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REVIEW ARTICLE

The Atlas-East Variscan -Elbe shear system and its role in the formation of the pull-apart Late Palaeozoic basins

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Abstract

The Variscan orogeny occurred as a result of the Late Devonian to Late Carboniferous collision and accretion of Gondwana-derived microcontinents and continental masses with those of Laurussia. The irregular boundaries of the colliding continents caused isochronous transpressional and transtensional tectonics, accompanied by a complex pattern of intracontinental shear zones at the scale of the southern European Variscides. These shear zones and their configuration controlled the subsequent evolution of Permian to Middle Triassic paleogeography. The geographic distribution, from Morocco to the Eastern Alps, of the Late Carboniferous–Permian up to Triassic basins, most of which are considered as pull-apart basins, was related with the development of the Late Palaeozoic intracontinental shear network. Our analysis of the stratigraphic, tectonic and volcanic features of the Late Carboniferous/Permian continental basins across the Laurussia/Gondwana boundary reveals the role of the East Variscan Shear Zone during this time as a precursory lineament for the development of the Permian to Triassic rifting of Pangaea and the following opening of oceanic basins (e.g., the Neothetyan Ocean).

Keywords Late Palaeozoic shear network · Carboniferous–Permian basin evolution · Mediterranean and Central Europe · Alpine Wilson cycle

Introduction

The Late Permian to Tertiary orogenic Wilson cycle that affected the Pangaea continent evolved through rifting, breakup and opening of an oceanic basin, followed by its closure and by the accretion of displaced terranes to form new continents (Dewey 1988; Vai 2003; Gutiérrez-Alonso et al. 2004, 2008). Weil et al. (2013) resume the origin of the Variscan orogen in the closing of at least two—and possibly four—oceans between Laurentia, Baltica, and Gondwana, and interposed micro-continents, during the Palaeozoic amalgamation of the Pangea supercontinent. Afterwards, late, to post-orogenic modification of the Western Europe Variscan Belt shaped the four complete arcs from Poland to Brittany, and then across the Bay of Biscay (Cantabrian Sea) into Iberia, where they are truncated by the Betic Alpine front in southern Spain (Weil et al. 2013).

Four different processes have been proposed to explain Pangaea rifting before the onset of the Early Jurassic breakup: (1) post-Variscan–Alleghenian orogenic collapse (Malavielle et al. 1990); (2) dispersal above a mantle superplume (Veevers 2005); (3) a combination of different mechanisms (Hynes 1990); and (4) self-subduction of the Pangaean global plate (Gutiérrez-Alonso et al. 2008).

Bonin et al. (1998) identified three major episodes for an orogenic cycle: (a) intracontinental rifting and plate divergence, followed by oceanic basin opening and ending with the onset of subduction along active margins; (b) plate convergence (due to ocean/ocean and/or ocean/continent subduction), oceanic basin closure and continent/continent collision associated with wrench and thrust tectonics; and (c) dominantly ensialic accretion of continental blocks or terranes by docking and/or hyper-collision, together with uplift and transcurrent fault tectonics, generating transpressional

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and transtensional regimes. The geodynamic settings of the three distinct episodes have been driven by the contrasting rheologies of the lithosphere and asthenosphere (Bonin et al. 1998; Ziegler and Stampfli 2001).

The Variscan orogeny is widely interpreted as a result of the Carboniferous collision and accretion of Gondwana-derived microcontinents and continental masses with those of Laurussia (Gutiérrez-Alonso et al. 2008; Padovano et al. 2014). The irregular boundaries of the colliding plates generated coeval transpressional and transtensional tectonics, accompanied by a complex pattern of intracontinental shear zones at the scale of the southern European Variscides (Arthaud and Matte 1977; Neubauer and Handler 2000; Gutiérrez-Alonso et al. 2004, 2008; Martínez Catalán 2011; Padovano et al. 2011, 2014; Dias et al. 2017; Ballèvre et al. 2018; Fig. 1). In particular, the broad-scale shear network is characterised by activity on several main intracontinental strike-slip shear zones. In the northern region of Pangaea, these shear zones include the Appalachian Minas Fault Zone (Murphy et al. 2011), the South and North Armorican Shear Zones (Tartese et al. 2012) and the Elbe Shear Zone (Schenk et al. 2002; Pressler et al. 2007), and in the southern region include the Atlas Shear System (Bouaziz et al. 2002, e.g., Fig. 1). This shear network was subsequently partially transposed by the Alpine orogeny to the east (Dinarides–Hellenides). Nevertheless, relics of Late Carboniferous shearing can be recognised in the Tisia and Moesia areas (Dornsiepen et al. 2001; Pamic and Jurkovic 2002; Cortesogno et al. 2004a, b; Carrigan et al. 2006), in the Alps (Schaltegger and Brack 2007) and in the Northern Apennines (Rau 1993; Pandeli 2002; Padovano et al. 2011). In the peri-Gondwana-derived microcontinents (e.g., Iberia and France), two important intracontinental strike-slip shear zones can be also identified: the sinistral antithetic Coimbra–Cordoba Shear Zone (Pereira et al. 2010) and the dextral North Pyrenees Shear Zone (Arche and Lopez-Gomez 2005; Gretter et al. 2015; Fig. 1). The western boundary between the peri-Gondwana-derived microcontinents and Gondwana is conversely represented by the East Variscan Shear Zone (EVSZ, e.g., Fig. 1) (Padovano et al. 2011, 2014).

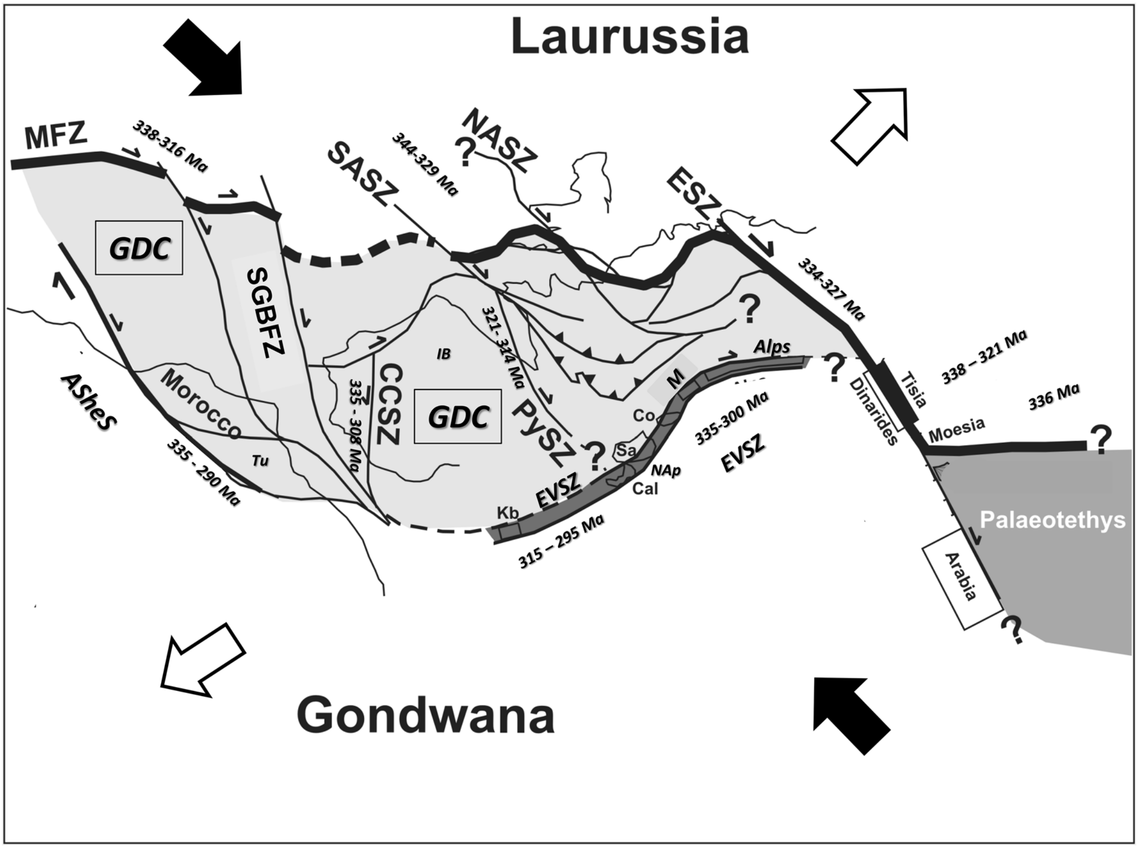

Fig. 1 Major intracontinental shear zones active during the Late Carboniferous and their ages of shearing (see in the text). *GDC* Gondwana derived continents, *ASheS* Atlas shear system, *SGBFZ* Southern Grand Banks Fault Zone (dextral), *EVSZ* East Variscan Shear Zone (dextral), *CCSZ* Coimbra–Cordoba Shear Zone (sinistral), *PySZ* North Pyrenees Shear Zone (dextral), *MFZ* Minas Fault Zone (dextral), *SASZ* South Armorican Shear Zone (dextral), *NASZ* North Armorican Shear Zone (dextral), *ESZ* Elbe Shear Zone (dextral), *Tu* Tunisia, *IB* Iberia, *Kb* Kabyles, *Sa* Sardinia, *Cal* Calabria, *NAp* Northern-Apennines, *Co* Corse, *MT.M* Maures (modified from Padovano et al. 2011). Black arrows: Late Carboniferous shortening. White arrows: Late Carboniferous extension

In this paper, we revised the structural framework of the EVSZ and of other intracontinental shear zones in different segments of the Variscan belt of Europe and of the other peri-Mediterranean countries (from Morocco to the Balkan peninsula), focusing on the stratigraphic, tectonic and volcanic features of the associated Late Carboniferous–Late Permian (pull-apart) basins (rhomb-graben-or domino-like pull-apart structures; Hatcher 1995).

This integrated analysis allowed us to (1) define the main tectono-sedimentary and magmatic stages as having occurred during the complex Carboniferous to Triassic shearing events in the analysed area and (2) speculate whether these structures might be prodrome to those developed in the following Alpine Wilson cycle that dismembered Pangaea.

The East Variscan Shear Zone

The EVSZ (Padovano et al. 2011, 2014, Fig. 1) was characterised by NW–SE shortening during the Late Carboniferous (Neubauer and Handler 2000; Bouaziz et al. 2002; Cassinis et al. 2012; Padovano et al. 2014). This was one of the largest Variscan intracontinental dextral strike-slip shear zones and extended from Slovenia through the Alps to North Africa. The EVSZ was active between 325 ± 1.3 Ma (U–Pb radiometric age on monazite) and 315 ± 1.3 Ma (U–Pb radiometric age on zircon) (Carosi et al. 2012; Padovano et al. 2014). Therefore, the EVSZ was connected in both time and space with the Atlas Shear System and the Elbe Shear Zone (Fig. 1).

The width of the EVSZ varies from a few kilometres (e.g., Emosson Lake, Aiguilles Rouges–Mt. Blanc massifs, in Genier et al. 2008; and in the Argentera Massif in Corsini et al. 2004) to 40 km (Sardinian Massif, in Elter et al. 2010; Padovano et al. 2014). This dextral shear zone shows an S-shape in plan view (Elter et al. 2011, Fig. 1), varying from an E–W trend in the eastern Central Alps to a N–S/NE–SW trend in the Western Alps/Corsica/Sardinia/Calabria and Tunisia.

A complex geological evolution can be locally pointed out for the EVSZ. In NE Sardinia (see data from HGMC in Elter et al. 2010; Padovano et al. 2011, 2014), the EVSZ underwent two episodes of shearing: an older dextral-shear stage, dated at 325 ± 1.3 Ma (U–Pb radiometric age on monazite), characterised by amphibolite-facies metamorphism, and a younger local sinistral-shear stage with greenschist-facies metamorphism imprint, which was contemporaneous with the synkinematic emplacement of peraluminous granitoid rocks, dated between 318 ± 3 and 315 ± 2 Ma (U–Pb radiometric age on zircon; Padovano et al. 2014). Furthermore, two different metamorphic zones of amphibolite-facies grade are distinguished in the EVSZ: an inner zone that was overprinted under the stability field of sillimanite and an external zone within the stability field of kyanite (Elter et al. 2010).

The EVSZ evolved simultaneously with other intracontinental shear zones between 335–300 Ma (e.g., Fig. 1 and references in Padovano et al. 2011, 2014), including the dextral Southern Grand Banks Fault Zone (SGBFZ), the sinistral Coimbra–Cordoba Shear Zone (CCSZ), the dextral Pyrenees Shear Zone (PySZ), the dextral Minas Fault Zone (MFZ), the dextral South Armorican Shear Zone (SASZ), the dextral North Armorican Shear Zone (NASZ) and the dextral Elbe Shear Zone (ESZ). The exhumation of high-temperature metamorphic rocks was driven by the formation of a coeval shallow restraining bend that involved the telescoping of isotherms (Padovano et al. 2011, 2014, and references therein) producing melts and mylonitic foliations, within the older dextral transpressive shear regime, as shown by field evidence and finite strain analysis in NE Sardinia (Elter et al. 2010).

The NW–SE Carboniferous shortening direction (Neubauer and Handler 2000; Bouaziz et al. 2002; Cassinis et al. 2012; Padovano et al. 2014) continued also in the Early Permian age (Stampfli et al. 2000; Stampfli and Borel 2002; Beltrando et al. 2007; Bergerat et al. 2007; Muttoni et al. 2009; Catalan et al. 2011; Aubele et al. 2012; Cassinis et al. 2012; Bachtadse et al. 2018).

Pohl et al. (2018) and Zanchi et al. (2019) evidenced pure extension in SSE-NNW direction instead of Permian dextral strike slip in the Central/Southern Alps. Zanchi et al. (2019) inferred deformations at shallow crustal level which occurred during the Early Permian along high-angle normal faults soling into the Low Angle Normal Faults, forming the northern boundary of the Orobic Basin. Pohl et al. (2018), however, highlighted the syn-kinematic emplacement of the Permian Val Biandino Quartz Diorite (287 Ma) with a D_2 mylonitic top-to-SE component of shear.

Moreover, Cassinis et al. (2012), Berra et al. (2014), described the Permian basins with a NE–SW direction of extension, possibly coeval with an E–W dextral sense of shear.

Anyway, the Late Carboniferous–Lower Permian dextral motion of Laurussia relative to Gondwana could have caused the fragmentation of the northern Gondwana margin into several crustal blocks (Fig. 2; Aubele et al. 2012; Padovano et al. 2014), designated as Gondwana Derived Continents (GDC). The GDC crustal blocks are subject to differential rotations due to a set of discrete continental shear zones (Aubele et al. 2012).

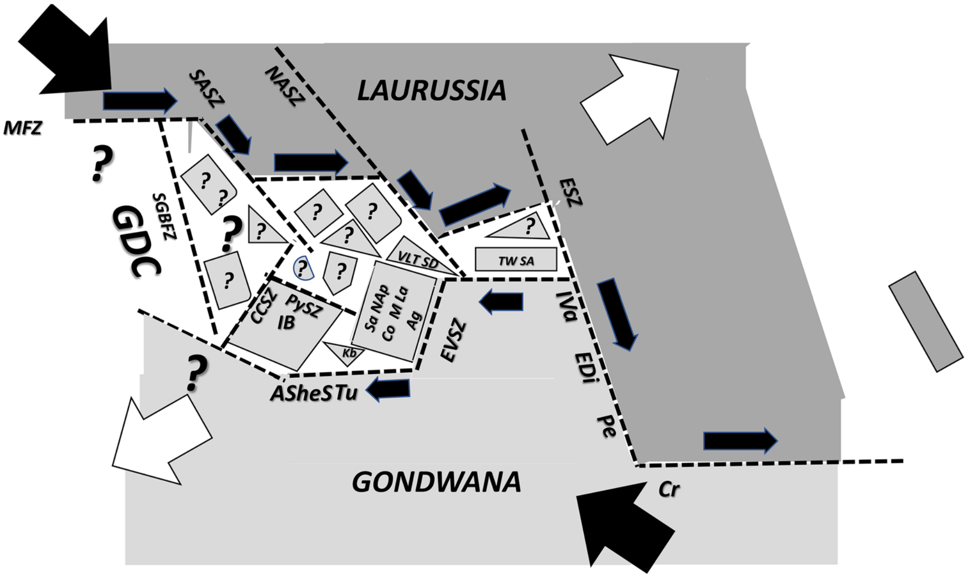

Fig. 2 The Late Carboniferous–Early Permian dextral shearing could have taken up the fragmentation of the northern Gondwana margin involving the Gondwana Derived Continents (GDC). *ASheS* Atlas shear system, *Tu* Tunisia, *IB* Iberia, *Kb* Kabyles, *Sa* Sardinia, *NAp* Northern Apennines, *Co* Corse, *M* Maures, *La* Ligurian Alps, *Ag* Argentera, *VLT* Versoyen–La Thuile Basin, *SD* Salvan–Dorénaz Basin, *TW* Tauern Window Basin, *SA* Southern Alps basins, *IVa* Idrjica Valley basin, *EDi* External Dinarides basin, *Pe* Peloponnese basin, *Cr* Crete basin, *MFZ* Minas Fault Zone, *SGBFZ* Southern Grand Banks Fault, *EVSZ* East Variscan Shear Zone, *SASZ* South Armorican Shear Zone, *NASZ* North Armorican Shear Zone, *CCSZ* Coimbra–Cordoba Shear Zone (sinistral), *PySZ* Pyrenees Shear Zone, black arrows: Upper Carboniferous-Early Permian direction of shortening; white arrows: Upper Carboniferous-Early Permian direction of extension (from Aubele et al. 2012, modified); areas with question marks: unknown terrains of GDC

Tectono-sedimentary evolution of Carboniferous–Permian to Triassic basins along EVSZ

The location of the EVSZ with respect to other main tectono-structural elements not only played a fundamental role during the Late Carboniferous geodynamics but also had major control over the subsequent evolution of Permian to Middle Triassic paleogeography (e.g., Ballèvre et al. 2018). The distribution of Late Carboniferous–Permian basins, from Morocco to the Eastern Alps, has generally been related with the development of this shear network, and therefore the basins are considered as pull-apart, in particular rhomb-graben-like or domino-like pull-apart structures (Hatcher 1995). In this regard, many Late Carboniferous to Early Permian pull-apart basins in the Southern Alps are related with the general dextral megashear (e.g., Cassinis et al. 2018; Ballèvre et al. 2018). Moreover, at *c.* 275 Ma, their sedimentation was interrupted for *c.* 10–15 My, leading to the development of a "mid-Permian" unconformity (Deroin and Bonin 2003; Schaltegger and Brack 2007). This main unconformity was related with (1) the post-collisional collapse of the Variscan orogen (Henk et al. 1997), (2) the post-tectonic extension that marks the beginning of the Alpine rifting and that was connected to the opening of the NeoTethys (Cassinis et al. 2018) and (3) the revival of large-scale strike-slip tectonics and erosion, locally attaining crustal thinning, upwelling, and partial melting of mantle, followed by the advection of melts and crustal heating (Prost and Becq-Giraudon 1989; Handy and Zingg 1991; Cadel et al. 1996; Schaltegger and Brack 2007; Marotta and Spalla 2007).

In the Northern Apennines, Rau (1993) and Pandeli (2002) identified several Late Carboniferous–Permian to Late Triassic sedimentary cycles. The unconformities between the sedimentary sequences have been related with tectonic events (Asturian, Saalian, Palatine, Late Scythian and/or Early Anisian and Late Ladinian events) and record repeated strong extensional or transtensional/transpressional activity within the Tuscan mobile belt between the Late Carboniferous and Late Ladinian periods, when Alpidic regional rifting finally began. Taking into account the change in shortening direction from NW–SE to W–E (e.g., Timmerman 2004), the Late Carboniferous shear network was probably active up until the Ladinian period, consistent with the evidence for the Southern Alps (Schaltegger and Brack 2007).

The tectono-sedimentary development and igneous evolution of Late Palaeozoic basins in the areas of interest are described and synthesised below (for details, see references).

Permian basins in Tunisia

In Tunisia (Figs. 3, 4), the Tebaga of the Medenine Basin (Raulin et al. 2011) trends E–W and represents an important outcrop of Permian marine rocks in Africa. This structure resulted from large-scale block tilting controlled by E–W faults (in particular the Aziza Fault, with a NE–SW direction of extension, as in the Atlas Shear System) extending along the Jeffara Plain (Raulin et al. 2011). The Upper Permian succession, unconformably lying on Early Permian or older successions, is characterised by four sedimentary sequences: (a) a basal unit represented by sandy, shale deposits with marine fauna; (b) a unit of carbonate biohermal sediments; (c) a shale unit; and (d) an uppermost unit represented by sandy, shale deposits (Khessibi 1985; Kilani-Mazraoui 1990). The last authors pointed to an important unconformity present at the Early Scythian level and marked by the absence of part of both the Upper Permian and Lower Scythian.

Permian basins in peri-Gondwana-derived microcontinents

Iberia

The Iberian Peninsula recorded the break-up of Pangea by a Permian Triassic rifting stage that originated the Pyrenean, Iberian, Catalan, Ebro and Betic basins, and the basins located in the present-day Balearic Islands (Lopez-Gòmez et al. 2019). The evolution went through an early phase characterised by large-scale transtensional and extensional regime, an initial tectonic step corresponding to basin definition, followed by a mature step characterised by thermal

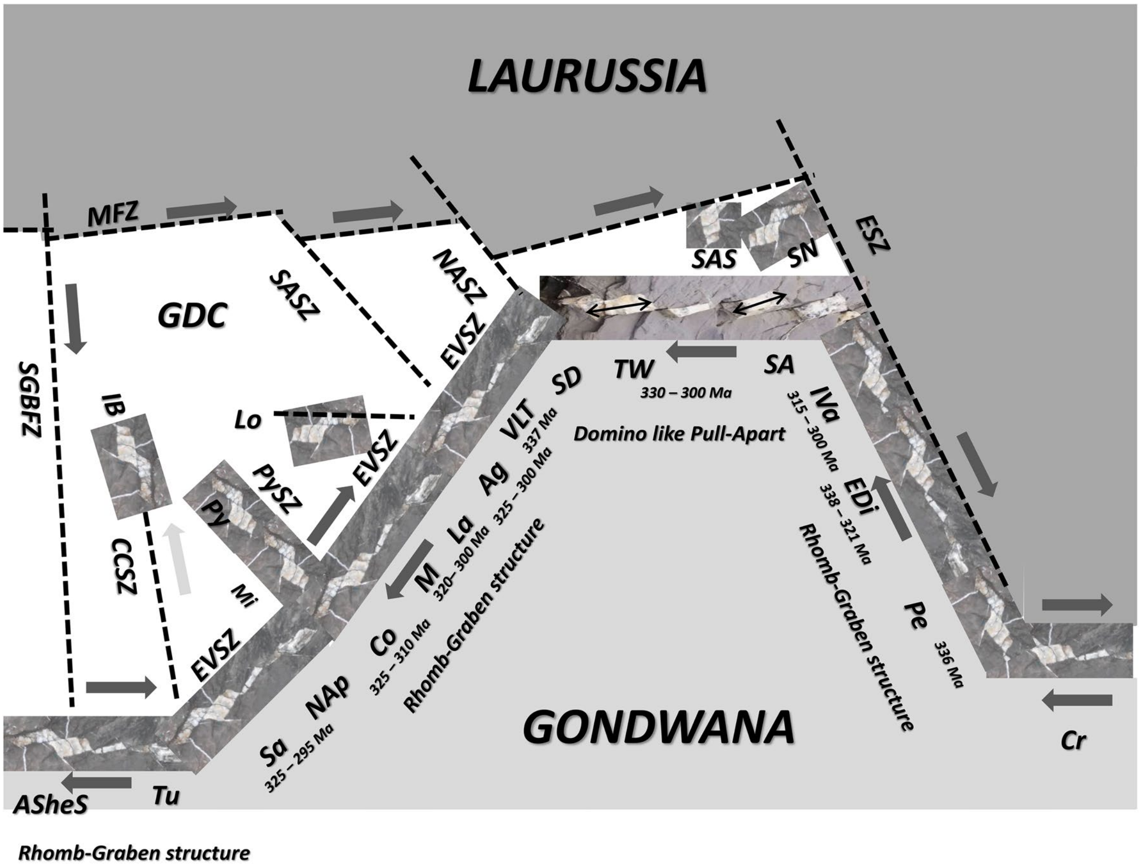

Fig. 3 Distribution of Permian basins (not to scale). *GDC* Gondwana derived continents, *ASheS* Atlas Shear System, *Tu* Tunisia, *IB* Central Iberia basins, *Mi* Minorca basin, *Py* Pyrenees basins, *Sa* Sardinian basins, *NAp* Northern Apennines basins, *Co* Corsican basin, *M* Maures basin, *La* Ligurian Alps basin, *Ag* Argentera basin, *VLT* Versoyen–La Thuile basin, *SD* Salvan–Dorénaz basin, *TW* Tauern window basin, *SA* Southern Alps basin, *SN* Saar–Nahe basin, *SAS* Saxonian Graben, *IVa* Idrjica Valley basin, *EDi* External Dinarides basin, *Pe* Peloponnese basin, *Cr* Crete basin, *SGBFZ* Southern Grand Banks Fault (dextral), *EVSZ* East Variscan Shear Zone (dextral), *CCSZ* Coimbra–Cordoba Shear Zone (sinistral), *PySZ* Pyrenees Shear Zone (dextral), *MFZ* Minas Fault Zone (dextral), *SASZ* South Armorican Shear Zone (dextral), *NASZ* North Armorican Shear Zone (dextral), *ESZ* Elbe Shear Zone (dextral). Photograph: schematic image of rhomb-graben structure and domino like pull-apart structures at the mesoscale in the Cretaceous Antola Unit (Northern Apennines, Italy); 335–300 Ma: ages of shearing (after Padovano et al. 2011)

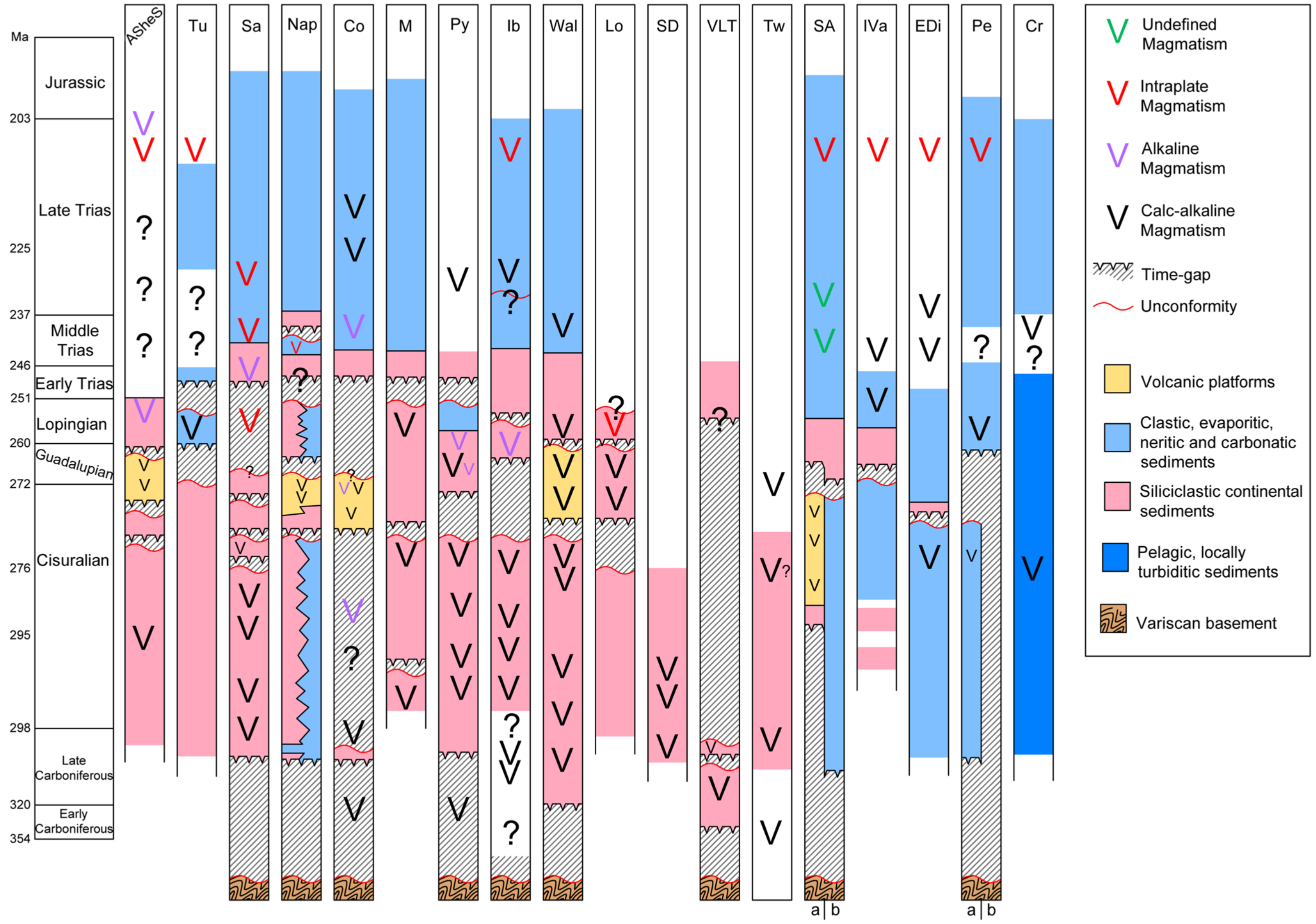

Fig. 4 Synthesis of the stratigraphic–sedimentary features of some Late Carboniferous–Permian basins in the considered areas' Permian basins. *ASheS* Atlas shear system, *Tu* Tunisia, *Sa* Sardinian basin, *NAp* Northern Apennines basins, *Co* Corsican basin, *M* Maures basin, *Py* Pyrenees basin, *Ib* Central Iberia basin, *Wal* Western Alps (including the Argentera and Ligurian Basins), *Lo* Lodève basin, *SD* Salvan–Dorénaz basin, *VLT* Versoyen–La Thuile basin, *TW* Tauern Window basin, *SA* Southern Alps basin, a-Dolomites, b- Carnic Alps; *IVa* Idrjica Valley basin, *EDi* External Dinarides basin, *Pe* Peloponnese basin, a- Plattenkalk Group, b- Tyros Group, *Cr* Crete basin

subsidence under extensional regime and lithospheric breakup into microplates.

The collapse and dismantling of the Variscan belt were associated with a transcurrent component that produced the Pyreneean basin in Early Permian times. The numerous basins were infilled by alluvial fan slope breccias, fluvio-lacustrine sediments and volcanic—volcaniclastic products, decreasing and ceasing at the mid-Permian. In the Pyrenees and eastern Iberian plate, following the mid-Permian event, the transtensional regime led to the development of symmetric basins bounded by lystric faults, probably as the response to dextral strike-slip movements at the margins of the Iberian Microplate and the crustal collapse of the overthickened roots of the Variscan orogen (Lopez-Gòmez et al. 2019).

The *Iberian* Basin developed on the Variscan basement comprising Ordovician–Silurian slates and quartzites of the Variscan basement (Arche and Lopez-Gomez 2005; Lopez-Gomez et al. 2005; Figs. 2, 3). Most faults related with this extensional basin can be interpreted as reactivated Variscan, or older, NW–SE or N–S-trending structural lineaments, which were active from the Late Carboniferous–Early Permian periods (Vargas et al. 2009; Gutiérrez-Alonso et al. 2015). The Permian–Triassic record in the Iberian Basin includes felsic and mafic magmatic rocks (i.e., Early Permian granitoid and volcanic rocks in Perini et al. 2004), different sedimentary cycles and three regional angular unconformities.

Continental sediments and shallow-marine carbonates and evaporites (related with several transgressive pulses) were deposited at Early Permian to Middle Triassic (Anisian) in the eastern part of the basin and typically pass laterally into coastal and continental siliciclastic rocks along the axis of the basin. In particular, four sedimentary cycles, which are separated by unconformity contacts, can be recognised (Arche and Lopez-Gomez 2005; Lopez-Gomez et al. 2005):

1. Early Permian in age and mostly made up of breccias and conglomerates (Tabarrena Fm. and Boniches Fm.) and associated andesitic to basaltic volcanic rocks locally overlain by variegated siltstones, dolomites and red breccias;
2. A Late Permian cycle consisting of alluvial-fan or braided-fluvial quartzite conglomerates (Boniches Fm.) of limited lateral extension and red siltstones, sandstones and conglomerates deposited by low- to high-sinuosity, avulsion-prone rivers with extensive floodplains (Alcotas Fm.); and
3. Represented by the Late Permian–Middle Triassic quartzite conglomerates of Hoz del Gallo Fm. with local top pink to red sandstones that lie unconformably above the Alcotas Fm. and, where missing, the Boniches Fm. During the Late Permian, intermediate to basic volcanic products erupted.
4. The continental Eslida Fm., consisting of lower Muschelkalk facies of the Late Anisian age, overlays (3).

Some Late Palaeozoic (Westphalian–Stephanian) basins are present in the Cantabrian zone of *NW Iberia* (e.g., the Ciñera–Matallana and Sabero Basins), which include calc-alkaline volcanic and pyroclastic rocks (Knight et al. 2000). The Stephanian Ciñera–Matallana Basin is an E–W-oriented pull-apart basin (Frings et al. 2004; Fig. 2). The basin is a small intramontane sinistral pull-apart basin (25 km^2) that developed during the late stages of the Variscan orogeny. It consists of Stephanian alluvial to lacustrine, coal-bearing sediments with a total thickness of 1500 m. The basin developed in response to transpressional and then transtensional movements along the E–W-trending Sabero–Gordón sinistral strike-slip fault.

In the *Balearic* Islands, the NNW–SSE-oriented Permian–Triassic Minorca Basin (Gras and Zarza 2003, Fig. 3) comprises a 670-m-thick Permian succession of red mudstones, sandstones and gravels unconformably overlying the Upper Carboniferous Culm Facies. A classic Triassic Germanic-type sequence fills the grabens. From base to top, the sequence comprises non-marine clastic deposits (Buntsandstein facies), shallow-marine carbonates (Muschelkalk facies) and evaporites and clastic deposits (Keuper facies). The initial stages of rifting took place from the Late Permian to Triassic periods, during which Africa and Europe moved apart under a transtensional regime, leading to the formation of the network of graben systems.

In the *southern Pyrenees*, Lago et al. (2004) and Rodrìquez-Mendèz et al. (2016) identified within the Stephanian–Permian Basins (e.g., the Cadì and Anayet Basins) magmatism characterised by an E–W trend and two compositionally different igneous episodes, from Upper Carboniferous (Moscovian) to late Early Permian (Kungurian) calc-alkaline phase at 309–276 Ma (in Pereira et al. 2014), a following calc-alkaline/transitional-alkaline mid-Permian phase at 266–265 Ma (in Pereira et al. 2014) and a Mid- to Late Permian mildly alkaline phase. These two igneous episodes were related with the attenuation of Late Variscan transtensional tectonics and the onset of extension associated with regional rifting (Figs. 3, 4). The strike-slip fault systems that affected the Pyrenees area during the Late Variscan orogeny controlled the development and configuration of the sedimentary basins (Lago et al. 2004). In addition, these basins were periodically affected by extension, leading to their subsidence and the simultaneous emplacement of magmas. The whole-rock trace-element patterns and isotopic signatures of the andesites suggest that they were derived from the upper mantle and were variably hybridised with late orogenic crustal melts, whereas the alkali basalts originated from a lithospheric mantle source that was enriched as a consequence of Variscan subduction.

French Massif Central

Among the Late Palaeozoic basins of the French Massif Central (e.g., Blanzy–Le Creusot, Autun and Rodez Basins), the Lodève Basin is one of the most complete and best-exposed Permian sections in Europe (Figs. 3, 4; Schneider et al. 2006). The basin is a half-graben structure with the E–W to NE–SW trending master strike-slip fault to the south (McCann et al. 2008) that can be interpreted as a conjugated branch of EVSZ (Fig. 3, Padovano et al. 2011). Permian sediments crop out over an area of 150 km^2 with a thickness of ~ 2500 m. These sediments consist of grey continental fluvial–lacustrine sediments and red beds (Schneider et al. 2006). The first Permian sedimentary cycle begins with fluviatile conglomerates, sandstones and black lacustrine shales (the Asselian to Sakmarian Usclas–St. Privat and Tuilières–Loiras Fms.; Schneider et al. 2006). The second sedimentary cycle starts above a tectonically induced erosional unconformity with fanglomerate deposits passing upward into sheet-flood and braided-river sandstones and pelites (the Kungurian to Tatarian Rabejac Formation) (Pochat et al. 2005; Schneider et al. 2006). The retreat of the alluvial system and a transition into playa sediment deposition (Salagou Formation) is evident towards the top of this cycle. Tuff and tuffite beds occur within these two last formations and correlate with both the early calc-alkaline cycle and the subsequent alkaline cycle of Permian magmatism in Corsica. The sedimentary cycle is topped by the La Lieude Formation (Wuchiapingian to Changhsingian) (Schneider et al. 2006), which has coarse fluviatile clastic sediments at its base.

Sardinia, Corsica and Maures (Provence)

The latest Carboniferous to Permian geological framework of the southern Variscides (e.g., Sardinia, Variscan Corse) developed within a regional continental transpressive and subsequently transtensile tectonic regime, with the deposition of continental sediments in pull-apart basins that were locally accompanied by plutonic and volcanic igneous events (Casini et al. 2012, 2015). The Permian–Carboniferous basins developed from south to north upon the low- to high-grade amphibolite-facies Variscan basement, locally intersecting the intrusive rocks of the Sardinia–Corsica batholith (Cortesogno et al. 1998a; Cassinis et al. 2003a, b; Buzzi and Gaggero 2008; Buzzi et al. 2008).

The record of sedimentation and its interplay with volcanism in the Sardinia–Corsica–Maures area have been investigated in many studies, including those of Rossi et al. (1991), Leroy and Cabanis (1993), Cassinis et al. (1997a, b, 1998,2003a, b), Cortesogno et al. (1998a), Deroin et al. (2001), Lapierre et al. (1999), Costamagna et al. (2000), Barca and Costamagna (2002, 2003, 2005, 2006), Costamagna and Barca (2002, 2008), Cassinis and Ronchi (2002), Aldinucci et al. (2006), Durand (2006), Bourquin et al. (2007), Durand (2008), Ronchi et al. (2008), Costamagna (2011a; b), Durand et al. (2011) and Gaggero et al. (2017) (Figs. 3, 4).

In Sardinia, Late Carboniferous–Permian or solely Permian basins are present both in the south-central region (the Seui, S. Giorgio, Perdasdefogu and Escalaplano-Mulargia Basins) and the north (the Nurra Basin) of the island. In the past, three main sedimentary cycles could be distinguished (i.e., the early molassic cycle in the Late Carboniferous–Early Permian, the molassic cycle in the Middle to Late Permian age and the post-molassic cycle in Early to Middle Triassic, Auct.). They are usually separated by marked unconformities, and even in the same tecto-sedimentary cycle there may exist important discontinuities, dividing different tectonic sub-phases (Deroin and Bonin 2003). Particularly in the Nurra area, the five sedimentary cycles are as follows (e.g., Cassinis et al. 2018):

(i) The first cycle is Gzhelian-Sakmarian in age and filled relatively small, half-grabens basins developed in a rugged and still well-articulated landscape related with the first extensional movements associated with local transpressive events. Its coal-bearing, fluvial-lacustrine filling (Punta Lu Caparoni Fm.) contains calc-alkaline volcanic intercalations that are also present at the top of the succession.

(ii) The second cycle consists of fluvial Sakmarian-Artinskian deposits (Pedru Siligu Fm.) with calc-alkaline volcanic rocks in the upper part (Casa Satta volcanic rocks).

(iii) The third cycle is represented by the fluvial Artinskian-Kungurian Portoferru Fm.

(iv) The fourth cycle includes fluvial deposits of Kungurian-Roadian age (Cala del Vino Fm.).

(v) The fifth cycle developed after a long mid-/late Permian to Early Triassic pp. tectonic stasis; it is represented by the well-known ‘Verrucano Sardo’ red beds of the Early to Middle Triassic times.

These deposits mark the renewal of extensional tectonic activity and are associated with different basins in Sardinia (Costamagna and Barca 2002), narrower in size and thinner in sedimentary filling, which are represented by prevalently continental Buntsandstein-type red bed siliciclastic successions (e.g., Porticciolo conglomerate Fm. and Cala Viola Fm. in Nurra), capped by Middle Triassic Muschelkalk to Keuper German-type facies.

The first and second cycles belong to the main regional Late Carboniferous–Early Permian cycle, whereas the third and the fourth can be correlated with the mid-Permian cycle as defined in typical areas of southern Europe (e.g., Southern Alps and Northern Apennines).

The widespread syn- to post-collisional plutonism in Sardina–Corsica covers a 340 to 288 My time interval (Poli et al. 1989; Cocherie et al. 2005). Monzogranite and leucogranite with minor gabbro-diorite to tonalite in Sardinia show ages between 307 and 281 Ma and a typical calc-alkaline chemical character (Poli et al. 1989). Cocherie et al. (2005) defined three main groups of granitoid rocks in Corsica:

(1) The earliest, U1, is made up of *c.* 340 Ma syn-collisional granitoid rocks.

(2) The second, U2, is composed of calc-alkaline early granodiorite and monzogranite (*c.* 300 Ma) and late leucomonzogranite (*c.* 290 Ma).

(3) The third, U3, is composed of anorogenic metaluminous and alkaline granites 291–287 Ma, associated with *c.* 286 Ma tholeiitic layered complexes and dykes.

The conspicuous volcanic record in Sardinia encompasses a wide range of intermediate–silicic magmas, including medium- to high-K calc-alkaline andesites, dacites and rhyolites. Interplay among syn- to late-orogenic volcanism, sedimentation and tectonic activity took place during the latest Carboniferous and Permian, post-dating the unroofing and erosion of the Variscan nappes.

Gaggero et al. (2017) identified within the igneous volcanic rocks three main groups of concordant U–Pb ages, using Laser Ablation–Inductively Coupled Plasma–Mass Spectrometry (LA-ICP-MS) analyses of zircon, that correspond closely with the biostratigraphic data of the Carboniferous–Permian successions:

(i) an oldest group of 332 ± 12 Ma (Mt. Cobingius andesite cutting the medium-grade metamorphic basement constraining the onset of igneous activity on unroofed middle crust) and a 302 ± 2.9 Ma rhyolite (Escalaplano rhyolite),

(ii) a second group with ages between 297 ± 2 (Lu Caparoni Ignimbrite) and 294 ± 3 (Perdasdefogu dacite) within the time interval of the first sedimentary cycle. It is notable that the youngest age (295 ± 3 Ma) was obtained from the southeastern basin and the oldest age (297 ± 2 Ma) from the northwestern one.

(iii) a youngest age of 288 ± 2 Ma (Case Satta ignimbrite, Nurra Basin). Ages (ii) and (iii) can be linked with the progressive development of continental strike-slip faulting from the south (the Escalaplano Basin) to the north (the Nurra Basin).

Finally, N–S-trending dolerite dikes are emplaced from north to southeast Sardinia across the Early Palaeozoic medium- to high-grade metamorphic basement, the Sardinia–Corsica batholith and Stephanian–Autunian calc-alkaline effusive deposits. The tholeiitic to transitional dolerites have an anorogenic affinity and are associated with E–W- to N–S-trending diorite to rhyolite dikes. The dolerite emplaced between 253.8 ± 4.9 and 248 ± 8 Ma (Late Permian–Early Triassic; ^{40}Ar–^{39}Ar ages on amphibole; Gaggero et al. 2007). The Nd isotopic ratios point to a source in a subcontinental lithospheric mantle. The E–W emplacement trend of the dolerite dike swarm matches the E–W orientation of Late Variscan transcurrent–extensional faults, whereas the subsequent N–S emplacement trend of the dolerite dike swarm is consistent with a general E–W-directed extension of the Sardinian crust and more generally with the direction of extension between the European and Insubric crusts at the beginning of Tethyan rifting (Gaggero et al. 2007). Alkaline pyroclastic rocks and lava flows are present within the Early Triassic Buntsandstein facies in Nurra (Cassinis et al. 1996). Finally, one Late Triassic lamprophyric dike, NE–SW oriented, cuts the E–W-trending Posada Valley shear zone (240 ± 11 to 224 ± 11 Ma, apatite fission-track dating; Baldelli et al. 1987). On the whole, the anorogenic geochemical affinity of the dikes is in agreement with an extensional regional tectonic regime in the Middle to Late Triassic times.

Ligurian and Western Alps

The Late Carboniferous–Early Permian volcano-sedimentary successions of the Ligurian Alps were deposited unconformably on the pre-Variscan basement (Cabella et al. 1988; Cortesogno et al. 1988, 1992, 1993, 1995, 1998a, b; Gaggero et al. 2004; Decarlis et al. 2013; Cassinis et al. 2018) and were truncated by a Late Permian unconformity. Although the Carboniferous intrusive record is patchy in the Ligurian Alps, sparse alkaline granitoid bodies are preserved in Alpine nappes (Cortesogno et al. 1996).

The basement of the Alpine Mallare Unit (Barbassiria orthogneisses) has been dated at ~ 320–315 Ma (i.e., early Late Carboniferous). This basement was then overprinted by a high-temperature (greenschist–amphibolite facies) Variscan metamorphic event that was likely associated with tectonic burial and compression during the final stages of the Variscan collision (Maino et al. 2012, 2019).

The Bashkirian–Moscovian basal conglomerate in the Ligurian Alps (Ollano and Lisio Fms.) is heteropic and contains calc-alkaline rhyolitic ignimbrites and tuffs (C. Lisetto Formation, 285.6 ± 2.6 Ma; Dallagiovanna et al. 2009). In addition, the Palaeozoic basement is locally cut by andesitic dikes (Buzzi and Gaggero 2008). The overlying conglomeratic–sandy–pelitic, fluvial–lacustrine deposits (Murialdo and Ollano Fms.) are interbedded with ignimbritic and pyroclastic agglomerates (the Osiglia Porphyries, dated at 278 ± 3.4 Ma). The continental suite evolves towards fine-grained sediments (Gorra Fm. and Viola schists), interbedded with andesitic lavas and pyroclastites up to 250 m thick (Eze Fm.). Above a *c.* 14 My unconformity, a huge volume of calc-alkaline rhyolitic to dacitic ignimbrites of the Melogno Porphyroids, dated at 272.7 ± 2.2 Ma was emplaced (Kungurian, Dallagiovanna et al. 2009).

The Late Palaeozoic igneous activity ends with polychrome K-rhyolitic fine to medium-grained ignimbrites dated at 258.5 ± 2.8 Ma (Wuckiapingian, Dallagiovanna et al. 2009). The K-rhyolites were coeval with the emplacement of rhyolite dikes cutting the Variscan basement (260.2 ± 3.1). and truncated by overlying Upper Permian unconformity with the Lopingian fluvial deposits (Briançonnais Verrucano conglomerates) passing upward into the well-sorted fluvial Scythian Ponte di Nava Quartzites Fm. (Cassinis et al. 1998; Costamagna 2018); in the Verrucano, phosphate mineralisations represent a chemical proxy for processes related with continental dismantling and arid climates (Cortesogno et al. 1987).

The Scythian–Anisian transition is represented by the ankeritic green shales of the Case Valmarenca Pelite, while, in the Prepiedmont units, thin-bedded, fine micaceous calcarenites and calcsiltites are present. Then follows the marine middle-upper Triassic succession.

In the Ligurian Alps basement, temperatures exceeding ~ 240 ± 25 °C before ~ 160–150 Ma (Late Jurassic) have been measured by zircon fission-track analyses on basement rock samples at a few kilometres depth (Decarlis et al. 2017). Such a heating–cooling cycle developed during the development of rifting at the Alpine Tethys margin and ended during the Late Jurassic (160–150 Ma). The subsequent onset of seafloor spreading was characterised by crustal and lithospheric thinning and high geothermal gradients (60–90 °C/km).

The Ligurian segment of the Southern Variscan belt is interpreted as recording transtension followed by extensional tectonics, as indicated by the evolution of associated volcanic activity (Fig. 3). The switch from a calc-alkaline to an alkaline chemical magmatic fingerprint corresponds to the transition from a post-orogenic to an anorogenic setting. This has been interpreted as a progressively increasing delamination of the continental lithosphere, accompanied by the partial melting of lithospheric mantle (Dallagiovanna et al. 2009**).**

Several Late Palaeozoic basins are present in the Western Alps (Ballèvre et al. 2018). There, the NW–SE-oriented St. Étienne and the E–W-oriented Tende Late Carboniferous basins (Figs. 3, 4) were developed in the Argentera area and related with a NW–SE-trending strike-slip shear zone (Corsini et al. 2004), active during the Late Carboniferous (the Valetta and Bersezio shear zones).

To the north, the N-MORB/T-MORB Versoyen tholeiites, dated at 337 Ma (Mugnier et al. 2008) suggest the presence of a small ocean (Beltrando et al. 2007) close to the continental margin where the coal-bearing Carboniferous basins of the Briançonnais Zone developed (La Thuile Basin in the Houilliére Zone; Ballèvre et al. 2018). The evolution of the NE–SW-oriented, Carboniferous La Thuile Basin (Valente and Borghi 2000) is consistent with lithospheric stretching, which peaked during the Visean, locally producing the Versoyen tholeiites (Timmerman 2004). The La Thuile Basin includes two sedimentary series (Valente and Borghi 2000): (1) the lower series (Namurian–lower Stephanian), which consists of anthracite-bearing sandstone and pelite with local sub-volcanic calc-alkaline intrusions and (2) the upper series, represented by variably coloured Middle–Upper Stephanian conglomerates and pelites with locally abundant volcanoclastic intercalations, unconformably overlain by Permian–Triassic 'Verrucano'-like, mostly ruditic redbeds.

In the Mt. Blanc area, the Late Westphalian–Early Permian, NE–SW-oriented Salvan–Dorénaz Basin of the Helvetic Zone is interpreted as syn-kinematic with a NE–SW-trending dextral-shear zone (Capuzzo and Bussy 2001; Figs. 3, 4). The authors distinguished four different fluvial units characterised by alluvial fan, anastomosed and meandering fluvial facies. Calc-alkaline volcanism was active throughout the evolution of the basin, as suggested by the 308–295 Ma U/Pb radiometric age of the magmatic products.

The same tectonic regime was inferred since the Upper Carboniferous in the nearby Emosson Lake by Genier et al. (2008) and Ballèvre et al. (2018). In agreement with Padovano et al. (2011, 2014), Ballèvre et al. (2018) associated the formation of these basins with the trans-tension process along the EVSZ and pointed out its reactivation in Permian times as well.

Central Alps

In the central Tauern Window (Austria), three plutonic-volcanic stages were recognised by Eichhorn et al. (2000):

(i) 340–343 Ma syn-collisional anatectic high-K, I-type plutonism and extrusive rhyolitic/dacitic products;
(ii) 296–279 Ma calc-alkaline, I-type granitoid rocks and minor coeval bodies of felsic and intermediate volcanic rocks connected to the Late Carboniferous trans-tensional/-compressional activity;
(iii) 271–279 Ma S-type granitoid rocks and rhyolites probably associated with extension phenomena along the persistent wrench zones.

Therefore, the magmatic events are coeval with the activity of a NE–SW-trending strike-slip shear zone, therefore constraining the evolution of the NE–SW-striking Stephanian-Early Permian, volcano-sedimentary basins (Eichhorn et al. 2000; Figs. 3, 4).

Northern Apennines

The Late Carboniferous–Permian successions in the Northern Apennines (Tuscany) are low-grade metamorphic sequences belonging to the deepest Tuscan metamorphic unit (Pandeli 2002, and references therein). The tectono-sedimentary evolution of these successions has been interpreted in terms of deposits in pull-apart basins linked to the extensional activity of megashears that developed during the Late Variscan orogeny and the early stages of Alpine rifting (Rau and Tongiorgi 1980; Rau 1990, 1993; Pandeli 2002). Currently, three main Late Palaeozoic post-Westphalian sedimentary cycles (separated by unconformity surfaces) can be defined as follows:

1. The Kasimovian/Gzhelian to Sakmarian (late Carboniferous-early Permian) cycle, which is coeval with Late Carboniferous half-graben sedimentation in Sardinia, consists of fossiliferous fluvial to neritic, organic-matter-rich sediments (S. Lorenzo Fm.: Rau and Tongiorgi 1974; Iano schists and sandstones: Landi Degl'Innocenti et al. 2008; Spirifer Schists: Costantini et al. 1998; and Rio Marina Fm.: Bortolotti et al. 2001) that were deposited in an extensional/transtensional regime at the end of Variscan shortening (Sudetian and Asturian events) under a humid equatorial climate.
2. The Sakmarian/Artinskian to Roadian (latest early Permian to mid-Permian) cycle is represented by reddish, mostly coarse-grained and immature sediments (Asciano

and Torri breccia and conglomerates; Rau and Tongiorgi 1974; Costantini et al. 1998; Pandeli 1998) that show interbedding and a lateral–vertical contact with acidic metavolcanic rocks (Iano Porphyritic Schists; Costantini et al. 1998; Pandeli 1998, 2002). The succession is interpreted as alluvial-fan or fluvial deposits laid down under an inter-tropical, semi-arid climate and originating during the block faulting of the Saalian rejuvenation extensional event. This succession can be correlated with Southalpine analogues, the Ponte Gardena Conglomerate and the Athesian Porphyry Plateau (see later discussion).

3. The Capitanian to Changhsian (latest mid-Permian to late Permian) cycle consists mainly of reddish fluvial, volcanic-rich sediments (Borro del Fregione siltstone and sandstone, Castelnuovo Red Sandstone; Pandeli 1998, 2002) in western Tuscany. These sediments are associated with the Palatine extensional event during which erosion of the volcanic relief occurred, similar to the Val Gardena sandstone–Verrucano Lombardo in the Southalpine area (see later), and grade upward into a Permian–Triassic marine transgressive succession. In eastern Tuscany, Upper Permian commonly turbiditic marine siliciclastic and fossiliferous carbonate sequences are exposed (e.g., Farma Fm., Carpineta Fm. and Poggio al Carpino Sandstone; Aldinucci et al. 2006) and are consistent with the subsurface geology (Elter and Pandeli 1990, 1991; Pandeli and Pasini 1990; Corsi et al. 2001).

The three cycles are unconformably overlain by ?Late Ladinian–Carnian, syn-rift, quartz-rich fluvial sediments (Verrucano Auct.) at the base of the main Alpine sedimentary cycle, but a ?Scythian–Ladinian continental-to-marine cycle with interbedded intraplate pillow lavas has been recognised locally in Tuscany (e.g., the first cycle of Verrucano at Punta Bianca, in Martini et al. 1986; Abbate et al. 2005). The Saxonian–Thuringian and (?) Scythian–Ladinian cycles are considered as ‘aborted rift basins’ from the repeated attempts of crustal breaking in the Tuscan sector of Gondwana. These phenomena are well explained in a transpressive/-tensional regime along long-living megashear structures (Rau 1990, 1993; Pandeli 2002).

Southern Alps

The Southern Alps contain several NE–SW-oriented domino-like pull-apart Permian basins, all of which developed concurrently with strike-slip shear events (Varesotto–Luganese area, Orobic Basin, Collio Basin, Val Rendena area, Tregiovo–Mt. Luco Basin, Bolzano–Trento Basin and Western Dolomites) (Cassinis and Perotti 1994; Cassinis et al. 1997a, b, 1998, 2008, 2012; Cortesogno et al. 1998a, 1998c; Bernoulli et al. 2018). Handy and Zingg (1991), Deroin and Bonin (2003) and Schaltegger and Brack (2007) proposed that the Mid-Permian unconformity originated during large-scale strike-slip tectonics and erosion, associated with crustal thinning, upwelling and the partial melting of mantle, as well as the advection of melts and heat into the crust (Figs. 3, 4).

In the Southern Alps domain (from Lombardy to the Carnic Alps), two main Carboniferous to Late Permian sedimentary cycles (Cassinis et al. 2007, 2018 and references therein) are separated by a Mid-Permian regional unconformity (Cortesogno and Gaggero 2011). As in the Carboniferous to Triassic sedimentary evolution of the Northern Apennines, three sedimentary cycles are recorded, as follows:

1. The Late Carboniferous–Early Permian cycle in the Carnic Alps and pre-Alps is represented by a succession containing immature basal conglomerates and breccias (Bombaso Fm.) passing upward and laterally to shallow-marine clastic and carbonate rocks (Auernig group) and in turn to the Upper Permian Pontebba Supergroup, including mainly carbonate rocks (e.g., Trogkofel limestone).
2. The “mid-Permian” (mid-/upper Cisuralian) cycle is represented particularly in the Central Alps (e.g., the Brescia area) and in the Dolomites as successions which directly overlie the Palaeozoic crystalline basement. The base consists mainly of conglomerates, which are overlain by fluvial–lacustrine clastic sediments (Collio Fm., Dosso dei Galli conglomerate, Ponte Gardena conglomerate; Cassinis 1988). Calc-alkaline magmatism, represented by rhyolites/rhyodacites, basaltic andesites and andesites, followed, producing volcanoes and thick volcanic platforms in the 285–274 time interval (e.g., the Athesian volcanic platform, Di Battistini et al. 1989; Bargossi et al. 1993; Marocchi et al. 2008) or locally as intrusive domes (Schaltegger and Brack 2007; Cassinis et al. 2007; 2018), which are coeval with basic intrusions in the middle-lower crust. The sub-intrusive bodies were locally also reworked in post-eruption mass flows (Breitkreuz et al. 2002).
3. The mid- to Late Permian cycle is represented in the entire Southalpine area as widespread syn-rift deposits at the base of the Alpine sedimentary cycle (Cassinis et al. 2018). These commonly coarse-grained, reddish continental fluvial sediments together form the Verrucano Lombardo o Val Gardena Sandstone (Groden Fm.) and were derived from the erosion of Mid-Permian volcanic rocks and of the Palaeozoic crystalline basement. In Lombardy, these deposits pass upward to finer clastic sediments, whereas in the Dolomitic area they grade upward into evaporitic deposits (Bellerophon Fm.)

that occur at the base of the Triassic marine succession (Werfen Fm.) (McCann et al. 2008).

Late Palaeozoic basins in the surrounding of EVSZ

Morocco–Algeria

The Stephanian and Permian sediments in central Morocco (Meseta Area, High Atlas Mountains; Voigt et al. 2011) document the evolution of this region during the formation of the Mauretanide portion of the Variscan chain and testify to the formation of Late Palaeozoic continental basins characterised by a NE–SW strike (Hmich et al. 2006) (Figs. 3, 4). These basins (e.g., the Khenifra and Souss Basins in Central Morocco) are characterised by a Late Stephanian-Lower Permian lithostratigraphy comprising three members (Hmich et al. 2006; Voigt et al. 2011). The lower member consists of stacked, mainly coarse-grained deposits of an alluvial-fan to alluvial-plain environment. The intermediate member contains predominantly red and grey mudstones, representing deposition on an extended floodplain, and contains lower Permian tetrapod footprints. The upper member, characterised by a basal erosional unconformity and consisting of fluvial conglomerates and fine-grained sandstones, is likely related with larger-scale syn-rift tectonics and/or climatic events (Olsen et al. 2000). Subsequently, late Early Permian rhyolitic–rhyodacitic volcanism and the following dacitic–andesitic igneous activity formed a widespread calc-alkaline Permian volcanic cover (Aït Chayeb et al. 1998). The overlying Late Permian cycle is made up of fluvial conglomerate and sandstones and includes the first product of alkaline/intermediate magmatism, i.e., basic necks and dykes (Aït Chayeb et al. 1998). The occurrence of overlying Late Triassic-Early Jurassic basalts, dated at 201–196 Ma (Verati et al. 2007), is interpreted as the beginning of the main rifting associated with the breakup of Pangaea (Saddiqi et al. 2009).

In Algeria, the filling of the sedimentary basins in the Algerian Saharan craton, south of the Saharan Atlas orogenic front (e.g., the Oued Mya, Murzuq, Illizi and Ahnet Basins; Figs. 1, 2) includes Early to Late Carboniferous, and, rarely, Early Permian successions, which are unconformably overlain by Triassic sediments and conspicuous Late Triassic volcanic rocks (Popescu 1995; Boote et al. 1998; Derder et al. 2009, 2014; Wang et al. 2009; Henry et al. 2014). Moreover Derder et al. (2009) underlined the presence of a syn-sedimentary compressive event during the Early Permian.

Germany

In central Germany, the Carboniferous–Permian Saar–Nahe Basin (Schafer 2011; Fig. 3) is formed as an asymmetric half-graben overlying the pre-Variscan basement rocks of the Saxothuringian Zone (metamorphic schists of the Northern Phyllite Zone) and granitoid rocks of the Mid-German Crystalline Rise. Schafer (2011) proposed that the Late Carboniferous South Hunsrück dextral strike-slip fault was the transtensional structure that allowed the formation of the basin.

The Elbe Shear Zone (ESZ in Figs. 1, 2, 3) is a NW–SE-trending dextral intracontinental strike-slip shear zone and was active between 320 and 300 Ma. The strain ellipsoid related with the kinematics of the N–S-trending Permian Lower Saxony Rift System (McCann et al. 2008) accounts for the final stage of the NW–SE-directed ESZ shearing.

Dinarides, Hellenides, Balkans and Moesia

In Slovenia, Schwarb and Spangenberg (2004) described the NW–SE-oriented Late Palaeozoic basin of the Idrjica Valley characterised by Mid-Late Permian clastic red beds that pass vertically to Late Permian–Early Triassic shallow marine carbonates (Figs. 3, 4). The External Dinarides successions comprise Carboniferous-Early Permian epeiric platform limestones that underlie syn-rift, late Early Permian, polymictic conglomerates grading upward into shallow marine carbonates (Aljinovic et al. 2008). In the Hellenides, the Peloponnesus succession is dominated by Late Carboniferous–Permian shallow, sub-tidal, mostly clastic sediments (Plattenkalk and Tyros Groups in Dornsiepen et al. 2001; Hymerrkus et al. 2007) that underlie Late Permian–Triassic neritic deposits through a late lower Permian unconformity. To the south, the E–W-striking Crete Basin has a complex Late Carboniferous-Permian pelagic filling: the western part is dominated by turbiditic siliciclastic deposits, whereas the middle and eastern parts are characterised by alternating carbonates and pelites (Phyllite-Quartzite Group in Dornsiepen et al. 2001); the latter change southwards to shallow water deposits on a carbonate platform (Plattenkalk Group of Crete in Dornsiepen et al. 2001). Most of these Late Palaeozoic basins developed along the ESZ–Tisia-Moesia megashear alignment during at least the Late Carboniferous times (Padovano et al. 2014), but also continued their activity locally during Permian–Triassic times (Dornsiepen et al. 2001).

This structure was also active during the collapse of the Balkan orogen and formed a series of diachronic, mostly E–W or WNW–ESE-striking, Late Carboniferous–Early Permian basins with calc-alkaline volcanic rocks and subvolcanic bodies (e.g., Svoge, Sofia-Stara Planina, Godech and Buchino-Petrohan Pass Basins in Cortesogno et al.

2004a). The Upper Permian continental red beds and overlying Triassic Buntsandstein sediments followed after a Mid-Late Permian stratigraphic gap. No evidence of magmatism was recognised in the Late Permian, but the extension before the Moesia breakup is recorded by Triassic alkali basalt and trachytic lavas that were erupted in continental successions grading to marine (Cortesogno et al. 2004b).

Discussion

A distinctive feature of the Carboniferous (locally since Namurian)–Permian to Triassic basins is their genetic relationships with coeval tectonics related with intracontinental shear zones, as established by several Authors (e.g., Bonin et al. 1987; Rau 1993; Cortesogno et al. 1998a; Ziegler and Stampfli 2001; Gutiérrez-Alonso et al. 2004, 2008; Padovano et al. 2011, 2014; Edel et al. 2015; Ballèvre et al. 2018). In particular, most of these basins are aligned along a zone of continental fragmentation running from the Alps to North Africa characterised by a NE–SW-trending dextral strike-slip movement (i.e., the EVSZ; Padovano et al. 2011, 2014) that was subsequently cut by other major WNW–ESE-trending shear zones (e.g., ESZ and SGBFZ in Fig. 1).

The location and tectono-sedimentary features of these basins and their relationship with subsequent igneous activities are fundamental elements in the reconstruction of the Carboniferous–Permian geodynamics. In particular, the widespread calc-alkaline magmatism was attributed in the past to an arc associated with Devonian subduction of the Paleotethys (Nicholls and Lorenz 1973; Buchs 2013), but this hypothesis conflicts with the regional igneous evolution (acid–intermediate–acid products) as well as with their geodynamic context. To account for the stratigraphic and tectonic constraints, the early interaction between subcrustal and crustal anatectic magmas, followed by assimilation and fractional crystallisation, has been proposed (Cortesogno et al. 1998a; Buzzi et al. 2007, 2008). Another important aspect is that the calc-alkaline magmatism changed into alkaline-type in the Upper Permian, although at the Mid-Permian the overlap of the two suites was locally evidenced and related with an important variation in the geodynamic framework (e.g., Deroin and Bonin 2003; Cortesogno et al. 2004a; Cocherie et al. 2005).

Evolution of pull-apart basins

In North Africa, the Carboniferous–Permian basins are located at the boundary of the Saharan shield to the south of the Atlas Orogenic belt. In Morocco-Algeria, the Meseta and Oued Mya Basins are linked to the dextral W–E-trending shearing along Atlas Shear System (ASheS) in the main. Instead, we interpreted the Late Palaeozoic basins in Tunisia (e.g., the Tebaga of Medenine Basin) as the southernmost one produced by the EVSZ that can be possibly continued eastwards into the ASheS (Fig. 1).

In southern Europe (i.e., the area of peri-Gondwana-derived microcontinents, GDC in Fig. 1), all the Late Carboniferous–Permian basins were related with the presence of a shear zone network. In particular, the Iberian Basins (the Iberian Ciñera–Matallana, Minorca and southern Pyrenees Basins) and the French basins (Lodève, Blanzy–Le Creusot, Autun, and Rodez Basins) are all regarded as pull-apart basins that formed concurrently with the shearing network (Van Wees et al. 1998; Gras and Zarza 2003; Frings et al. 2004; Lago et al. 2004; Arche and Lopez-Gomez 2005; Lopez-Gomez et al. 2005; Schneider et al. 2006; McCann et al. 2008). Their tectonic evolution ceased with the onset of Triassic rifting, as in the Morocco–Algeria–Tunisia region.

Many Late Palaeozoic basins can be recognised along the intracontinental EVSZ: the Western, Central and Eastern Alps, Sardinia, Corsica, Maures and Northern Apennines Basins are all considered to be half-graben/pull-apart basins (e.g., Rau 1993; Eichhorn et al. 2000; Valente and Borghi 2000; Capuzzo and Bussy 2001; Pandeli 2002; Cassinis et al. 2003b, 2008, 2012; Corsini et al. 2004; McCann et al. 2008; Mugnier et al. 2008; Ballèvre et al. 2018; Costamagna 2019). Notably, the Late Carboniferous, N-MORB/T-MORB tholeiites were emplaced during the opening of the Versoyen Basin of the Western Alps (Mugnier et al. 2008), which is consistent with EVSZ activity. In particular, it has been interpreted as an incipient oceanisation zone contiguous with the coeval Carboniferous continental La Thuile Basin (Valente and Borghi 2000) developed on the Briançonnais margin. In the Helvetic area, a NE–SW-trending dextral-shear zone was active between the Carboniferous and the Permian, producing the syn-kinematic Emosson Lake and Salvan–Dorénaz Basins in the Mt. Blanc sector (Capuzzo and Bussy 2001; Genier et al. 2008). In the Tauern Window (Central and Eastern Alps), within an evolving NE–SW-oriented Carboniferous–Permian basin related with a NE–SW-trending strike-slip shear zone, granitoid bodies were emplaced between 279 and 271 Ma (Eichhorn et al. 2000) similar to that defined in the basement of the Aar, Aiguilles–Rouges and Mt. Blanc massifs of the Helvetic zone in Western Alps.

In central and eastern Europe (i.e., the Saxonian–Dinarides–Hellenides tectonic realm), the Late Carboniferous–Early Triassic basins substantially record the same tectono-sedimentary evolution as that of the North Africa and Southern Europe basins. The EVSZ is probably cut by the NW–SE-trending ESZ at its eastern end (Fig. 1; Dornsiepen et al. 2001). The ESZ is a mainly dextral intracontinental strike-slip shear zone that was active between 320 and 300 Ma, so partially coeval with EVSZ. Taking into account the strain ellipsoid related with the kinematics of the ESZ shear zone, the N–S trend of the Permian Lower Saxony Rift System (McCann et al. 2008) is in agreement with the final stage of the shearing along this structure.

In addition, the Saar–Nahe Basin in western Germany (Saxothuringian Zone) was interpreted by Schafer (2011) as a pull-apart basin related with the NE–SW-trending dextral South Hunsrück Fault, which was active from the Late Carboniferous to the Permian, similarly to the ESZ.

The ESZ probably continued southwards along the NW–SE-trending Tisia–Moesia lineament up to the island of Crete, through the scattered Permian–Triassic rhomb-graben structures in the Dinarides (the Idrjica Valley in Slovenia), in the Hellenides (e.g., the Peloponnese; Dornsiepen et al. 2001; Schwab and Spangenberg 2004; Aljinovic et al. 2008; Bortolotti et al. 2013) and in the Balkan area (Cortesogno et al. 2004a). It is also noteworthy that the Carboniferous–Permian sedimentation changed from shallow marine to deep marine, locally characterised by siliciclastic turbiditic successions (e.g., western Crete). The presence of a pelagic basin in this area suggests its probable genetic link with the PaleoTethys (Fig. 1).

The previous chapter showed that these structures are genetically linked to the syn- to late-orogenic Variscan shearing events that occurred during the Carboniferous–Early Permian (e.g., Arthaud and Matte 1977; Ballèvre et al. 2018), but at least some of their activity continued locally during at least the Mid- and Late-Permian times and later (e.g., the reactivation of EVSZ several times, in Ballèvre et al. 2018) and is coeval with the Cimmerian rifting that allowed the opening of the NeoTethys to the east (Cassinis et al. 2018; Stampfli and Borel 2002; Stampfli and Kozur 2006).

Tectono-sedimentary cycles and magmatism

The sedimentary evolution of the various asymmetric intracontinental basins in the studied areas is synthesised in Fig. 4. The basins can be broadly divided into sediment- or volcanic-dominated basins. In particular, the sediment-dominated successions exhibit unconformities believed to have originated from changes in tectonic style (compressive vs. extensional). Instead, the regular emplacement of Late Permian calc-alkaline rocks followed by transitional and then alkaline volcanic rocks, is a widespread feature of the volcanic-dominated basins. In these basins, changes in tectonic kinematics and subsidence within structures are indicated by sedimentary features (fluvial-lacustrine to marine) and by the relative proportions of intrusive versus effusive igneous products. At least three main unconformities can be identified in the Carboniferous–Permian record in most of the considered basins, thus defining them as the result of several different sedimentary cycles. Most of these cycles are related with concurrent transtensile activity upon the major shear zones, producing sedimentary basins whose filling was interrupted by transpressive events that produced the basal unconformities for the following cycles. Taking into account the data from the different areas, the following main unconformities can be pointed out.

Upper Carboniferous (Lower Pennsylvanian, i.e. Moscovian) unconformity. This unconformity is generally related with the Asturian orogenic phase of the Variscan Orogeny that marks the main dextral megashear activity within the orogen itself. In the associated pull-apart basins, the typical clastic and organic-matter-rich Stephanian–Autunian successions were generally deposited in a humid, reducing fluvial–lacustrine to neritic environment. At any rate, the oldest basins are also present locally, as in the Namurian-Stephanian La Thuile Basin in the Western Alps. Acidic to intermediate volcanic rocks (rhyolites, rhyodacites and quartz latites) are locally intercalated in the sedimentary successions (e.g., the Ligurian and Southern Alps). Calc-alkaline and anatectic granodiorite and tonalitic plutons, as well as composite batholiths, are also present, particularly in Sardinia and Corsica.

Early Permian (mid-upper Cisuralian, i.e. Sakmarian/Artinskian*) unconformity.* This unconformity is related with a rejuvenation of the Variscan landscape (the Saalian event), due to the local reactivation of the compressional tectonics. As a result, this sedimentary cycle is not as widespread along the studied shear zones as are the other cycles. The filling of these basins is represented generally by alluvial-fan to fluvial, coarse- to medium-grained, commonly immature, red beds that were deposited in a semi-arid continental environment. Calc-alkaline volcanic bodies (generally rhyolitic to rhyodacitic ignimbrites, pyroclastic flows and tuffs) are common and locally thick (e.g., the Athesian Volcanic Platform). Elsewhere, the intrusion of leucogranite bodies and porphyritic granitic dikes is recorded (e.g., Sardinia).

Mid-Permian (Kungurian-Roadian) unconformity. This unconformity is associated with the so-called Palatine event, during which the volcanic edifices and their host basements were eroded. These younger basins contain typical alluvial-fan or fluvial to coastal-plain red beds (conglomerates grading to sandstones) characterised by volcanic-rich compositions (e.g., Val Gardena Sandstone and Verrucano Lombardo in the Southern Alps and Castelnuovo red sandstones in the Northern Apennines). Locally (e.g., the Southern Alps) these deposits represent the base of the Alpine sedimentary cycle passing conformably upward to transgressive, Permian–Mesozoic marine sediments. No Late Permian continental successions are present in the eastern parts of the Northern Apennines where coeval Late Permian clastic (e.g., the turbiditic Farma Fm.) and carbonate, neritic to probably deep-marine sediments were found. Alkaline magmatism (including alkaline granites and syenites) is typical and locally well developed (e.g., in the Sardinia, Corsica and Provence regions).

The early Permian event represents a main "watershed" in sedimentary evolution because at least part of the organic-matter-rich Carboniferous–Early Permian successions pass sharply upward to generally immature, coarse-grained red beds that are related not only to an important tectonic pulse but also to a climatic variation. In fact, during Mid- to Late Permian times the considered areas passed from a wet equatorial climate to arid, oxidising conditions of the boreal intertropical belt (Rau and Tongiorgi 1974; Scotese 2001; Stampfli and Borel 2002; Schneider et al. 2006; Stampfli and Kozur 2006; Scotese and Wright 2018). This event can be related in part to the movement along the mega shear zones, but also to the reorganisation of the terrains in a new paleogeographic configuration (e.g., the transformation of Pangaea A in Pangaea B). Another important change occurred in late early/mid-Permian times because in some sectors the 'anorogenic' alkaline magmatism (which was typical in Late Permian–Triassic) overlapped the dominant 'orogenic' calc-alkaline one (Bonin 1988, 1998; Cocherie et al. 2005). According to different authors, this also marks a variation of the tectonic regime, i.e., post-Variscan orogenic extension and beginning of the Alpine rifting (e.g., Cassinis et al. 2018), or the inversion of the movements from dextral to sinistral within the main shear bands (e.g., Deroin and Bonin 2003).

We have no new data to support one of the above hypotheses, but the local appearance of Late Permian marine successions at the base of the Alpine transgressive sedimentary cycle in eastern areas suggests the beginning of an important regional extensional/trans-tensional stage probably connected with the opening of NeoTethys ocean. This led first, to the development of seaways and then to the Western Tethys, such as the Jurassic Ligurian–Piedmont Ocean, through a main sinistral transcurrent regime (Bortolotti et al. 1990, 2001). In other places, this transgressive sedimentary trend was interrupted during the Late Permian–Middle Triassic time interval, as shown in the Northern Apennines (the 'aborted rift' cycles in the Late Permian and Early–Middle Triassic, in Martini et al. 1986; Pandeli 2002). The main Alpine cycle began with the Late Ladinian Verrucano red beds (the Middle Triassic unconformity). These aborted events point to the idea that that some sectors of the considered belt were subjected to frequent variation in the shearing regime (transtension to transpression) along a single shear zone or were characterised by the influence of shear zones with different regional strikes until the final breakup of the Variscan crust.

Conclusion

The geographic distribution and structures of the Carboniferous–Permian to Triassic basins, together with their sedimentary and igneous features, allow us to determine that the Late Palaeozoic network of intracontinental shear zones formed an axis of tectonic weakness along which these basins (here interpreted as pull-apart-type basins) were formed and evolved (Fig. 3). The tectono-sedimentary features of the basins point to the idea that the main structures were active in several stages during the geological evolution of the peri-Mediterranean area (see also Ballèvre et al. 2018). In particular, after the development of the Carboniferous–Early Permian dextral megashear, this axis became the locus of shear reactivations up to the main rifting in this sector of Pangaea during the Mid- to Late Permian to Middle Triassic.

The sedimentary and magmatic features categorise these intracontinental basins as sediment- or volcanic-dominated basins. At least three main stratigraphic gaps (i.e., the Mid-Carboniferous, Mid-Permian and Late Permian unconformities) can be identified in the Carboniferous–Permian record in most of the considered sectors, thus defining them as result of many different sedimentary cycles (e.g., the Kasimovian/Gzhelian to Sakmarian, Sakmarian-Artinskian to Roadian and Capitanian to Changhsian cycles). During Mid-Permian times the sharp change (i.e., the Mid-Permian event) from the previous organic-rich fluvial to marine successions to continental, often immature, red beds occurred in some sectors of the EVSZ, supporting tectonic reactivations and climatic changes. Moreover, in these times, still characterised by calc-alkaline products, the first appearance of an alkaline magmatism, typical in the Late Permian–Triassic successions, suggests a variation of the general geodynamic framework (e.g., the beginning of the inversion of the main shear movements in the megastructures).

In particular, we suggest not only that the EVSZ controlled the development of Late Carboniferous–Early Permian and Mid- to Late Permian basins but also that this major tectonic lineament continued its trans-tensional activity into the Triassic and controlled the opening of the Ligurian–Piedmont Ocean (Alpine Tethys) in a wide shear zone between the European and Adria–Africa continents (Coward and Dietric 1989; Nirta et al. 2007; Ballèvre et al. 2018) characterised by an overall sinistral-type shearing regime (Bortolotti et al. 1990). Finally, it is possible that these lines of weakness in the proposed configuration also helped the opening of the Neogene back-arc basins in the western Mediterranean Sea, which resulted in the present fragmentation of the Alpine Chain.

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