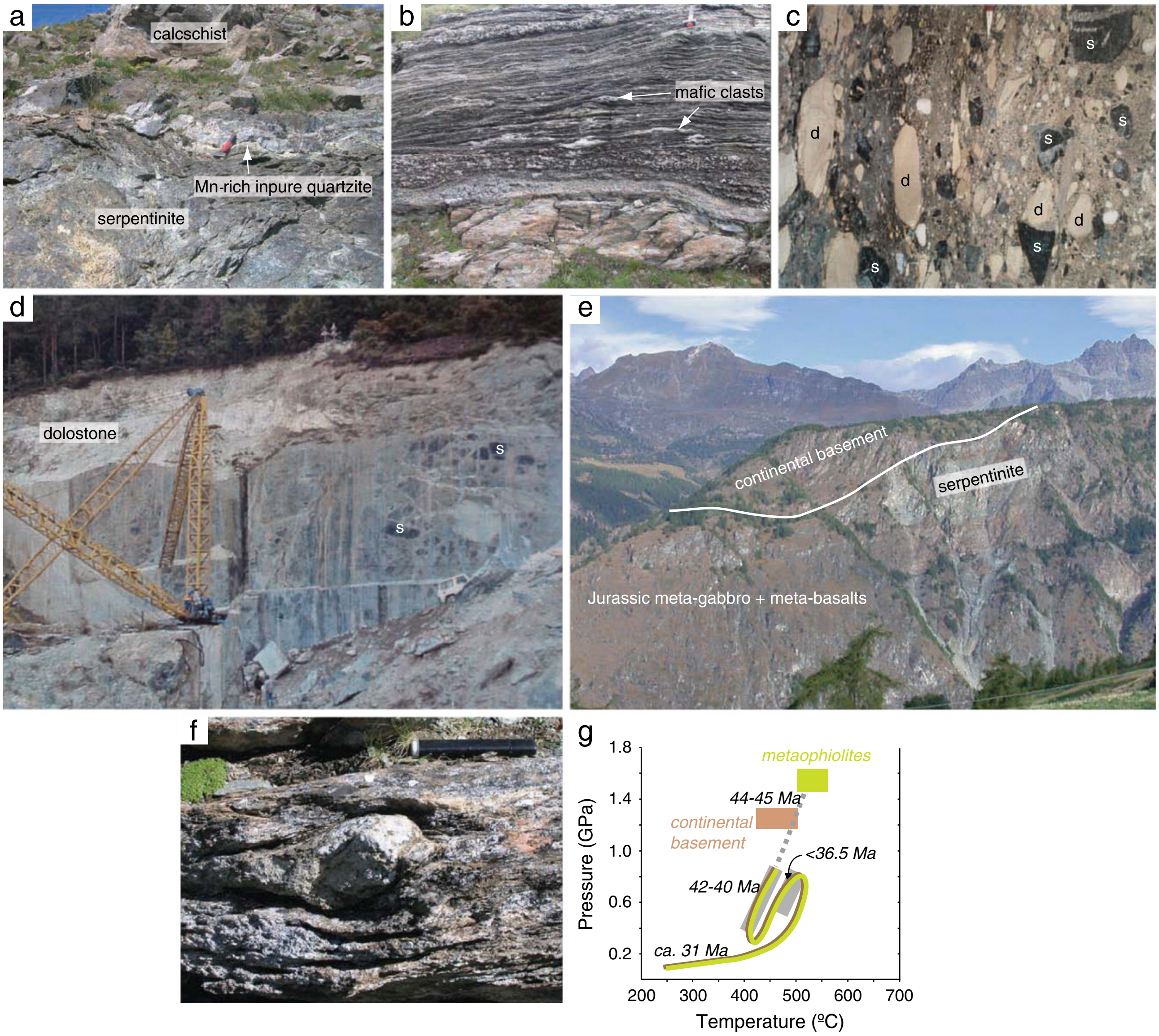

Fig. 11. Key lithostratigraphic observations in the Zermatt-Saas Zone and Avic massif (eclogitic Piemonte units), indicating regional exhumation of subcontinental mantle at the basin floor and proximity with continental crust. Serpentinized ultramafic rocks are locally found directly in contact with 1–30 dm thick Mn-rich inpure quartzites, which are interpreted as the metamorphic equivalent of the cherts with Mn hydrothermal deposits or nodules of middle to upper Jurassic age characteristically found in the Western Mediterranean belts (a); Urtier Valley; UTM WGS84 32N: 374625E; 5052236N; for details on this outcrop see Compagnoni et al. (1979). Serpentinized ultramafic rocks are often capped by sedimentary breccias, containing clasts of meta-mafic rocks (b); Val Champorcher; UTM WGS84 32N: 384599E; 5051200N or consisting of clasts of serpentinized peridotites ('s' in Fig. 11c) and rare shelf dolostone ('d' in Fig. 11c; Raffort quarry, lower Valtournenche; UTM WGS84 32N: 391134E; 5067890N; for details see Dal Piaz, 1999). Large slivers of dolostone are locally directly overlying ophicalcites (d); Blavasse quarry. Note that this outcrop has been quarried out). Slivers of Paleozoic continental basement are commonly found juxtaposed with metabasalts and serpentinized mantle peridotites intruded by Jurassic gabbros (e; Etirol-leval slice, Valtournenche). Clasts of meta-granitoids are rare within the calcschists that were deposited in the Alpine Tethys (f); Lago Loie area, Urtier Valley; UTM WGS84 32N: 376187E; 5049067 N). Studies of the *PT*td evolution of continental basement slivers (brown box and line) and associated meta-ophiolites (green box and line) indicate that they underwent the same tectono-metamorphic evolution starting from the oldest mineral fabrics that can be correlated across lithologies (g; data refers to the Urtier Valley and is compiled from Beltrando, 2007; Beltrando et al., 2007a,b, 2009).

providing a valuable test to this early intuition (Fig. 11g; Dal Piaz et al., 2001; Beltrando, 2007; Dal Piaz et al., 2010). More specifically, in the eclogitic Piemonte units located to the south of the Aosta-Ranzola fault, the Acque Rosse continental basement slivers and the associated ophiolitic mafic rocks underwent the same Alpine evolution starting from the oldest metamorphic mineral assemblages and fabrics that could be detected (Fig. 11g). This evolution involved eclogite facies metamorphism at ca. 44–48 Ma, followed by exhumation to greenschist facies conditions at ca. 42 Ma and subsequent isoclinal folding at $t < 36.5$ Ma, prior to final exhumation to near-surface conditions (Beltrando, 2007; Beltrando et al., 2007b, 2008, 2009). Further to the north, the Emilius and Glacier-Refray continental basement slivers, demonstrably underwent a *PT*t evolution similar to the interlayered eclogitic ophiolites of the Avic massif (Dal Piaz et al., 2001, 2010).

Original proximity of continental basement slivers and ophiolites is also suggested by the Middle to Upper Jurassic zircons commonly found in the Etirol-Levaz slice (Fig. 11e; Beltrando et al., 2010a) and in the Acque Rosse slice (Beltando, unpubl), recording melt infiltration during the intrusion of mafic melts in the underlying ultramafic rocks. Furthermore, extensive pre-Alpine interaction of the Emilius basement sliver with marine fluids is indicated by highly saline fluid inclusions in eclogites (Scambelluri et al., 1998). Clasts of lithologies that could be readily attributed to Paleozoic basement (i.e. micaschists and meta-granitoids) are rarely found within the meta-sediments associated with continental basement slivers (Fig. 11f). The wealth of studies cited above allow the conclusion that the eclogitic Piemonte units, at least in the North-Western Alps (Zermatt–Saas Zone *sensu stricto* and its southern continuation, labeled Mont Avic massif) largely consist of lithostratigraphic associations typical of areas floored by hyper-extended lithosphere, as already argued for less deformed parts of the Central and Eastern Alpine belt (see Manatschal and Müntener, 2009 for a review). Therefore, the so-called 'lower Austroalpine units' should not be viewed any longer as independent tectono-metamorphic units, but rather as extensional allochthons that underwent a common evolution with the serpentinized ultramafics, metabasalts and meta-sediments starting from the Middle to Late Jurassic (Dal Piaz, 1999; Dal Piaz et al., 2001; Beltrando et al., 2010a).

Another group of 'exotic' rock types consists of laterally discontinuous pre-rift limestone, dolostone and siliciclastic deposits that are characteristically found both along the tectonic interface between eclogite and blueschist Piemonte units and within the lower part of the latter (Bucher et al., 2005, Blatt Matterhorn). These meta-sedimentary successions (Fig. 10) have been grouped in the Pancherot–Cime Bianche unit, to the north of the Aosta–Ranzola fault (Dal Piaz, 1999 and references therein), Frilihorn unit (Sartori, 1987; Sartori et al., 2006), Faisceau de Cogne and Faisceau de Prariond, between the Aosta–Ranzola fault and the Gran Paradiso massif (Elter, 1971, 1972) and Gazzo–Isoverde Unit, in the Voltri massif (e.g. Marini, 1998; Fig. 4). In all these localities, dolostones are capped by mono- or polymictic breccias followed by calcschists. The type of pre-rift dolostone and the composition of the breccia, with clasts of Permian to Triassic meta-sediments, has traditionally led to its paleogeographic attribution to the Triassic platform and Jurassic escarpment (pre-Piedmont domain, e.g. Elter, 1972a) separating the Briançonnais rise from the South Penninic basin, characterized by abundant coarse clastic sedimentation supplied by the continental shelf. However, the recent discovery of ophiolitic detritus within the breccia in the Pancherot–Cime Bianche unit (Gasco and Gattiglio, 2011) casts some doubts on this original interpretation, suggesting that these slivers, at the end of the rifting process, may have been located at the bottom of the Western Tethys, possibly as extensional allochthons. This interpretation is strengthened by the rare findings of shelf carbonate clasts within ophicalcites resting on top of serpentinized ultramafics in the eclogitic Piemonte units (Fig. 11c–d; Dal Piaz, 1999).

Therefore, a large number of observations suggest that serpentinized subcontinental mantle, gabbros and basalts were already juxtaposed with continental basement and pre-rift shelf deposits at the end of the Jurassic rifting. Importantly, primary Jurassic contacts have commonly been extensively reworked during the Alpine orogeny (e.g. Gosso et al., 1979; Polino et al., 1990; Reddy et al., 2003; Pleuger et al., 2007) and no coherent section consisting of serpentinized ultramafics, continental basement and syn- to post-rift sediments of the type described in the Punta Rossa unit has been detected, yet. However, coherent sections comprising exhumed mantle, ophicalcites and early post-rift sediments, without extensional allochthons, have already been described from different parts of the blueschist and eclogitic Piemonte units throughout the Western Alps (e.g. Lemoine, 1980; Tricart and Lemoine, 1983; Lagabrielle et al., 1984; Tricart and Lemoine, 1991; Lagabrielle and Lemoine, 1997; Angiboust et al., 2011). Lateral transitions from ophicalcites to continental allochthons to early post-rift meta-sediments overlying serpentinites or meta-gabbros are found locally (e.g. on the western side of Valtournenche; Fig. 10). However, the presence of intervening shear zones (often polyphase) prevents assessing whether the present-day geometry arose from minor deformation of a Jurassic area floored by mantle rocks or from the subduction-related assembly of different sections of the hyper-extended margin. Despite these difficulties, the observations listed above still allow concluding that the different rock types found in the eclogitic Piemonte unit were already located in close proximity within the Jurassic Tethys.

6.1.3. Lanzo massif

The Lanzo massif records multi-stage lithospheric thinning, with progressive exhumation of mantle peridotites from garnet-facies conditions followed by melt infiltration at plagioclase facies conditions, intrusion of gabbroic and basaltic dykes in the Middle Jurassic and brittle extensional tectonics (e.g. Piccardo et al., 2007; Kaczmarek and Müntener, 2008; Kaczmarek et al., 2008; Piccardo et al., 2010). Recent studies showed that the serpentinized carapace rimming the otherwise well-preserved Lanzo peridotites was formed through ocean floor hydration of the mantle rocks (Debret et al., 2013). Middle to Upper Jurassic exhumation to the seafloor is also indicated by relatively poor exposures of a Mesozoic sedimentary cover, consisting of meta-ophicarbonate, metabasalt, calcschist, quartzite, and monometamorphic gneiss locally resting upon serpentinized mantle in the central and northern Lanzo massif (Pelletier and Müntener, 2006). Further occurrences of rift-related contacts between meta-sediments and ophiolitic basement have been reported from the western margins of the Lanzo massif (Lagabrielle et al., 1989). However, this poorly exposed area is located along a major late-Alpine brittle–ductile movement zone characterized by predominant strike slip kinematics (Balestro et al., 2009), preventing the unambiguous attribution of specific outcrops to the Lanzo Massif or to the neighboring Piemonte units. Slivers of continental basement of variable size, recording pre-Alpine granulite facies metamorphism and located at the interface between serpentinized ultramafic rocks and Mesozoic meta-sediments, have been interpreted as rift-related extensional allochthons (Pelletier and Müntener, 2006). Their presence, together with the abundance of paragneisses potentially originated from arkose among the Mesozoic meta-sediments, are taken as evidence that the Lanzo massif was adjacent a continental margin (Pelletier and Müntener, 2006).

Maximum metamorphic conditions of $P > 2.0$ GPa and $T = 550$–620 °C are recorded in kyanite–chloritoid–talc bearing meta-gabbros of the Lanzo ultramafics, as opposed to estimates of $P = 0.9$–1.3 GPa and $T = 500 \pm 50$ °C for extensional allochthons and meta-sediments (Pelletier and Müntener, 2006). This discrepancy has been attributed to extensive post-eclogitic re-equilibration of the latter two rock types during a late-stage metamorphic evolution, as indicated by petrographic observations (Pelletier and Müntener, 2006).

6.2. Regionally exhumed serpentinized mantle in Alpine Corsica

The metaophiolite-rich tectono-metamorphic units in Alpine Corsica have invariably been attributed to the South Penninic basin (e.g. Dal Piaz, 1974; Beccaluva et al., 1984; Rossi et al., 1994; Lahondère, 1996; Marroni and Pandolfi, 2007; Molli, 2008). The widespread occurrence of siliciclastic deposits in close association with supra-ophiolitic sediments (e.g. Santo Pietro di Tenda formation, Caron and Delcey, 1979) led several authors to suggest that the ophiolitic units originated from a section of the Tethyan basin located in a proximal position with respect to continental margins (e.g. Caron and Delcey, 1979; Vitale Brovarone et al., 2011a, 2013 for a recent review). Similarly to the Western Alps, the units that underwent Alpine metamorphism at blueschist to eclogite facies conditions are typically characterized by the direct juxtaposition of Paleozoic continental basement, Jurassic ophiolites and Mesozoic meta-sediments. This lithological association has been alteratively attributed to subduction dynamics, based on the frequent reactivation of lithological interfaces (e.g. Mattauer et al., 1981; Péquignot and Potdevin, 1984; Jolivet et al., 1990; Fournier et al., 1991), rift-related tectonics (e.g. Lahondère, 1996; Vitale Brovarone et al., 2011a; Meresse et al., 2012) or tectono-sedimentary processes (olistostromes, Lahondère, 1996). However, recent studies provided detailed evidence of the preservation of sections of hyper-extended lithosphere both in the blueschist facies Serra di Pigno unit (Meresse et al., 2012) and in the eclogite facies San Petrone unit (Vitale Brovarone et al., 2011a).

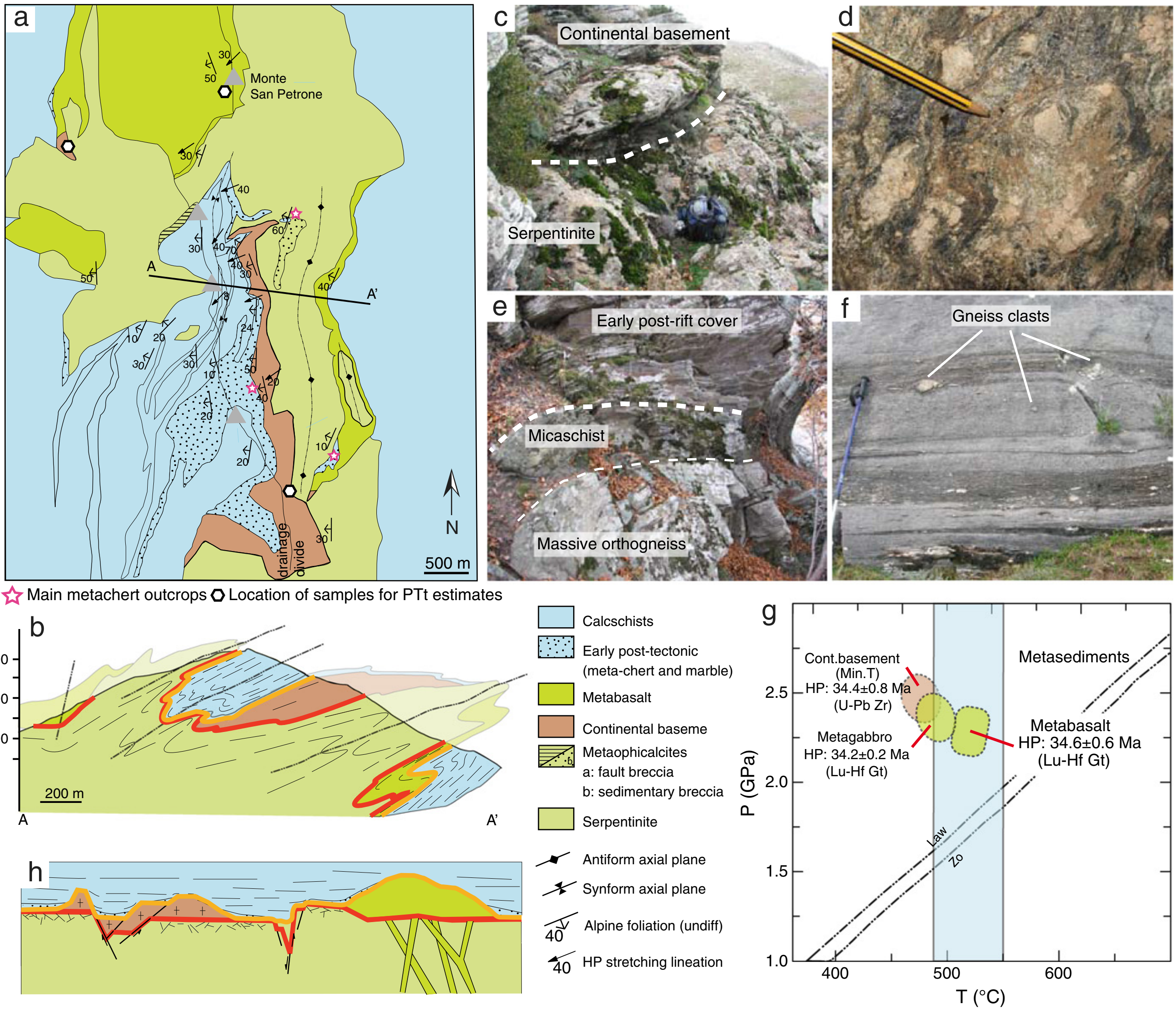

Fig. 12. The San Petrone unit (Alpine Corsica). Simplified geological map (a), modified from Vitale Brovarone et al., 2011a) and schematic interpretative cross section (b), modified from Vitale Brovarone et al., 2011b); (c); UTM WGS84 32N: 527124E 4691700N) continental basement slivers rest directly onto serpentinized mantle peridotites, locally preserving evidence of pre-metamorphic cataclastic deformation (d); UTM WGS84 32N: 527699E 4688822N); (e); UTM WGS84 32N: 527069E 4691843N) early post-rift Mn-rich metacherts are located directly above continental basement, which is capped by a thin micaschist layer; (f); UTM WGS84 32N: 527167E 4691255N) clasts of continental basement are locally found in the post-rift marble, also indicating original proximity of the meta-sediments and continental allochthons; (g) *PT* diagram with petrological estimates of maximunm recorded P conditions and timing of HP metamorphism for the different lithologies of the San Petrone unit, including continental basement rocks and meta-ophiolites (from *PT* pseudosections in Vitale Brovarone et al., 2011a,c, in press). Note that meta-gabbros, which are rare in the San Petrone unit, were studied a few km to the north of this area, still within the same ultramafic body. All the combined observations allow proposing a pre-subduction architecture typical of areas floored by exhumed subcontinental mantle, depicted in (h).

The San Petrone unit consists of a complex lithological association comprising serpentinized ultramafic rocks, metavolcanics, slivers of continental basement and Mesozoic meta-sediments (Fig. 12a). A thick serpentinite sliver forms the core of a large recumbent antiform (Fig. 12b). On its upper limb, the serpentinite is alternatively overlain by (i) slivers of continental basement (orthogneiss–paragneiss dissected by metaigneous dykes) preserving relicts of pre-Alpine granulite facies metamorphism, dated at ca. 290 Ma (U–Pb on zircon; Martin et al., 2011; Vitale Brovarone et al., 2011a) (Fig. 12c), (ii) metavolcanics (meta-pillows and basaltic meta-breccias) and (iii) meta-sediments, consisting of manganese-rich metacherts, marbles and calcschists (Fig. 12e). Pre-metamorphic brittle deformation affected both the serpentinized ultramafic rocks, which are locally capped by ophicalcites, and the continental basement slivers, where angular polymineralic clasts are wrapped around by a lawsonite-bearing *HP* foliation (Fig. 12d and Vitale Brovarone et al., 2011a). No evidence of brittle deformation is observed either in the meta-sediments or in the meta-pillowed basalts lying above this contact. Mesozoic meta-sediments are never found between the serpentized ultramafics and the overlying continental slivers or metabasalts, indicating that the latter were most likely emplacement onto exhumed mantle rocks prior to sediment deposition. Importantly, Mn-rich quartzites are scattered along the base of the meta-sedimentary pile, alternatively in contact with continental basement, metabasalts and serpentinized ultramafics (Fig. 12a). As discussed in Section 6.1.2 these meta-sediments, which are also locally interbedded with metavolcanics, are interpreted as the metamorphic equivalent of

Late Jurassic radiolarian cherts by analogy with other Tethyan supra-ophiolitic suites. Metacherts form a discontinuous layer, with lateral thickness variations attributed to ocean floor morphology (Vitale Brovarone et al., 2011a,b). Metacherts are overlain by marbles containing both continental basement and ophiolitic clasts ranging in size from a few cm to several dm (Fig. 12f; Péquignot and Potdevin, 1984; Vitale Brovarone et al., 2011a). Clast lithology is closely tied to the presence of continental basement allochthons or metabasalts nearby. The meta-sedimentary sequence preserved in the San Petrone area terminates upward with calcschists.

Studies of the tectono-metamorphic evolution of the different lithologies found in the San Petrone unit indicate that they underwent a common polyphase deformation history (Péquignot and Potdevin, 1984; Vitale Brovarone et al., 2011a). Strain gradients towards the main lithological contacts are locally observed, but the general lack of shear sense indicators is suggestive of an origin through dominant flattening deformation, without significant relative lateral displacement. Importantly, the limited extent of exhumation-related re-equilibration allows comparisons of the maximum *PT* conditions recorded by the different rock types found within this unit. Meta-gabbros included in the serpentinized ultramafic rocks (Vitale Brovarone et al., in press), meta-pillowed basalts (Vitale Brovarone et al., 2011c) and mafic rocks within a continental basement sliver (Vitale Brovarone et al., 2011a) all record maximum *PT* conditions in the 490–530 °C range at ca. 2.3 GPa, within the lawsonite–eclogite stability field. In the meta-sediments, where application of standard thermobarometry is hampered by more pervasive re-equilibration during exhumation, peak-*T* estimated by means of Raman Spectroscopy of Carbonaceous Material (RSCM) provide comparable *T* estimates of ca. 500–530 °C (Vitale Brovarone et al., 2011a, 2013). Geochronological studies also provided evidence that the HP re-equilibration was attained at the same time in the different rock types (Fig. 12g). U–Pb geochronology of Alpine zircon rims formed in equilibrium with H*P* assemblages in a continental basement sliver yielded an age of 34.4 ± 0.8 Ma (Martin et al., 2011), while Lu–Hf estimates in meta-gabbros and metabasalts yielded ages in the 34–35 Ma range (Vitale Brovarone and Herwartz, 2013).

Therefore, the combined lithostratigraphic and tectono-metamorphic studies from the San Petrone unit indicate that the ultramafics-continental basement pair was juxtaposed by fault activity prior to the effusion of pillowed lavas and the deposition of typical pelagic Mn-rich radiolarian cherts (Fig. 12h). Partial reworking of the ophiolitic and continental rocks into the overlying sediments was especially efficient in the topographic lows. Despite pervasive subduction/exhumation-related deformation, the rift-related lithostratigraphy was deformed coherently during the Alpine cycle and marker horizons, including the top of the serpentinites and the base of the post-tectonic meta-sediments, can be followed for several kilometers across the axial planes of Alpine folds. Studies of the *PT*td evolution of the different rock types further indicate that they shared the same evolution starting from the oldest mineral assemblages preserved, which were formed at lawsonite–eclogite facies conditions.

6.3. Regionally exhumed continental basement in the Western Alps

In the Western Alps, evidence of extensive continental basement exhumation at the floor of the most distal margin of the Jurassic Tethys is preserved both in the Canavese Zone (Elter et al., 1966; Ferrando et al., 2004; Beltrando et al., in press.) and in the Sesia Zone (Pognante et al., 1987).

6.3.1. Canavese Zone

The Canavese Zone, which underwent minor Alpine deformation/metamorphism, has traditionally been interpreted as the distal Adriatic margin in the Southern Alps, equivalent to the Err–Bernina domain in the Eastern Swiss Alps (Elter et al., 1966; Sturani, 1975; Ferrando et al., 2004). In this domain, high-grade migmatitic gneisses are directly overlain by Middle to Late Jurassic radiolarian cherts, with the local presence of a polymictic breccia (Ferrando et al., 2004). At the southern end of the Canavese Zone extensional deformation led to widespread brittle deformation in the continental basement, which consists of banded amphibolites, migmatitic gneiss and associated anatectic granitoids (Beltrando et al., in press). Cataclasites and fault gouges are more frequent towards the contact with the sediments, indicating top-basement brittle deformation (Fig. 13a). Based on these observations as well as on the relatively low- to moderate-angular discordance between sedimentary layering and top-basement surface, the occurrence of a Jurassic low-angle detachment fault was proposed in analogy with the Eastern Swiss Alps (Ferrando et al., 2004). The overlying supra-detachment basin is characterized by syn-rift polymictic breccias (Figs. 13b and 13c), which record the first exhumation of basement rocks along the low-angle detachment fault, followed upsection by interlayered arkose and pelites, with a fining–thinning upward evolution. These deposits have been attributed to the Pliensbachian to Bajocian, based on their similarities with sedimentary formations of the Eastern Swiss Alps (Ferrando et al., 2004). This basin was then sealed by the Radiolarian Formation, marking the onset of post-rift sedimentation.

Pre-rift Triassic dolomite pods, a few tens of meters in size, now largely or totally removed by quarrying, are found throughout the area (Beltrando et al., in press). Poor outcropping conditions do not allow the assessment of the original relationships between continental basement, Jurassic syn- to post-rift sediments and these pre-rift dolostones. However, the dolomite clasts observed in the polymictic breccia (Fig. 13c) suggests the presence of dolomitic source rocks nearby. This pre-rift sedimentary cover may have been dismembered and delaminated by low-angle detachment faulting, forming extensional allochthons (see Fig. 6c for comparison).

6.3.2. Sesia Zone

The Sesia Zone is defined as the tectonic domain consisting predominantly of continental basement rocks that underwent early Alpine metamorphism at blueschist to eclogite facies conditions, located between the Insubric Line, the Piemonte units and the Lanzo massif (Compagnoni et al., 1977; Bigi et al., 1990). Based on Alpine metamorphism, presence of major bounding shear zones and type of pre-Alpine basement, the Sesia Zone is generally subdivided into three major units, labeled Eclogitic Micaschist Complex (EMC), Second Dioritic–Kinzigitic Zone (2DK), Gneiss Minuti Complex (GM) and the minor Rocca Canavese Unit (Dal Piaz et al., 1972; Compagnoni et al., 1977; Pognante, 1989). Rare Mesozoic meta-sediments have so far been observed only in the EMC (Venturini et al., 1994) and GM (Gosso et al., 1979; Minnigh, 1979; Pognante et al., 1987). As shown below, the occasional preservation of pre-Alpine relationships between continental basement and post-rift sediments calls for a re-assessment of both the original nomenclature and the lateral extent of the more westernly located tectono-metamorphic unit of the Sesia Zone.

6.3.2.1. External Sesia Zone. The westernmost unit of the Sesia Zone has traditionally been labeled Gneiss Minuti Complex (Compagnoni et al., 1977 and refs. therein). Originally, this term was adopted to indicate a tectonic unit consisting predominantly of Permian granitoids intruded in a pre-existing basement, then affected by pervasive Alpine re-equilibration under blueschist to greenschist facies conditions (Dal Piaz et al., 1972; Compagnoni et al., 1977; Cortiana et al., 1998). The Gneiss Minuted Complex has alternativey been considered as separated from the EMC by an Alpine 'transition zone' (Dal Piaz et al., 1972) or shear zone (Williams and Compagnoni, 1983; Venturini, 1995) or as originally intrusive into the EMC (Spalla et al., 1991; Babist et al., 2006). Studies carried out in the south-western part of the Sesia Zone showed that the orthogneisses are locally directly in contact with micaschists, carbonate-bearing schists and Mn-rich quartzites, interpreted as Mn-bearing metacherts of probable Middle Jurassic

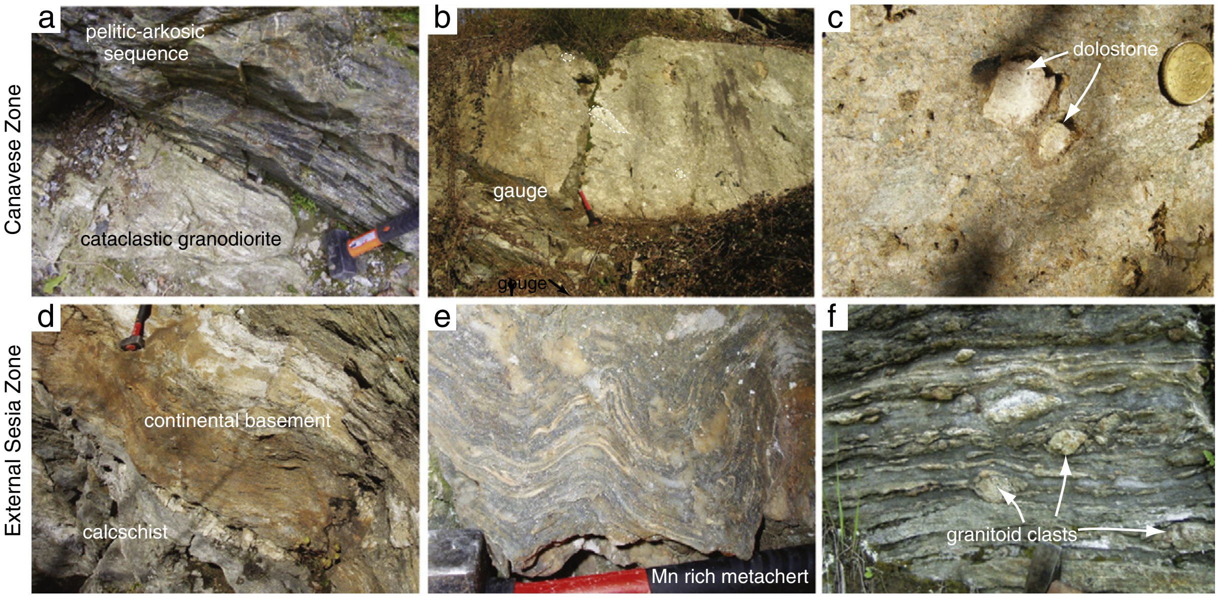

Fig. 13. Key lithostratigraphic observations from the southern Canavese Zone and the External Sesia Zone, indicating regional exhumation of continental basement at the basin floor in the Jurassic. In the relatively little deformed Canavese Zone (photographs from Beltrando et al., in press), continental basement is alternatively overlain by interlayered arkose-pelites (a; UTM WGS84 32N: 390310E; 5019885N) or by polymictic breccias (b; UTM WGS84 32N: 390332E; 5019807N), similar to the Saluver C in the Err nappe (Masini et al., 2011). Dolostone clasts are locally found in the polymictic breccia (c), alongside more abundant clasts of granodiorite and felsic volcanics. In the External Sesia Zone, in the Aosta Valley, 10-cm thick Mn-rich inpure quartzites are locally preserved at the (overturned) interface between continental basement and meta-pelites meta-marls of the so-called 'calcschists' (d and e; UTM WGS84 32N: 400421E; 5056828N; see Fig. 10 for location of these outcrops). Further to the south, in the Orco valley, large basement clasts are locally found in the ophiolites-free calcschists (f; UTM WGS84 32N: 383006E; 5029656N; photo courtesy of I. Gasco).

age (Minnigh, 1979; Pognante et al., 1987). Differently from Paleozoic metacherts associated with continental basement granitoids and impure marbles in the Dent Blanche nappe system (Manzotti et al., 2012), the metacherts described here lack any evidence of pre-Alpine metamorphism and are typically associated with micaschists and meta-marls similar to the so-called calcschists of the Piemonte units (Pognante et al., 1987). As a result, Pognante et al. (1987) suggested that the Sesia Zone might have been located along the distal Adriatic margin, where continental basement was directly onlapped by post-rift sediments. New observations on the basement–calcschists interface further to the north (Figs. 10, 13d and e) indicate that this relationship is much more common than previously recognized, suggesting that continental basement might have been regionally exposed at the bottom of the Western Tethys, in the Jurassic. Typical Mn-rich metacherts crop out in the Aosta Valley, at the western termination of the Gneiss Minuti Complex, at the contact with the underlying calcschists, which are generally attributed to the blueschist Piemonte unit (Fig. 13d and e). The preservation of such a distinctive lithology, which could be easily excised by orogeny-related deformation, due to the originally limited thickness, indicates that the calcschists represent, at least in parts of this area, the sedimentary cover originally deposited over the Paleozoic granitoids. Importantly, calcschists associated with Paleozoic basement host thick micaschist layers and, more rarely, dm-sized meta-granitoid clasts (Fig. 13f; Gasco and Gattiglio, 2010), indicating a significant terrigenous input, hinting at original proximity of exhumed basement rocks. In specific circumstances, transitional contacts between leucocratic gneisses and calcschists over a thickness of 10 cm have been interpreted as primary sedimentary contacts between altered/re-sedimented basement and calcschists or as gradual transitions between meta-arkose layers and calcschists (Gasco and Gattiglio, 2010). These observations suggest that the protoliths of the Gneiss Minuti Complex were regionally exhumed at the bottom of the Alpine Tethys, where they were locally overlain by Mn-rich cherts and calcschists, occasionally reworking the underlying continental basement. Alpine deformation, culminating in early metamorphism of the similar and neighboring Pillonet klippe at ca. 75–73 Ma (Cortiana et al., 1998) and later greenschist facies metamorphism at ca. 38 Ma (Inger et al., 1996; Inger and Ramsbotham, 1997) resulted in different final geometries of this basement–cover interface. According to the views presented here, the exhumation surface is regionally overturned along the Aosta Valley (Fig. 13d). Detailed mapping along the more southerly located Orco Valley, instead, reveals that the Paleozoic basement/Mesozoic meta-sediment interface is deformed by all folding stages detected in the field (Gasco and Gattiglio, 2010). Importantly, the three fold generations that have been recognized were entirely developed along the exhumation path of this tectono-metamorphic unit (Gasco et al., 2009), providing further evidence that structural analyses alone cannot univocally prove/disprove earlier juxtaposition during early-subduction dynamics.

Therefore, the calcschists located at the interface between the Sesia Zone and the Piemonte units to the south of the Aosta–Ranzola fault, should be considered, at least partly, as the autochthonous sedimentary cover of the Gneiss Minuti Complex (Fig. 10). As a result, we suggest that the lithostratigraphic unit consisting of GMC and its Mesozoic sedimentary cover should be labeled 'External Sesia Zone' hereafter, even though the exact location of its western termination is presently unknown. Our observations indicate that major Alpine shearing was accommodated within the calcschists, located in-between the preserved basement exhumation surface and the eclogitic Piemonte unit, to the west, rather than along the calcschists–continental basement interface, which was previously considered to mark a major nappe boundary between Sesia Zone and Piemonte units (e.g.Gosso et al., 1979; Inger and Ramsbotham, 1997; Babist et al., 2006; Gasco et al., 2009). Indeed, along the full length of the contact between external

Sesia Zone and Piemonte units, extensive multi-stage Alpine shearing (e.g. Wheeler and Butler, 1993; Bistacchi et al., 2001) generally prevents the unambiguous attribution of intervening calcschists to either tectono-stratigraphic units (Fig. 10).

7. Rift-related hyper-extension and exhumation of subcontinental mantle in the Western Alps: first-order implications for the evolution of convergent plate margins

As apparent from this review of the lithostratigraphic and tectono-metamorphic evolution of several tectonic units from the North-Western Alps and Corsica, several lithological associations that have traditionally been considered the result of subduction/orogenic dynamics acting upon 'typical' continental and oceanic lithosphere were rather established by pre-orogenic tectonics and variably reworked during the Adria–Europe convergence. These findings, combined with a wealth of existing studies from the rest of the Western Alps, where exhumed mantle overlain by pelagic sediments or clastic layers rich in ophiolitic detritus has long been recognized, have important implications for the understanding of the mechanisms responsible for the tectonic sampling and subsequent exhumation of tectono-metamorphic units in (U)HP orogenic belts, as discussed in Section 7.2.

These findings also suggest that the most deformed-metamorphosed part of the Western Alps was formed at the expense of distal rifted margins. Therefore, it appears that distal rifted margins are more easily deformed than proximal margins and the architecture and rheological stratification of hyper-extended domains controls the tectono-metamorphic evolution of the internal parts of the belt during tectonic inversion (see Section 7.3).

7.1. The origin of "anomalous" lithological associations in (U)HP terrains

Lithological associations consisiting of serpentinized mantle lithosphere, meta-sediments and continental basement are common within Alpine-type orogens and other orogenic belts worldwide. Interestingly, the mechanisms that have been proposed to establish similar lithostratigraphic associations, which are generally referred to as 'mélanges', are somewhat related to the extent of orogeny-related metamorphic re-equilibration and deformation. A range of tectono-sedimentary processes, including rift-related hyper-extension in magma-poor environments (e.g. Manatschal, 2004; Fig. 1) or the deposition of syn-rift (Lagabrielle and Bodinier, 2008; Clerc et al., 2012; Fig. 2d) or syn-orogenic (Marroni et al., 2002; Fig. 2e) sedimentary deposits have been proposed for tectono-stratigraphic units within little deformed/metamorphosed sections of orogenic belts. However, these mechanisms are largely set aside in the study of high-pressure metamorphic terrains, apart for some notable exceptions (e.g. Dal Piaz, 1999). Studies in high-pressure orogenic belts have generally favored an origin through complex subduction dynamics, invoking mechanical mixing within serpentinite or sedimentary channels (Fig. 2c; e.g. Cloos and Shreve, 1988; Gerya et al., 2002; Bousquet, 2008). The emphasis on orogeny/subduction-related deformation is, at least in part, justified by the extensive exhumation-related reworking of the majority of high-pressure metamorphic units commonly observed worldwide.

In this contribution we argue that an origin through rift-related tectonics in magma-poor environments should also be taken into account, when approaching the study of (U)HP units characterized by 'anomalous' lithological associations. The set of key observations than enable the recognition of hyper-extended domains in (U)HP metamorphic units is defined based on existing lithostratigraphic studies of little deformed/metamorphosed examples from the Eastern Swiss Alps, combined with traditional *PT*td studies. This methodology, which is illustrated through an extensive review of the *PT*td evolution and lithostratigraphy of the main Alpine tectono-metamorphic units, indicates that lithological associations consisting of continental basement, serpentinized mantle, meta-mafic rocks and different types of meta-sediments can also originate through rift-related hyper-extension. Therefore, several (U)HP tectono-metamorphic units from the Western Alps and Corsica sample remnants of Jurassic hyper-extended margins that were variably reworked during subduction/orogeny. These findings call for caution when approaching the study of hyper-extended margins preserved in orogenic belts, as the possible lack of a pre-orogenic layer-cake geometry must be taken into account (cfr. Figs. 6, 9 and 11). As a result, the presence of discontinuous lithological units consisting of thin slices of hydrated continental basement, pre-rift sediments and syn-rift sediments should not be taken *per se* as indicative of complex orogenic dynamics. Similarly, the presence of regional contacts between continental basement and post-rift sediments, as documented for the External Sesia Zone and the Canavese Zone (Figs. 10, 13d and e) is not necessarily related to orogenic dynamics leading to the excision of the pre- and syn-rift cover or to sampling of middle to lower crustal rocks from the hanging wall of subduction systems (e.g. Polino et al., 1990; Stöckhert and Gerya, 2005). Indeed, the potential preservation of the marker horizons that are typical of hyper-extended magma-poor margins should be tested, before making inferences on subduction/orogenic dynamics. However, as shown for the Piemonte unit case study, it is important to note that complex pre-orogenic lithostratigraphic associations may indeed undergo extensive orogeny-related reworking, often resulting in slip being accommodated along the main lithological interfaces. Despite these limitations potentially disrupting the internal coherence of specific sections of magma-poor rifted margins, lithostratigraphic observations might still allow the original proximity among the different rock types to be inferred.

7.2. Implication for subduction/exhumation dynamics

The discovery that several lithological associations were established during rift-related tectonics calls for a re-assessment of the relative role of rift- and subduction/orogeny-related tectonics in establishing the present-day architecture of the Alpine belt. Most importantly, these findings help constraining the size of Alpine tectono-metamorphic units, allowing important inferences on the mechanisms controlling the tectonic sampling of fragments of the downgoing lithosphere and their subsequent exhumation to the surface. Indeed, the size of Alpine tectonic units has been the subject of a long-standing debate, which is best illustrated for the eclogitic Piemonte units in the North-Western Alps, commonly labeled Zermatt–Saas Zone (Fig. 10). The unexpected presence of slivers of Paleozoic continental basement associated with ophiolites led some authors to propose that the present-day lithostratigraphy of the Zermatt–Saas Zone resulted from 'serpentinite channel' dynamics, where hydration of mantle wedge peridotites drives the buoyant return flow of originally unrelated rock types within a subduction mélange (Gerya et al., 2002; Bousquet, 2008). The unambiguous evidence of multi-stage Alpine shearing, especially in the upper part of the Zermatt–Saas Zone (Dal Piag and Ernst, 1978; Wheeler and Butler, 1993; Reddy et al., 1999, 2003; Forster et al., 2004; Pleuger et al., 2007), has been indicated as responsible for significant exhumation-related shuffling of the tectono-metamorphic stack, leading to tectonic sampling of originally unrelated slivers of continental basement (Ballèvre and Merle, 1993; Lister and Forster, 2009). At the other end of the spectrum, the Zermatt–Saas Zone has been regarded as a coherent sliver of Tethyan lithosphere, based on the relative homogeneity of the recorded high-pressure conditions throughout a vast area (Angiboust et al., 2009). An alternative interpretation suggests that the Zermatt–Saas Zone consists of at least three lithotectonic units, characterized by different groups of lithological associations, separated by major shear zones (Dal Piaz, 1999, 2004). While a solution to this debate still lies beyond the resolution of the existing data set, here we only wish to highlight how different approaches can result in widely different interpretations. Importantly, the recognition of the rift-related juxtaposition between Paleozoic basement and ophiolites discussed in this paper does not rule out a significant role for Alpine multi-stage shuffling in establishing the final architecture observed in the field (e.g. Reddy et al., 2003). However, we suggest that at least part of the apparent complexity of multi-stage Alpine movement zones is due to partial tectonic reworking of complex rift-related lithological associations.

However, observations from neighboring areas shed light on the potential thickness of Alpine tectono-metamorphic units, which in the Zermatt–Saas Zone might be masked by relatively second-order exhumation-related shear zones. In the ultramafic Avic massif (Fig. 10), which mostly lacks continental allochthons, the characteristic layers of ophicalcites extensively capping serpentinized peridotites provide a good marker to estimate the thickness of individual slivers to ca. 1.5 km. Estimates of several hundred meters can be provided from the Punta Rossa unit, in the Valaisan units and the San Petrone unit, in Alpine Corsica, which escaped significant exhumation-related shearing. The thickness of the Punta Rossa unit can be calculated from the base of the preserved ultramafics to the youngest stratigraphic marker available, located in the Mesozoic cover, at the transition between Marmontains quartzite and the St. Christophe calcschists (Beltrando et al., 2012). The resulting value, obtained by retro-deforming rigidly all the folds observed in the field, amounts to >600 m. This is only a crude estimate of original nappe thickness, as it ignores the possible existence of undetected isoclinal folds and of significant flattening/thickening of the original sequence during deformation. These values are in line with recent estimates proposed for the Monviso massif, which is also part of the eclogitic Piemonte units, where individual tectono-metamorphic units preserving a coherent section of Tethyan ocean floor, ranging in thickness from ca. 300 m to ca. 1.1 km, can be followed for more than 10 km along strike (Angiboust et al., 2011). Therefore, the literature data from the Western Alps and Corsica reviewed here indicates that Alpine (U)HP tectono-metamorphic units originated from tectonic sampling from the downgoing lithosphere, which largely consisted of hyper-extended crust and exhumed mantle domains (Fig. 2b). The original thickness of the newly formed tectono-metamorphic units probably amounted to several hundreds of meters. As shown in this review of the different tectonic domains from the Western Alps and Corsica, this original thickness may be preserved during exhumation or significantly diminished by exhumation-related tectonic shuffling.

Comparisons with seismic reflection and refraction studies along the Lusigal 12 and CAM144 profiles, off the Iberia margin (Beslier, 1996; Chian et al., 1999), calibrated with drillhole data from ODP Legs 149 and 173 (Sawyer et al., 1994; Whitmarsh et al., 1998), provide important insights on the nature of the potential décollement horizon along which specific sections of rifted continental margins can be tectonically sampled (Fig. 14). A downward increase in seismic velocities has been documented in hyper-extended domains, where it has been related to progressive hydration of exhumed ultramafics and continental basement during rift-related brittle tectonics and hydrothermal circulation. The rheological barriers resulting from decreasing basement alteration may provide key décollement horizons, along which the overlying altered basement and sediments can be detached from the downgoing plate during basin inversion. In the CAM144 section, seismic velocity attenuation indicates that important rheological barriers should be placed at 0.5–2 km under the basin floor. These estimates, correspond to the thickness of several Alpine tectono-metamorphic units. Therefore, we suggest that different sections of hyper-extended

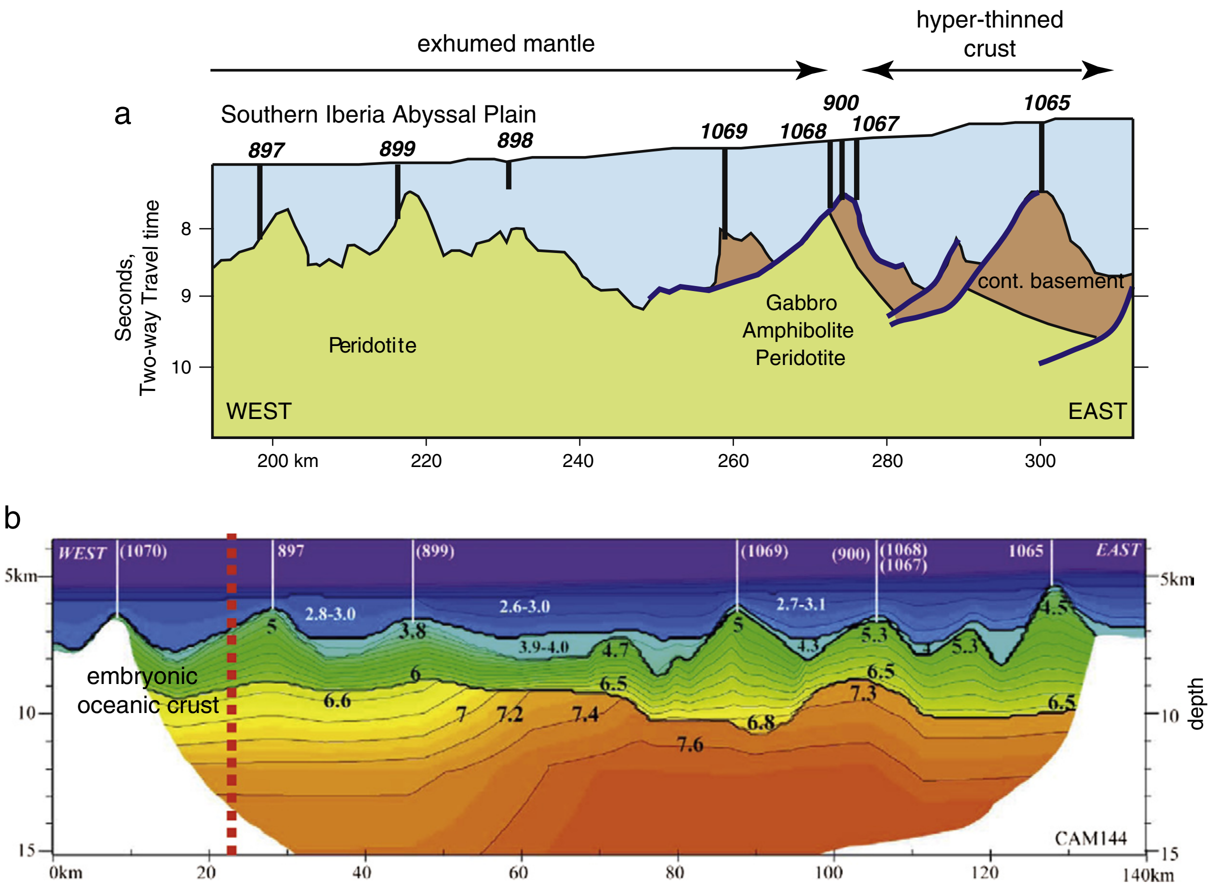

Fig. 14. (a) Geological interpretation of the reflection Lusigal 12 seismic section through the Iberian hyper-extended crust and exhumed mantle domain (Beslier, 1996); (b) Velocity model of the adjacent CAM 144 seismic section after Chian et al. (1999). The contour interval of velocity is 0.2 km/s^{-1}. Note the similar velocity gradient recorded in areas floored by hyper-extended crust and exhumed subcontinental mantle. ODP drill sites are indicated.

margins are preferentially detached from the downgoing lithosphere along a rift-related rheological barrier resulting from downward-fading hydration. Local morphology is likely to exert an important role, too, with topographic highs probably being more likely to be sampled during subduction and accreted to the evolving accretionary prism or orogenic wedge (e.g., Polino et al., 1990; Manatschal et al., 2006, 2011).

7.3. Rift inheritance and tectono-metamorphic evolution

The observations reviewed in the previous sections indicate that several tectono-metamorphic units that underwent an Alpine tectono-metamorphic overprint at (U)HP conditions in the Western Alps and Corsica originated from areas floored by hyper-extended crust and exhumed mantle, related to Jurassic rifting. The recognition of pre-orogenic lithostratigraphic associations within the main Alpine tectono-metamorphic units provides new constraints on their paleogeographic positions (Fig. 15), shedding light on the relationship between *PT*t evolution and rift-related margin architecture. As discussed in this section, the regionally most significant gaps in the recorded Alpine metamorphic pressure, which correspond to the Insubric Line, Piemonte Movement Zone and Basal Briançonnais Movement Zone (Fig. 8) may be related to (and partly explained by) the complex rift structure.

Although a complete review of basement–cover relationships from all Western Alpine tectono-metamorphic units is still beyond the existing dataset, it is immediately apparent that the relative position of the tectono-metamorphic units demonstrably sampling areas floored by regionally exhumed continental basement and subcontinental mantle is analogous to the one documented in the less deformed/metamorphosed Eastern Swiss Alps (cfr. Figs. 3, 5 and 15). This analogy allows extending the generally accepted pre-convergence margin architecture (Fig. 3) to the areas that were later involved in Western Alpine subduction (Fig. 15). The proposed scenario is in accordance with several published paleogeographic reconstructions (e.g. Dal Piaz et al., 1972; Lemoine, 1985; Froitzheim and Manatschal, 1996; Dal Piaz, 1999; Babist et al., 2006), which rely heavily on the stacking order and on the age of Alpine high-pressure metamorphism. Importantly, the approach adopted here provides additional lithostratigraphic constraints. This reconstruction should not be considered as the only possible pre-orogenic restoration, although observations of high-quality reflection seismic sections from present-day magma-poor rifted margins show similar architectures. Most importantly, the width of the former margins is difficult to constrain, since the absolute amount of relative displacement between the Western Alpine tectono-metamorphic units cannot be estimated, due to the widespread exhumation-related overprint of the main tectonic contacts.

As apparent from Fig. 15, the proximal Adriatic margin, preserved in the Southern Alps, grades westward into the Canavese and Sesia Zone, with lithostratigraphic features typical of areas floored by hyper-extended crust (e.g. Ferrando et al., 2004; Babist et al., 2006). Local mantle windows within this thinned crust are preserved in the southern part of the Canavese Zone (Beltrando et al., in press). The Sesia Zone is then juxtaposed with the Piemonte units, which, similarly to the South Penninic units of the Eastern Swiss Alps (Figs. 3 and 5) preserve a lithostratigraphy characteristic of areas floored by exhumed mantle lithosphere, with frequent continental basement allochthons (e.g. Dal Piaz, 1999; Beltrando et al., 2010a). The Briançonnais rise separated the South Penninic basin from the more westernly located Valaisan basin, consisting of hyper-extended crust with windows of exhumed mantle, as sampled in the Punta Rossa unit (Beltrando et al., 2012). The latter gives way to the west to the Helvetic basement and cover units, derived from the proximal European margin (Loprieno et al., 2011).

The improved understanding of the margin architecture has a number of implications for the role of rift inheritance and hyper-extension during tectonic inversion, a topic that is attracting increasing attention (e.g. Lundin and Doré, 2011; Lester et al., 2013; McIntosh et al., 2013). As pointed out by Lundin and Doré (2011), hyper-extension rift-related processes may lead to significant weakening of the pre-orogenic lithosphere, thus playing a critical role on the reactivation and inversion of rifted margins. Recent studies of the transition between the Eastern and Central Alps (Mohn et al., 2011) confirm this view, pointing out a major gap in Alpine metamorphic grade and deformation style within the inverted distal margin of the Adriatic plate (Fig. 8). This observation was interpreted to indicate that the Late Cretaceous plate motion of the Adriatic plate, in this area, was largely accommodated by a deformation zone that nucleated within the distal Adriatic margin, outboard with respect to the Adriatic necking zone. A similar scenario can be proposed for the Western Alps, where a major gap in metamorphic grade and deformation style is observed across the Canavese Zone, which marks the transition between the proximal part of the Adriatic margin and the distal continental margin units sampled in the Sesia Zone (Figs. 8 and 15). This tectono-stratigraphic unit separates the Ivrea Zone, which locally underwent Alpine re-equilibration at sub-greenschist facies conditions, from the Eclogitic Micaschist Complex (Sesia Zone), which underwent Alpine metamorphism at $P > 1.8$ GPa starting from ca. 80 Ma (Rubatto et al., 2011). Strike slip deformation within the Canavese Zone at ca. 75–60 Ma (Zingg et al., 1976), combined with plate kinematic considerations (Rosenbaum et al., 2002), indicate that this Late Cretaceous metamorphic evolution took place along a left-lateral deformation zone nearly parallel to the inherited Jurassic structural trends and to the Adriatic movement vector (Beltrando et al., 2010b). The first-order correlation between Alpine metamorphic/deformation history and rift-related paleogeography, already noted in Dal Piaz et al.

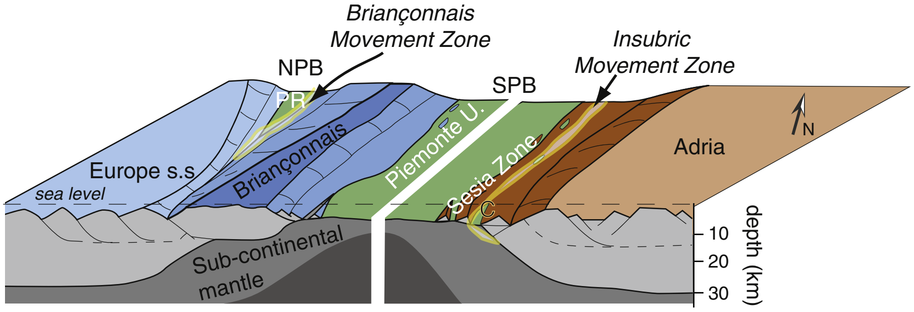

Fig. 15. Proposed position of the main western Alpine tectono-metamorphic units within the Late Jurassic paleogeographic scenario. The future location of the Insubric and Basal Briançonnais Movement Zones is also indicated. Note that the different sections of the Adriatic and European margins that are now stacked in the Western Alps were not conjugate originally (see Beltrando et al., 2010b for a discussion). C: Canavese Zone; PR: Punta Rossa Unit; NPB: North Penninic basin; SPB: South Penninic basin.

(1972), indicates that early deformation probably nucleated at the transition between proximal and distal Adriatic margin (Fig. 15). This deformation zone, referred to as 'Insubric Movement Zone', was later reactivated during several stages of the Alpine evolution, including right-lateral shearing, up to the Miocene (Schmid et al., 1989; Pleuger et al., 2012).

A second major pressure gap is located at the transition between the eclogitic and blueschist Piemonte units, which in the North-Western Alps corresponds to the well studied Piemonte Movement Zone (Fig. 8; e.g. Reddy et al., 2003; Forster et al., 2004). The Zermatt–Saas Zone, which is part of the eclogitic Piemonte units, underwent high-pressure metamorphism at ca. 48–44 Ma, immediately before the onset of Alpine metamorphism of the Briançonnais tectonic units. Beltrando et al. (2010a) proposed that exhumation of the eclogitic Piemonte units in the footwall of the Piemonte Movement Zone was possibly related to the arrival of the Briançonnais micro-block at the trench. In that scenario, thick continental crust would have resisted subduction, as indicated by the lower pressure metamorphism recorded by the Briançonnais nappe stack (Fig. 8), potentially favoring the exumation of the just-subducted areas floored by exhumed subcontinental mantle, located in a more distal position (Fig. 3 in Beltrando et al., 2010a).

A third regionally significant pressure gap preserved in the Western Alps is located along the Frontal/Basal Briançonnais Thrust (Fig. 8). This multi-stage movement zone, referred to as 'Briançonnais Movement Zone' hereafter, accommodated both extensional and shortening deformation (e.g. Cannic et al., 1996; Freeman et al., 1998). It separates the so-called Zone Houillèr, which underwent low grade Alpine metamorphism ($P = 0.6 \pm 0.2$ GPa and $T = 280–300$ °C; Lanari et al., 2012), from the underlying Valaisan nappe system, which underwent Alpine metamorphism up to $P = 1.5–1.7$ GPa and $T = 350–400$ °C (Fig. 8; Bousquet et al., 2002). Stratigraphic considerations in the Houillèr Zone and in the rest of the Briançonnais nappe system have long been interpreted to indicate that they were originally part of a continental ribbon partly detached from the proximal European margin (Fig. 15). On the other hand, the Punta Rossa unit, which crops out only a few hundreds of meters underneath the Basal Briançonnais Thrust, preserves evidence of exhumed subcontinental mantle (Fig. 10; Beltrando et al., 2012). Furthermore, the other sub-units described from the rest of the Valaisan units document the transition from the proximal European margin to the North Penninic trough (Loprieno et al., 2011). These considerations indicate that the North Penninic hyper-extended margin was preferentially underthrusted beneath the Briançonnais micro-block, under a cool thermal regime, thus reaching significantly higher pressure at low-T (Figs. 8 and 15). Significantly, the extent of this pressure gap decreases southward and vanishes where the Valaisan basin tapered out originally (Bigi et al., 1990), as indicated by marked similarities between the sedimentary cover of the Briançonnais nappe system and Helvetic–Dauphinois domain. This observation suggests that significant underthrusting, in the south-western Alps was hampered by the widespread presence of normal continental crust.

These first-order considerations based on combined lithostratigraphic, paleogeographic and tectono-metamorphic observations indicate that lateral variations in the crustal and lithospheric architecture control the fate of different sections of magma-poor rifted margins during plate convergence. The main deformation zones, where most of the plate convergence is accommodated and significant tectonic burial is achieved, are likely to nucleate along lateral gradients in the crustal thickness, corresponding both to the transition between proximal and distal margins and to the transition between micro-blocks and hyper-extended lithosphere (Fig. 15). Therefore, areas floored by hyper-extended crust and exhumed mantle are likely to undergo a greater amount of tectonic burial with respet to proximal domains and continental micro-blocks, which generally rest in the hanging wall of these movement zones.

8. Conclusions

This study outlines and discusses the methodology allowing the detection of sections of magma-poor rifted margins lacking a layer-cake architecture within highly deformed/metamorphosed orogenic belts. This tool is mainly aimed at testing the overall consistency/coherency of the lithostratigraphy and the available evidence for original proximity of the different rock types. In this context, the recognition of key marker horizons that can be followed throughout the study areas plays an important role in distinguishing between rift-related lithostratigraphic sections and chaotic subduction or sedimentary mélanges. These marker horizons correspond to the top-basement surface and to the base of the post-rift sediments. Importantly, all lithological units located in-between these two surfaces are likely to terminate laterally as a result of rift-related thinning, potentially leading to complex outcropping patterns following multi-stage deformation and metamorphism. These criteria should be used in conjuction with the more widely adopted comparison of *PT*td paths followed by different rock types, as the latter approach might be insufficient to assess the internal coherence of tectono-metamorphic units. The methodology outlined in this paper, applied to the North-Western Alps, indicates that several major tectono-metamorphic units originated from domains floored by hyper-extended crust and lithosphere bounding the Western Tethys. Basement–cover relationships comparable to those observed in the little deformed equivalents preserved in the Eastern Swiss Alps are found locally. More commonly, convergent margin dynamics resulted in variable Alpine reworking of the Jurassic contacts, as hyper-extended lithosphere is significantly more prone to accommodating deformation than proximal margins.

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