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Serpentinite–Sediment Associations: Provenance Controlled by Competing Extensional–Contractional Tectonic Processes During the Evolution of the Northern Apennines (Eastern Elba Island, Tuscany)

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Keywords: Apennine orogeny | Ligurian Ocean | serpentinite | zircon provenance

ABSTRACT

Orogenic wedges juxtapose tectonic units that originated far from each other, and tracing these back to their origin is often difficult. We have studied two contrasting serpentinite–sediment associations of the Alpine-Apennine orogenic wedge of eastern Elba Island with the help of a detrital zircon study of the sediments and a geochemical comparison of the relic phases of their associated serpentinites. We demonstrate that these very likely originated in different branches of the Ligurian Ocean and in contrasting tectonic settings, one during opening of Alpine Tethys and the other during Apenninic contraction-exhumation. First, the Early Cretaceous Palombini shales are associated with abyssal ocean floor serpentinite–ophicalcites of a Ligurian ophiolite (LO) that originated in the western branch of the Ligurian Ocean during ultraslow spreading. They have an Adria/African zircon provenance, indicating proximity to Adria rather than Corsica-Europe and the associated serpentinites are highly depleted and relatively little deformed. The second sediment–serpentinite association has a tectonised serpentinite band in contact with highly deformed, Miocene blueschist facies metasediments. Detrital zircons of these metasediments (Acquadolce (AD) and Pseudomacigno) record major Eocene–Oligocene U–Pb zircon age peaks, with an igneous provenance in the western and central Alps respectively. An age peak at ca. 38 Ma links the Pseudomacigno sediments to calc-alkaline volcanic rocks of the central Adamello massif, whilst an Oligocene age peak at ca. 32 Ma indicates western Alpine sources for the AD Unit. The associated massive, highly tectonised AD serpentinite represents most likely a mantle sliver of subcontinental lithospheric mantle, which together with Oligocene blueschist facies rocks underwent synorogenic Apenninic tectonic extrusion during W-directed subduction–rollback of the eastern branch of the Ligurian Ocean.

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Summary

- Contrasting serpentinite–sediment associations tracked back to their origins in the eastern and western Ligurian Ocean branches.
- Different Apennine foredeep sediments testify to different provenances in the Eastern and Western Alps.
- Two different serpentinite–sediment associations relate to (a) extensional abyssal mantle exhumation, (b) contractional subduction-exhumation mantle slice.

1 | Introduction

Serpentinite–sediment associations are rare matches in geology. However, when they occur next to each other, they indicate very specific tectonic settings in extension or contraction. Examples of serpentinite–sediment assemblages include seafloor serpentinites from slow-ultraslow midocean spreading zones, ophiolite tectonic mélanges, as well as olistostromes from subduction zone environments. Here, we examine the provenance of two very different serpentinite–sediment associations in eastern Elba Island and use these to shed light on the complex Jurassic-Cenozoic tectonics of the Northern Apennines.

The western Mediterranean is a tectonically complex region that evolved in the wake of the opening and closure of Alpine Tethys from Jurassic to Cenozoic times (e.g. Handy et al. 2010; Jolivet et al. 2021; Marroni, Meneghini, and Pandolfi 2017; Molli and Malavieille 2011; Romagny et al. 2020; Rossetti et al. 2002; van Hinsbergen, Vissers, and Spakman 2014; Vignaroli et al. 2008). Its tectonic evolution is governed by two major plates, Iberia-Europe and Africa, and several smaller plates in between, including the Adria microplate.

On Elba Island, the south-western Northern Apennines host excellent records of the opening and closure of Alpine Tethys, including a well-preserved ophiolite complex, an orogenic wedge, as well as high-pressure rocks of the subducted western margin of Adria. In the orogenic wedge of eastern Elba, many different lithologic units, both with oceanic and continental affinities are closely juxtaposed. Although it is undisputed that Elba Island is part of the north-east-vergent Northern Apennines, the existence of an earlier Alpine imprint is debated. Many authors tend to relate the entire accretionary tectonic evolution of Elba Island to Apenninic west-only subduction–accretion (e.g. Bortolotti et al. 2001; Papeschi et al. 2020, 2021; Principi and Treves 1984; Rossetti et al. 2001; Ryan et al. 2021; Viola et al. 2018), whilst others view most of the Northern Apennines as having evolved from successive Alpine and Apennine tectonic processes (e.g. Boccaletti, Elter, and Guazzone 1971; Carminati, Lustrino, and Doglioni 2012; Doglioni 1991; Marroni, Meneghini, and Pandolfi 2010, 2017; Molli 2008). The different views and uncertainties reflect the difficulty to 'see through' the pervasive late Apenninic high-T overprint related to the Tyrrhenian igneous province (Poli and Peccerillo 2016), which hampers age dating of preceding tectonic events.

On Elba Island, two contrasting serpentinite–sediment associations occur. An older serpentinite–sediment association incorporates Late Jurassic-Early Cretaceous abyssal serpentinites and the youngest sedimentary rocks of Alpine Tethys (Palombini shales). This association was later transposed in a tectonic mélange at the base of a LO. An apparently much younger serpentinite–sediment association is represented by a highly sheared serpentinite sheet that is in structural contact to highly deformed high-P metasedimentary rocks. The latter have an early Oligocene max. deposition age (Jacobs et al. 2018) and an early Miocene metamorphic age (Bianco et al. 2019) and form the youngest sedimentary record of the Adria plate margin in the study area.

In current models however, the two serpentinite units are interpreted to be the same and their 'repetition' has so far either been interpreted by out-of-sequence thrusting (Keller and Pialli 1990; Massa et al. 2016; Papeschi et al. 2021; Pertusati et al. 1993; Ryan et al. 2021), or large scale folding (Massa et al. 2016; Papeschi et al. 2021). However, based on their distinct field occurrences and differing sediment associations, we hypothesise that they originated diachronous in different tectonic settings during opening and closure of Alpine Tethys. If correct, then alternative reconstructions of the Alpine-Apennine accretionary prism could be envisaged for this part of the Northern Apennines.

The present work investigates the two serpentinite–sediment associations in two ways. First, we provide new U–Pb zircon provenance data for sedimentary rocks of the two serpentinite–sediment associations and discuss these in the light of opening and closure of Alpine Tethys. Second, we contrast the two different associated serpentinite units by providing new electron microprobe data for the serpentinite relic phases (mostly clinopyroxene). These new data combined with field observations are used to derive alternative models for the accretionary/orogenic prism on Elba Island (Figure 1).

2 | Geodynamic and Geological Framework of Elba Island

The geodynamic evolution of the Elba Island region as part of the Northern Apennines, resulted from the interplay of the Adria microplate with Europe and two major continental ribbons in between, the Jurassic AlKaPeCa (Alboran-Kabylia-Peloritani-Calabria) ribbon and the Oligocene Corsica-Sardinia block (Handy et al. 2010; Marroni, Meneghini, and Pandolfi 2017; Carminati, Lustrino, and Doglioni 2012) (Figure 2). Opening of Alpine Tethys, also known as the Ligurian Ocean, correlates with the opening of the central Atlantic by ca. 170 Ma and is associated with widespread rifting elsewhere in Africa and Europe, relating to large scale extensional tectonics and mantle convection patterns at the time (Handy et al. 2010; Jolivet et al. 2021; Stampfli 2000; Stampfli and Borel 2002). Rifting of the Ligurian Ocean was highly asymmetric and largely non-volcanic, with the lower plate margin developing on Adria and the upper plate margin on the European side (Bracciali et al. 2007; Lemoine, Tricart, and Boillot 1987; Marroni et al. 1998). The Ligurian Ocean developed into a western and an eastern branch, separated by the AlKaPeCa continental ribbon as some authors envisage (Handy et al. 2010; Marroni, Meneghini, and Pandolfi 2017; Marroni and Pandolfi 2007). The narrow western branch was floored by oceanic crust that records slow-ultraslow spreading

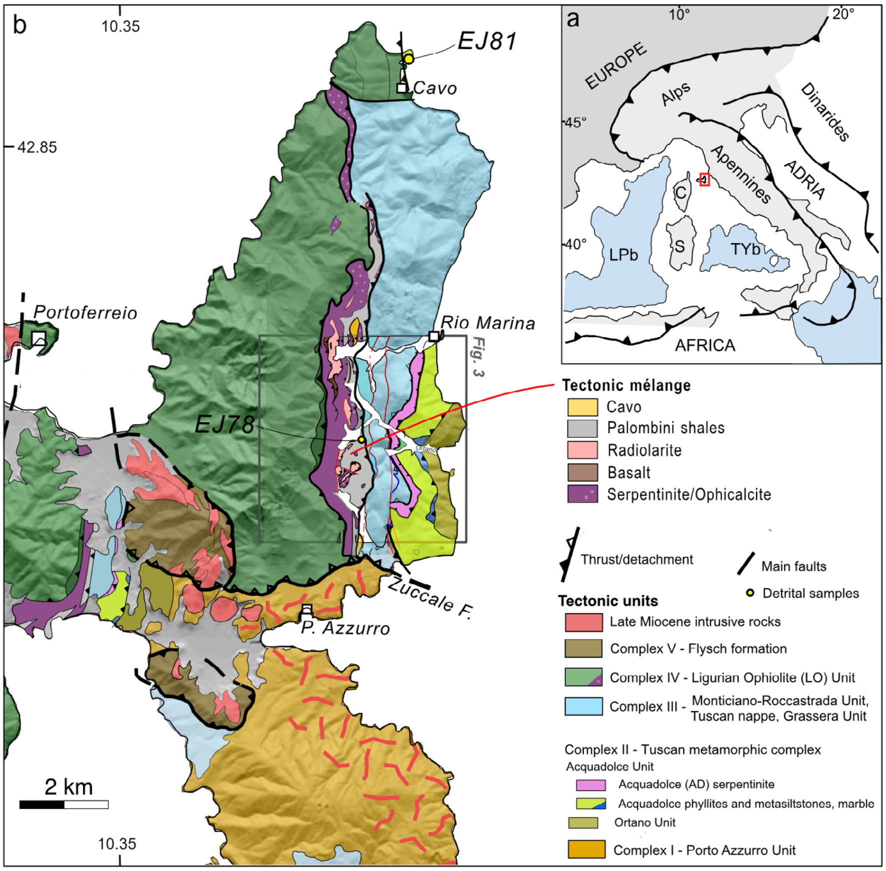

FIGURE 1 | Geological setting of Elba Island. (a) Geodynamic sketch map of the central Mediterranean region with location of Elba Island. (b) Simplified geological map of eastern Elba Island, showing the stacked tectonic units in the transition zone of the Tuscan metamorphic complex to the Ligurian Ophiolite (LO) (modified after Barnes, Selverstone, and Sharp 2006; Bortolotti et al. 2001; Bortolotti, Pandeli, and Principi 2016; Rocchi et al. 2010). The LO is floored by a tectonic mélange. Sample locations in the Pseudomacigno unit (EJ81) and the Palombini shales (EJ78).

with widespread evidence for mantle exposure at the evolving Jurassic sea-floor (e.g. Barnes, Selverstone, and Sharp 2006). The wide eastern branch was largely underlain by thinned continental crust, the External Allochthons (Figure 2), representing a hyperextended continental margin, similar to the western Iberian margin today (Davy et al. 2016).

Jurassic to Early Cretaceous extension was followed by Late Cretaceous convergence that commenced by 85 Ma (e.g. Marroni, Meneghini, and Pandolfi 2017) (Figure 2). Successive closure of first the western, then the eastern branch of the Ligurian Ocean formed the Internal and External Ligurides respectively (e.g. Marroni, Meneghini, and Pandolfi 2017). During basin closure and after substantial counter-clockwise rotation of Adria, Adria/AlKaPeCa collided with Europe to form the double verging Alps, including Alpine Corsica and the Betics (Michard et al. 2006). Convergence led to widespread Eocene Alpine HP and UHP metamorphism in the entire Mediterranean region, resulting from characteristic large-scale *Tethyan Tectonics* between Africa and Adria-Europe from 110 to 35 Ma (Jolivet et al. 2021; Romagny et al. 2020). Contraction was magma-poor until ca. 35 Ma, as subduction underneath Adria was moderate to shallow, resulting in strong coupling between the two plates (Doglioni et al. 2015). First major magmatism commenced after continental collision and subsequent slab break-off, or slab steepening giving rise to substantial calc-alkaline magmatism along the Periadriatic line (Ji et al. 2019; Lustrino, Duggen, and Rosenberg 2011; von Blanckenburg and Davies 1995).

Collision was followed back-to-back by the development of the Apennines on its western margin after 35 Ma, with the large remaining eastern branch of the Ligurian Ocean now undergoing NW-directed subduction underneath Europe (and AlKaPeCa) (e.g. Handy et al. 2021), (Figure 2). Apennine tectonics contrasts with the earlier Alpine-style tectonics, representing a typical retreating accretionary orogen in which slab pull and roll-back led to local high strain rates along plate margins (*Mediterranean Tectonics*, Jolivet et al. 2021). As a consequence, the Corsica-Sardinia block detached from Europe (Gueguen, Doglioni, and Fernandez 1997, 1998). Continued roll-back led to the rise of mantle asthenosphere, high heat flow, significant crustal melting and subsequent substantial extensional shearing. The foredeep progressively migrated E-ward and sediment infill was sourced from the Alps, where parts underwent subsequent Apenninic subduction and exhumation (Jacobs et al. 2018). The steep, fast, NW-directed Apenninic subduction may have been fostered by a general eastward mantle flow (Doglioni et al. 2015; Ficini et al. 2017). Thus, the Alpine-Apennine orogenic system evolved back-to-back during the convergence and closure of Alpine Tethys and as orogens with very different tectonic styles. The high

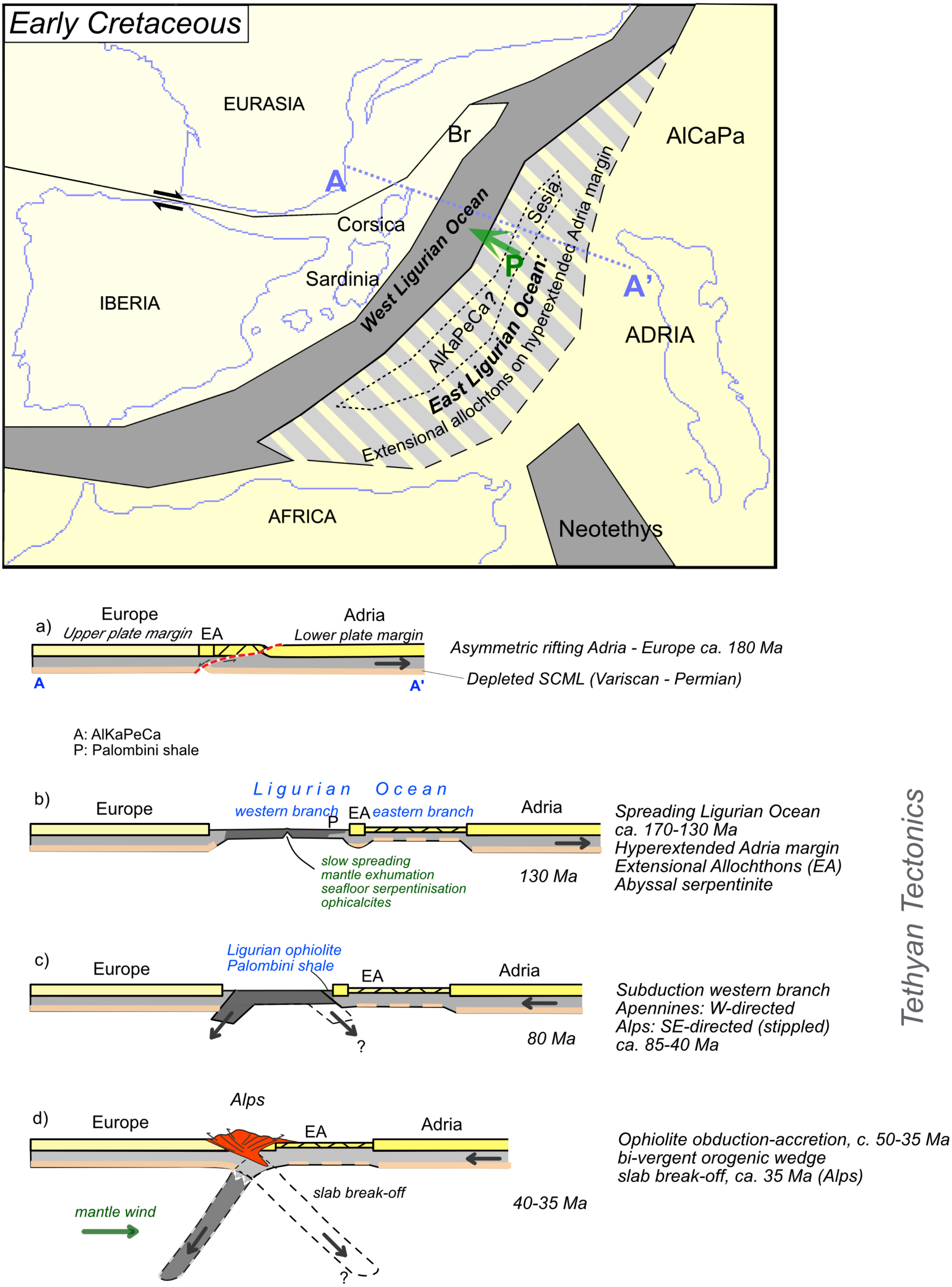

FIGURE 2 | Legend on next page.

FIGURE 2 | Cretaceous-Eocene geodynamic evolution of the western Mediterranean with formation of the Ligurian Ocean (Alpine Tethys). Rifting was highly asymmetric with a hyperextended plate margin leading to the development of Extensional Allochthons (EA), including AlKaPeCa (e.g. Marroni and Pandolfi 2007). The eastern part of the Ligurian Ocean was underlain by continental crust that later formed the External Ligurides (e.g. Marroni, Meneghini, and Pandolfi 2017). The oceanic West Ligurian Ocean formed by ultraslow spreading with an approximate max. width of no more than ca. 400 km. At the end of Cretaceous, convergence started, which successively consumed first the West, then the East Ligurian Ocean (e.g. Handy et al. 2010). Whether the study area is affected by an early E-directed Alpine subduction is tentative. Proposed provenance of the studied Palombini Shales sample (P) in this study. Redrawn after published geodynamic reconstructions (Handy et al. 2010; Le Breton et al. 2021; Molli and Malavieille 2011; Stampfli and Borel 2002). AlCaPa, Alps-Carpathians-Pannonian Basin; AlKaPeCa, Alboran-Kabylia-Peloritani-Calabria continental ribbon; Br, Briançonnais.

strain-rate *Mediterranean Tectonics* oversteered the slower convergence of Africa—Iberia-Europe and effectively dominated the tectonic evolution of the Western Mediterranean after c. 35 Ma (Jolivet et al. 2021; Romagny et al. 2020).

Eastern Elba records excellent exposures of the Apennine orogenic wedge displaying the transition from the western Adria plate margin (Tuscan rocks) into an overlying LO (Ligurian rocks). The fundamental work of the orogenic wedge has been outlined by Trevisan (1950), Bortolotti et al. (2001), Bortolotti, Pandeli, and Principi (2016) and Bianco et al. (2015). Trevisan (1950) subdivided the thrust stack of eastern Elba into five tectonic complexes that Bortolotti et al. (2001) and Bortolotti, Pandeli, and Principi (2016) subdivided further into nine lithological units. Bianco et al. (2015) largely renamed the previously defined complexes into seven different continental and oceanic units, whilst Massa et al. (2016) and Papeschi et al. (2021) grouped the various units into a Lower Complex and an Upper Complex, separated by a serpentinite unit. In this work, we stick to the original subdivision into complexes (Trevisan 1950) and further subdivisions into units (Bortolotti et al. 2001; Bortolotti, Pandeli, and Principi 2016):

Complexes I–III represent basement and thrust sheets of rocks with mostly continental (Tuscan) affinity. These are structurally overlain by a LO unit (Complex IV) and flysch formations (Complex V) (Figures 1 and 3).

The basement of the thrust stack (Complex 1) is predominated by the Calamita schists, which have a Cambrian maximum deposition age of ca. 520 Ma and an African provenance with a main source from the Sahara meta-craton (Sirevaag et al. 2016 and ref. therein).

Complex II consists of Ordovician to Oligocene Tuscan metamorphic continental units. At its base, Ordovician metavolcanic rocks (c. 460 Ma) of the Ortano unit are interpreted as representing active continental margin magmatism along the northern margin of Gondwana (Sirevaag et al. 2016 and ref. therein). The Ortano unit is structurally overlain by the AD Unit, which is the subject of this study. It includes marbles, calcschists, phyllite and metasiltstones and at its structural top a distinct serpentinite sheet, the AD serpentinite. Phyllites and metasiltstones just below the AD serpentinite provide an early Oligocene max. deposition age (Jacobs et al. 2018) and record blueschist facies assemblages (Bianco et al. 2015, 2019). The latter are interpreted as foredeep sediments of the Apenninic subduction zone and probably correlate with similar-aged rocks along strike, the Pseudomacigno sediments (exposed at Cavo, Figure 1).

Complex III is formed by metasedimentary and sedimentary rocks of continental origin with a maximum deposition age of 280 Ma and a significant Variscan provenance, recording the first juxtaposition of Adria along Europe (Sirevaag et al. 2016). Thick dolomitic carbonates (Tuscan nappe) are also part of this complex.

Complex IV is the LO Unit, the base of which forms another subject part of this study. It includes lherzolite-harzburgite serpentinites, gabbros, basalts and deep-sea sediments, the latter of which comprising radiolarites, shales, limestones and the lithostratigraphically uppermost Palombini shales. The LO is floored by a thick tectonic mélange (Jacobs et al. 2018; Papeschi et al. 2022), along which the ophiolite is in structural contact to the continental units (complexes I–III) below.

Finally, Complex V has two flysch formations, an older upper Cretaceous and a younger Eocene one (Pandeli et al. 2013).

The accretionary wedge is strongly influenced by the Tuscan magmatic province (c. 14–1 Ma) that resulted in granitic and hypabyssal intrusions, widespread contact metamorphism, ore mineralisations and extensive extensional tectonics. The Tuscan magmatic province rose from Apenninic subduction roll-back, subsequent assent of mantle asthenosphere and successive E-ward migrating crustal melting (Dini et al. 2002; Poli and Peccerillo 2016). On Elba Island, tectono-magmatic processes of this event are confined to ca. 7–4 Ma and the associated thermal metamorphism significantly hampers precise age-dating of the preceding accretionary tectonics (e.g. Bianco et al. 2019; Deino et al. 1992; Ryan et al. 2021).

3 | Samples and Methods

The two investigated serpentinite–sediment assemblages occur at the top of Complex II and at the base of Complex IV in the orogenic wedge of the easternmost Elba thrust stack (Figures 1 and 3).

One sample each of sedimentary rocks of the two serpentinite–sediment assemblages underwent detrital U–Pb zircon provenance analyses. Complementary grain typology (e.g. Pupin 1980; Belousova, Griffin, and O'Reilly 2006) and trace element analyses (Corfu et al. 2003; Rubatto and Hermann 2007) of the Paleogene zircon population in one of the samples aimed

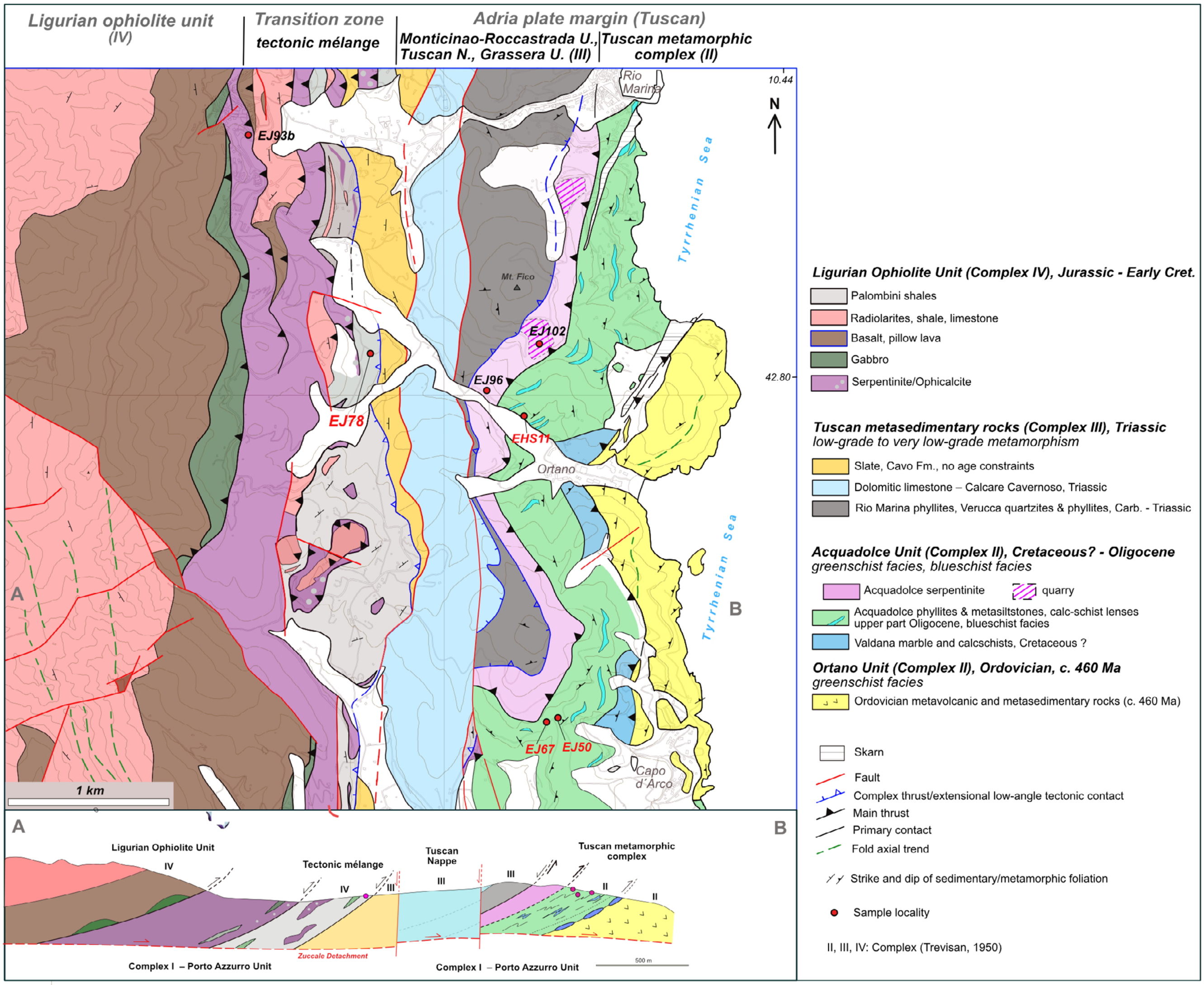

FIGURE 3 | Geological map of the study area, modified after Bortolotti et al. (2001) and Bortolotti, Pandeli, and Principi (2016) and own mapping. Sample localities of Palombini shale sample EJ78, serpentinite samples and previously dated samples of the AD Unit (Jacobs et al. 2018). For Pseudomacigno sample EJ81 see Figure 1. The difference of the two serpentinite bands had readily been recognised by quarry engineers, who preferentially placed extraction sites (Rio Marina, Monte Fico) in the more pristine and massive AD serpentinite rather than in the ophicalcite serpentinite of the LO.

at a more detailed provenance analysis of this youngest age population. For comparative purposes, trace element analysis was extended to detrital zircons of three samples of AD sediments (Jacobs et al. 2018)).

Sample EJ78 is from the Palombini shales of the ophiolite complex (IV). The Palombini shales are the stratigraphically youngest sedimentary rocks of the Ligurian Ocean. They form a main mélange component at the base of the ophiolite complex, where they occur strongly intermingled with serpentinites and other lithologies of Ligurian affinity. The sample comes from the upper Ortano Valley (Figure 3), where decimetre thick silty layers occur within the Palombini shales. To our knowledge, this is the first successful attempt to undertake a provenance analysis for northern Apennine Palombini shales.

The AD serpentinites are closely associated with the phyllites and metasiltstones portion of the AD Unit. Provenance data of this succession are already available (Jacobs et al. 2018). Keller and Pialli (1990) additionally describe mica-rich quarzitic layers in the uppermost part of the AD succession and relate those to the Pseudomacigno unit of mainland Italy (e.g. Keller and Pialli 1990). Like the AD sediments, Pseudomacigno sediments are interpreted as foredeep sediments and although these are not mapped in our main study area (Figure 3), they are described along-strike to the north at Cavo (Figure 1), from where one Pseudomacigno sample underwent a provenance analysis (EJ81).

Zircons were mounted in 2.5 cm large circular epoxy mounts and were ground and polished to half-thickness. SEM-Cathodoluminescence imaging was carried out to reveal the internal structure of the zircons. Analyses spots were carefully chosen after considering detailed transmitted, reflected and cathodoluminescence imaging, in order to avoid inclusions and cracks.

U–Pb zircon and trace element analyses were carried out on two different instruments at the Universities of Bergen and Pisa. The U–Pb zircon analyses of sample EJ81 were carried out on a HR-SC-ICP-MS (Nu Instruments Attom ES) attached to a 193 nm ArF excimer laser ablation system (RESOlution M-50 LR) at the Bergen Geoanalytical Facility, University of Bergen. The U–Pb zircon analyses of sample EJ 78, as well as trace element analyses of EJ81 and three previously dated samples of the AD Unit were analysed on a quadrupole ICP-MS (PerkinElmer NexION 2000) coupled with a 193 nm ArF excimer laser ablation system (Elemental Scientific NWR-193) at the Department of Earth Science, Centre for Instrument Sharing, University of Pisa (CISUP).

Analytical details of the two systems are documented in File S1. Details of the grain morphology studies are provided in File S1.

The two different serpentinite occurrences at the base of Complex IV and at the top of Complex II were analysed at the meso- and micro-scale. Field investigations clarified their first order field relationship, composition, structure and degree of serpentinisaton. As available geochemical analyses of the relict mineralogy are very limited so far, we undertook an electron microprobe study of the serpentinite relict phases (mainly clinopyroxene) in order to constrain their most likely mantle sources in the larger framework of the Alpine Tethys.

Electron microprobe analyses of clinopyroxene were carried out on a CAMECA SX-100 at the Fachbereich Geowissenschaften, University of Bremen. Further details are provided in File S1.

4 | Lithological and Structural Framework of the Two Serpentinite–Sediment Association

4.1 | AD Serpentinite–Sediment Association and Pseudomacigno Unit

The serpentinite–sediment association at the top of Complex II includes the upper part of the AD metasedimentary rocks and the structurally overlain AD serpentinites. The metasedimentary rocks of the AD Unit embrace from structural bottom to top the Valdana marbles, calcschists and phyllites and metasiltstones (Bortolotti et al. 2001) (Figure 3). Keller and Pialli (1990) report small occurrences of quarzitic layers at the top of the AD Unit that they correlate with the Pseudomacigno sediments of mainland Italy. The phyllites and metasiltstones are characterised by abundant felsic mobilisates that show frequent meso- to microfolding (Figure 4). Fold geometries are highly asymmetric, mostly isoclinal, often with folds highly dragged out. Rootless folds occur frequently and sheath folds are observed in calcschists at Rio Marina. Structural boudinage is a common feature at coastal outcrops S of Rio Marina. Based on the occurrence of microfossils, the deposition age of the AD phyllites and metasiltstones was originally thought to be early Cretaceous, with a hypothetical correlation of either the Palombini shales of the Ligurian units (Duranti et al. 1992), or to the metamorphic rocks of Gorgona Island ('Schistes Lustrés') (Corti et al. 1996). However, a U–Pb zircon provenance study showed that at least the tectonically upper part of the unit has a maximum deposition age of only 32 Ma, based on very significant detrital Oligocene zircon age peaks recorded in three different samples (Jacobs et al. 2018). The AD phyllites and metasiltstones were therefore reinterpreted as trench deposits, sourced from the Alps. Mafic enclaves within these AD metasedimentary

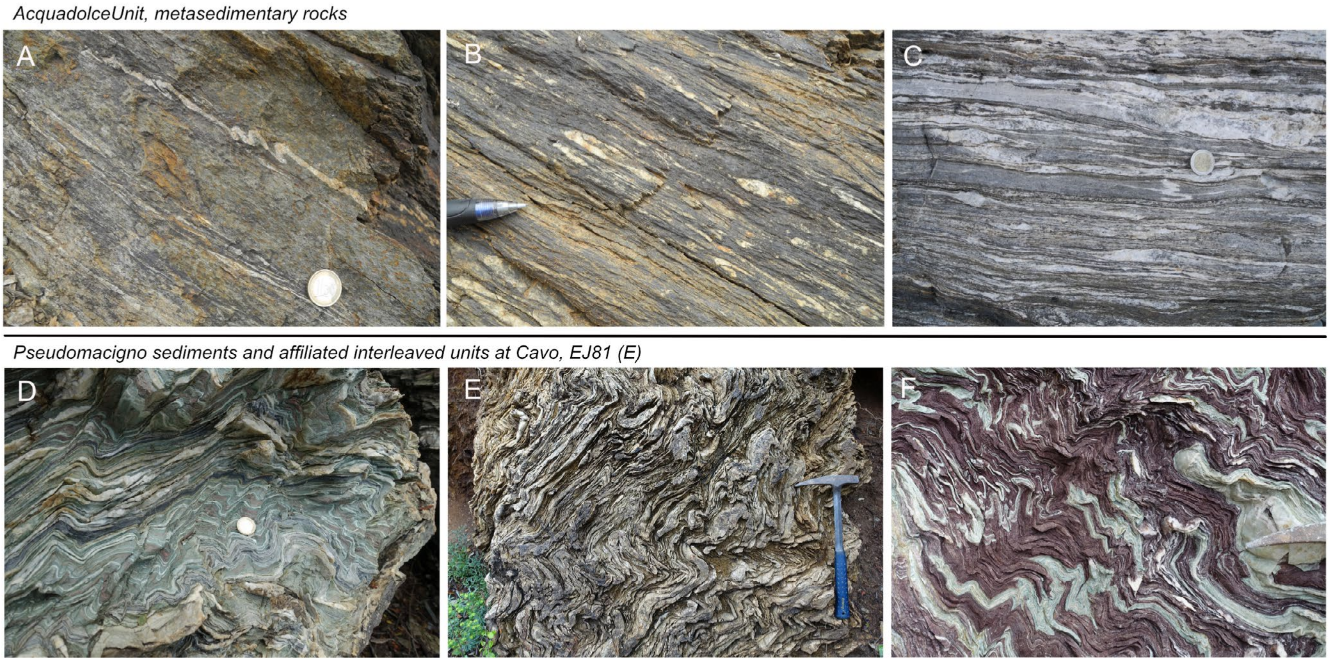

FIGURE 4 | Field occurrence and styles of deformation of highly deformed AD phyllites and metasiltstones versus sandstones of the Pseudomacigno Unit. (A–C) AD phyllites and metasiltstones: Shear folding and strong transposition of phyllites and metasiltstones along the road to Capo D'Arco, close to sampling sites for samples EJ50, EJ67. (D, E) Tight to open folding of Pseudomacigno sandstones (E) and interleaved calcschists (D) and Scaglia shales/calcareous shales with type 3 refolding structures (F), Capo Castello, Cavo.

rocks show epidote-blueschist facies metamorphic conditions at $p = 0.9$–1.0 GPa and $T = 330$°C–350°C (Bianco et al. 2015) and possibly up to $p = 1.8$ GPa and $T = 450$°C–500°C (Bianco et al. 2019; Papeschi et al. 2020). Therefore, at least the upper part of the AD phyllites and metasiltstones appear to represent the post-Oligocene first subducted, and thereafter exhumed part of the Adria plate margin.

Following the stratigraphic revision of the AD Unit, the closest age correlates of the AD Unit in eastern Elba are rocks of the Oligocene-Miocene Pseudomacigno Unit of which small outcrops occur close to Cavo along strike of the main study area to the N (Figure 1). The Pseudomacigno is commonly acknowledged to represent Northern Apennine foredeep deposits (Bortolotti, Pandeli, and Principi 2016; Keller and Pialli 1990), with the difference to the AD Unit being that they lack high-P metamorphism as well as being apparently less strained (Figure 4).

The AD metasedimentary rocks are structurally overlain by massive, greenish and highly sheared AD serpentinites that reach a thickness of ca. 50–80 m in the Ortano valley (Figure 3). The upper and lower contacts of the AD serpentinites are mostly concealed. They show a high-T foliation, as evidenced by dynamic recrystallisation and core–mantle structures of olivine and clinopyroxene (e.g. Tartarotti and Vaggelli 1995), (Viti and Mellini 1996, 1997). The AD serpentinites are mostly spinel lherzolites (>10 vol% clinopyroxene) and therefore differ in composition from the predominantly harzburgites of the LO Unit. A common Jurassic serpentinization age is assumed for both the AD and LO serpentinites (Bortolotti et al. 2001; Barnes, Selverstone, and Sharp 2006).

4.2 | LO Serpentinite–Sediment Association

The serpentinite–sediment association at the base of the LO Unit (Complex IV) consists of a tectonic mélange that predominantly comprises LO serpentinites mingled with Palombini shales (but also with other Ligurian rocks) and that is structurally overlain by massive LO serpentinite (Figures 1 and 3). The Palombini shales form the stratigraphically uppermost early Cretaceous sediments of the Ligurian Ocean. On Elba Island, they are rarely exposed in their normal stratigraphic position, instead, they occur in substantial volumes in the tectonic mélange at the base of the ophiolite complex (Figure 3). All other mélange ingredients are also entirely Ligurian and include Calpionella limestone, radiolarites and basalt which occur as up to several hundred metre elongate and angular blocks within the mélange. In addition, serpentinites and characteristic ophicalcite-serpentinites occur as matrix fragments (Figure 5). The tectonic mélange is not metamorphic.

Characteristic for the ophiolite serpentinites are ophicalcites that are absent in the AD serpentinite.

5 | Provenance Analyses

5.1 | Zircon Provenance Analyses: U–Pb Ages and Trace Element Analyses

Analytical results are tabulated in Tables S1–S3. Analyses with large analytical uncertainties were excluded and no corrections were applied. Discordant analyses were excluded. The concordance filter was set to +10/−5. We report a 'best age', which corresponds to the $^{206}\text{Pb}/^{238}\text{U}$ age for ages <1500 Ma and to the $^{207}\text{Pb}/^{206}\text{Pb}$ age

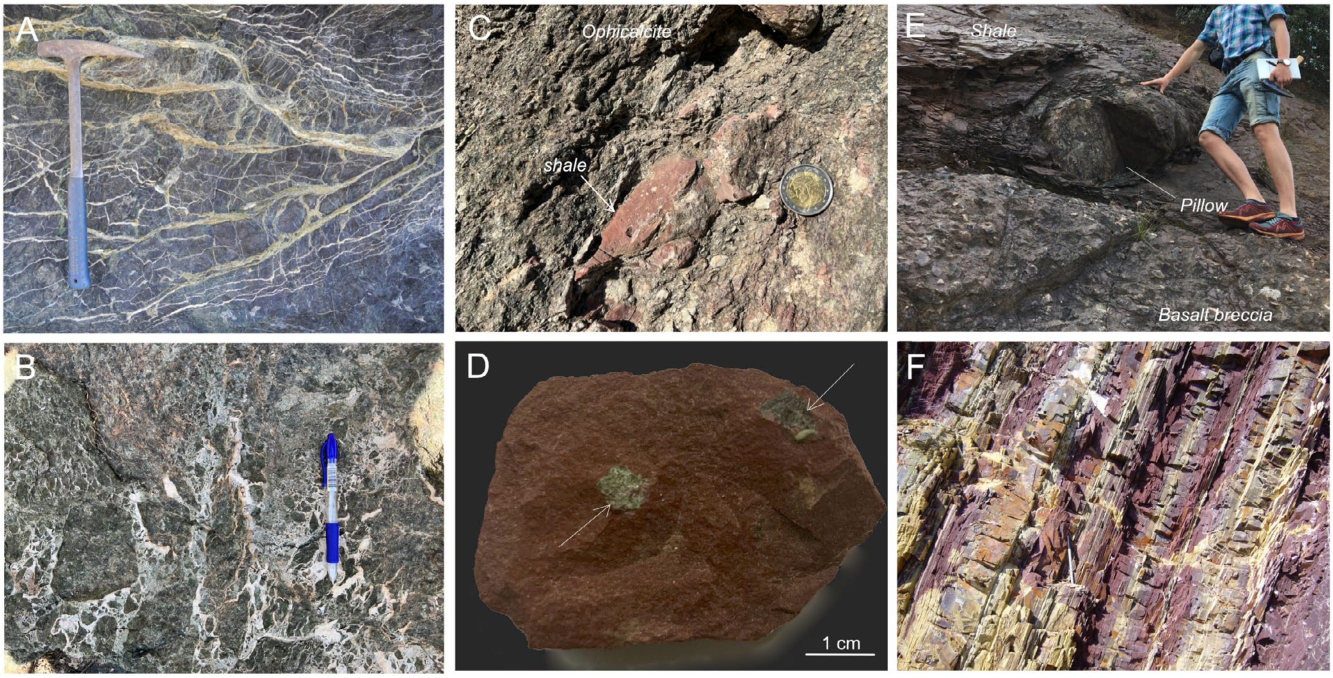

FIGURE 5 | Examples of serpentinite–ophicalcite association and related rocks of the ophiolite complex. (A, B) Types of ophicalcite serpentinite; (C) Siliceous shale enclave in ophicalcite; (D) Small serpentinite enclaves (arrows) in siliceous shales; (E) Ligurian ocean floor exposed within a tectonic mélange raft, with brecciated basalt and a single pillow at the basalt/sediment contact; (F) Typical Ligurian deep sea sediments—radiolarite/shale.

for ages larger than 1500 Ma. Concordia ages are also provided, which were calculated using IsoplotR (Vermeesch 2018).

5.1.1 | Palombini Shales (Sample EJ78)

Sample EJ78 yielded the first detrital zircon age data for the Palombini shales in the Northern Apennines. EJ78 provided 111 concordant analyses (Figure 6). The vast majority of ages fall into the age group 200–700 Ma (67/111). Only five grains are younger than 500 Ma, and ca. 20% of all ages are older than 1800 Ma. The youngest concordant grain is 279 Ma. The sample thus shows a typical African provenance with the main age peak being Pan-African and smaller peaks occurring at 1000 Ma and 1800–2200 Ma. No major Variscan and Ordovician age peaks are recorded.

5.1.2 | Pseudomacigno (Sample EJ81) and AD Sediments

In total, 161 zircons of Pseudomacigno sample EJ81 were U–Pb dated of which 153 are concordant (Figure 6). More than half of all ages (85/153) are late Eocene in age, ranging from 36 to 42 Ma with a peak at 38 Ma. Most of the older ages range from 250 to 700 Ma (*n* = 61/153), reflecting significant Variscan, Ordovician and Pan-African age components. A significant age gap occurs between 1250 and 1800 Ma. Only six ages are older than

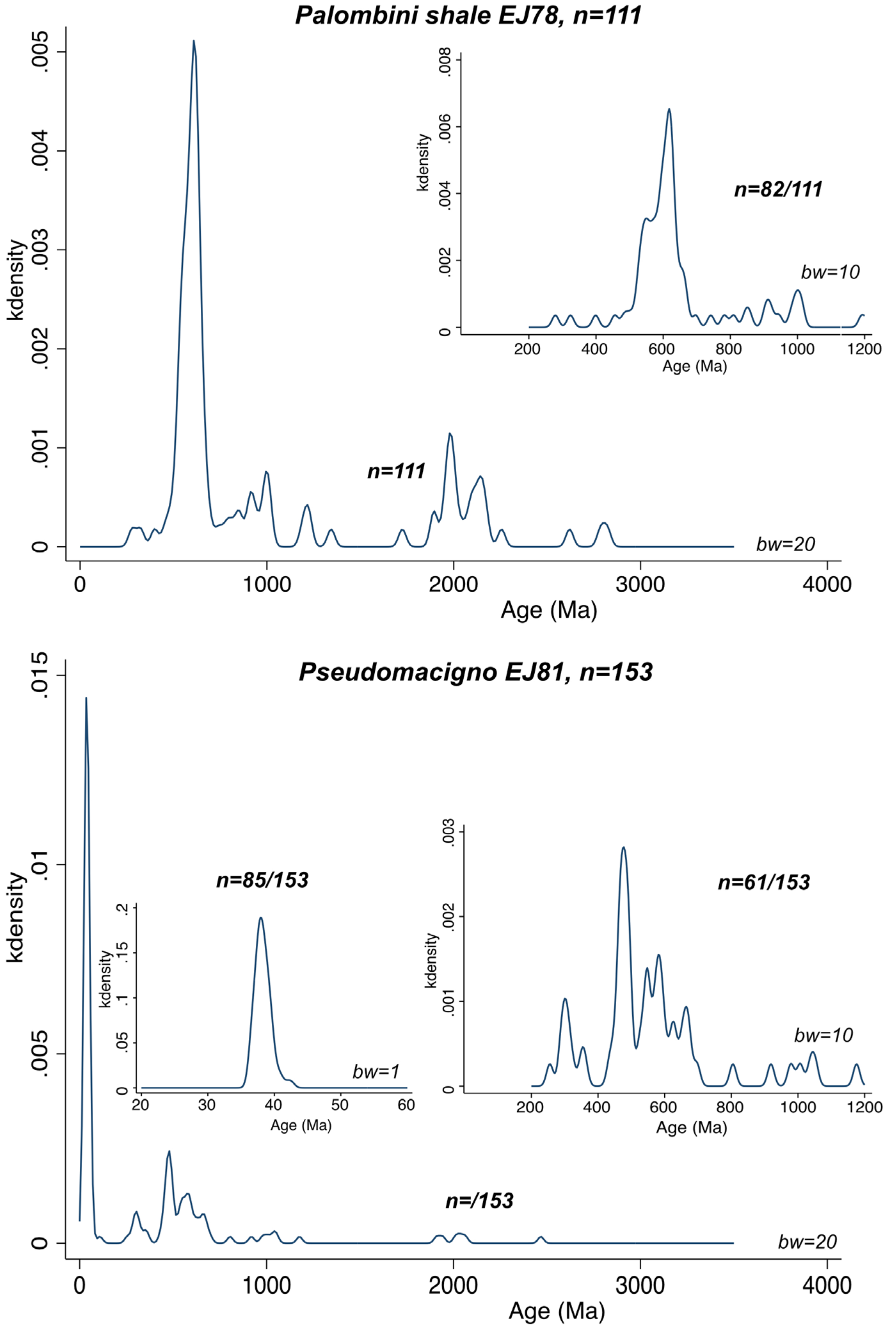

FIGURE 6 | U–Pb zircon age distribution of concordant U–Pb data of Palombini shale sample EJ78 and Pseudomacigno sample EJ81. In sample EJ81 more than half of the ages are Cenozoic. Kernal densities shown at bandwidth (bw) of 1, 10, or 20 Ma.

1800 Ma. Zircons that form the distinct Oligocene age peak are mostly euhedral and characterised by distinct oscillatory zoning (Figure 7).

Zircon crystal morphology and trace element chemistry provide additional provenance information of the detrital Oligocene zircons. The typology analysis of 84 Oligocene zircons reveal morphologies mainly confined to the S2 to S5 fields (Pupin 1980), indicative of rather low crystallisation temperatures from a granitic melt, likely originating from a mixed crust–mantle source in an orogenic setting. A similar, although not identical result was found for the AD samples. Their zircon morphologies point at derivation from a calc-alkaline magma with minor contribution of peraluminous crustal components (Jacobs et al. 2018).

Trace element analyses were carried out on 18 Eocene/Oligocene zircon grains from the Pseudomacigno and 33 grains from the AD sediments (Table S3). Trace element distributions of igneous zircons can infer the primary zircon origin and its igneous source (Belousova et al. 2002) to a certain extent and remain largely unmodified during weathering and low-grade metamorphism. As the AD sediments reached HP metamorphism (Bianco et al. 2015, 2019), recrystallization associated with plagioclase breakdown could theoretically have led to trace element mobilisation in the zircon lattice. However, this did obviously not occur, as shown by the characteristic negative Eu anomaly that is common for igneous zircons (Rubatto and Hermann 2007) and which are very similar for the non-metamorphic Pseudomacigno sediments (average Eu/Eu* = 0.38 ± 0.10) and the blue-schist facies AD sediments (average Eu/Eu* = 0.36 ± 0.13). Our zircon trace element data of both units are comparable, plot well outside the mantle array and overlap with data from the Adamello intrusion, a compositional representative of post-collisional magmatism (Figure 8) (Grimes et al. 2015).

5.2 | Serpentinite Characterisation: Textures and Mineral Composition of Relic Phases

The AD and LO serpentinites have significant mesoscopic, textural and compositional differences. The AD serpentinites show a wide range of serpentinization, the least serpentinised portions are found in the Ortano valley. The AD serpentinites represent moderately to strongly serpentinised spinel-lherzolites and harzburgites with a well-developed tectonic fabric. They lack plagioclase. Relic clinopyroxene is several mm in size and shows thin exsolution lamellae of orthopyroxene, dynamic (neo)-crystallisation, unduluse extinction and folding (Figure 9). Orthopyroxene, olivine and spinel are stronger serpentinised, relic orthopyroxene shows undulose extinction. Relic anhedral spinel is highly altered. Pentlandite and heazlewoodite occur as accessories. Besides serpentine minerals, chlorite and tremolite occur as secondary phases. Metamorphic olivine is oriented parallel to the mylonitic foliation.

The LO serpentinites are plagioclase-bearing spinel-lherzolites that are generally courser grained and stronger serpentinised than the AD serpentinites. They show a characteristic mesh structure that occasionally shows pure shear deformation, but lacks the characteristic simple shear high-T deformation that the AD serpentinites record (Figure 9). Whilst olivine is completely serpentinised, clinopyroxene, orthopyroxene and spinel are only preserved as rare relict phases. Heazlewoodite occurs as accessory, chlorite and andradite as minor secondary phases. Small amounts of plagioclase occur as rims around spinel (Tartarotti and Vaggelli 1995).

From ca. 10 representative samples of the AD and LO serpentinites each, three samples per serpentinite unit were prepared for electron microprobe analyses. Of these, two AD samples (EJ96, EJ102) and one LO sample (EJ93b) returned good quality microprobe data of the relic phases spinel, clinopyroxene, orthopyroxene and olivine, when present. All apparent spinel in the AD serpentinites proved to be ferritchromite rather than spinel. We therefore focus our comparison largely on the clinopyroxene compositions of the two different serpentinite bodies (Figure 10, Table S4).

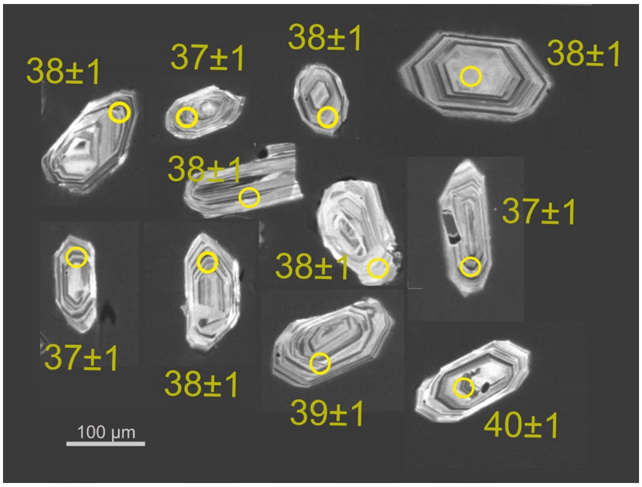

FIGURE 7 | Cathodoluminescence images of Oligocene zircons from sample EJ81 (Pseudomacigno sediments) reveal distinct oscillatory igneous zoning.

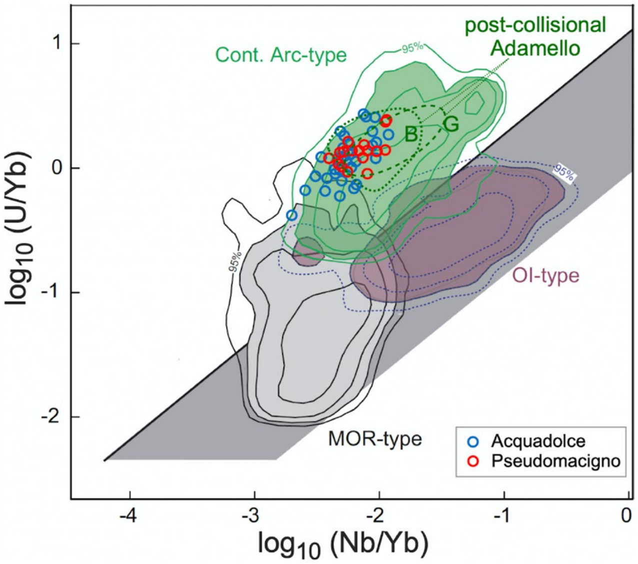

FIGURE 8 | Trace elements (U/Yb vs Nb/Yb) for dated Eocene–Oligocene zircons from (meta-)sedimentary rocks of the Pseudomacigno and AD units plotted against fields for zircons from different Alpine geodynamic settings, including the well-documented post-collisional Adamello pluton (Grimes et al. 2015; Broderick et al. 2015).

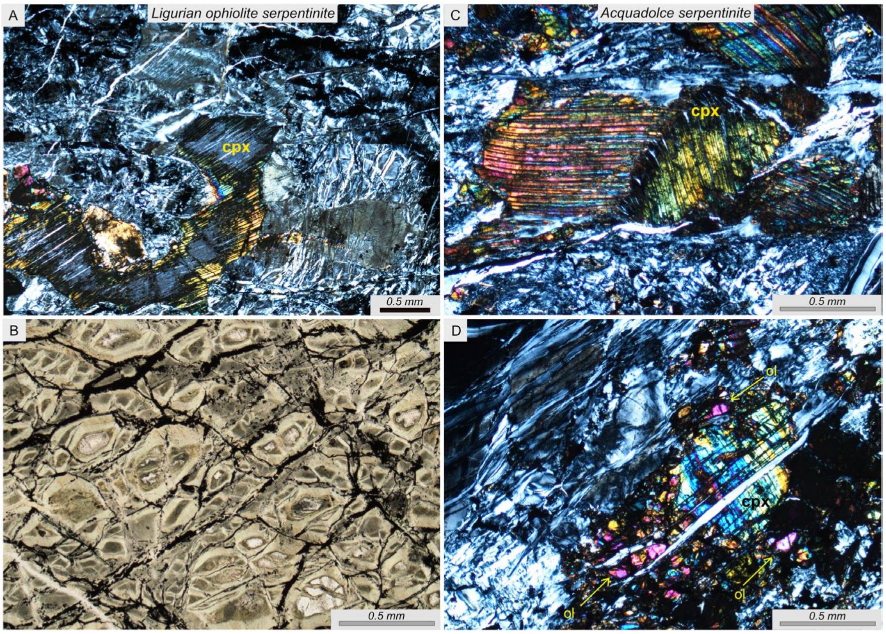

FIGURE 9 | Microphotographs of the LO serpentinites (A, B) and the AD serpentinites (C, D). The former are coarser grained with larger relic minerals of orthopyroxene and clinopyroxene than the latter. The AD serpentinites are additionally highly foliated, have metamorphic olivin (D, arrows) and show folded clinopyroxene (C). A, C, D shown in crossed polarised light, B in plane polarised light. Note different scales of A versus B, C, D. LO serpentinites: (A) Clinopyroxene cores preferentially serpentinised; (B) Mesh structure, undeformed. AD serpentinites: (C) Mantle clinopyroxene with serpentinised exolution lamellae of orthopyroxene; (D) Mylonitic AD serpentinite with relic clinopyroxene and metamorphic olivin that is aligned parallel to the foliation.

The clinopyroxene of the LO serpentinite are extremely depleted in Na_2O (<0.2 wt.%), whilst those of the AD serpentinites are less depleted, with concentrations ranging mostly between 0.2 and 0.4 wt.%. Both groups have low TiO_2 concentrations, but LO serpentinites are lower in TiO_2 than AD serpentinites. At the same time, clinopyroxene of the AD serpentinites usually have higher Al_2O_3 contents (4–8 wt.%) than the LO serpentinites (2–4 wt.%), with the exception of some metamorphic clinopyroxenes within the AD serpentinites. The Cr# are uniformly low in clinopyroxenes of the serpentinites, with values of ca. 0.1 for the AD and ca. 0.2 for the LO serpentinites. As in the AD serpentinites, many apparent spinels of the LO serpentinites are altered to ferritchromite. A few analyses in relic spinel of the LO serpentinite provide Cr# and Mg# that both lie between 0.35 and 0.5, whilst the TiO_2 concentrations range from ca. 0.2 to 0.5 wt. %.

Summarising, besides the substantial general mesoscopic, textural and compositional differences, the two serpentinite units also show significant compositional differences of their relic clinopyroxene. The LO serpentinites show a higher degree of depletion than the AD serpentinites, with very low Na_2O and TiO_2 contents. They are also lower in Al_2O_3, with the exception of some metamorphic neocrystallised clinopyroxene of the AD serpentinites, and they have a higher Cr#.

6 | Interpretation and Discussion

Two closely juxtaposed but contrasting serpentinite–sediment assemblages within the eastern Elba thrust stack show major compositional and age differences. Within the LO of Complex IV, serpentinites with significant proportions of ophicalcites are juxtaposed to Jurassic Palombini shales, but also to other Ligurian sedimentary rocks within a tectonic mélange. The entirely oceanic affinity of this rock assemblage relates the LO serpentinite–sediment association to the western branch of the Ligurian Ocean. The AD serpentinites on the other hand are sandwiched in between the continental complexes II and III and they show significant textural and compositional differences to the LO serpentinites. The close affiliation with highly strained Oligocene-Miocene HP metasedimentary rocks points to an origin outside the western branch of the Ligurian Ocean. A closer look at the provenance of the different sedimentary rocks and their affiliated serpentinite counterparts allows for a more detailed reconstruction of their serpentinite–sediment provenance.

6.1 | Contrasting Provenance of Complex II and Complex IV Serpentinite–Sediment Associations

6.1.1 | Provenance of LO Serpentinite–Sediment Association (Complex IV)

The LO serpentinite–sediment association relates to the western branch of the Ligurian Ocean. The uppermost Ligurian Palombini shales were deposited in a wide time range from the end of ocean spreading until onset of Alpine subduction; they are biostratigraphically dated at Valanginian-Santonian (ca. 135–85 Ma) (Marroni, Meneghini, and Pandolfi 2017). It is unclear from what stratigraphic level our Palombini shale sample is, as it comes from the tectonic mélange at the base of the LO. The detrital zircon age spectrum of the analysed siltstone layer

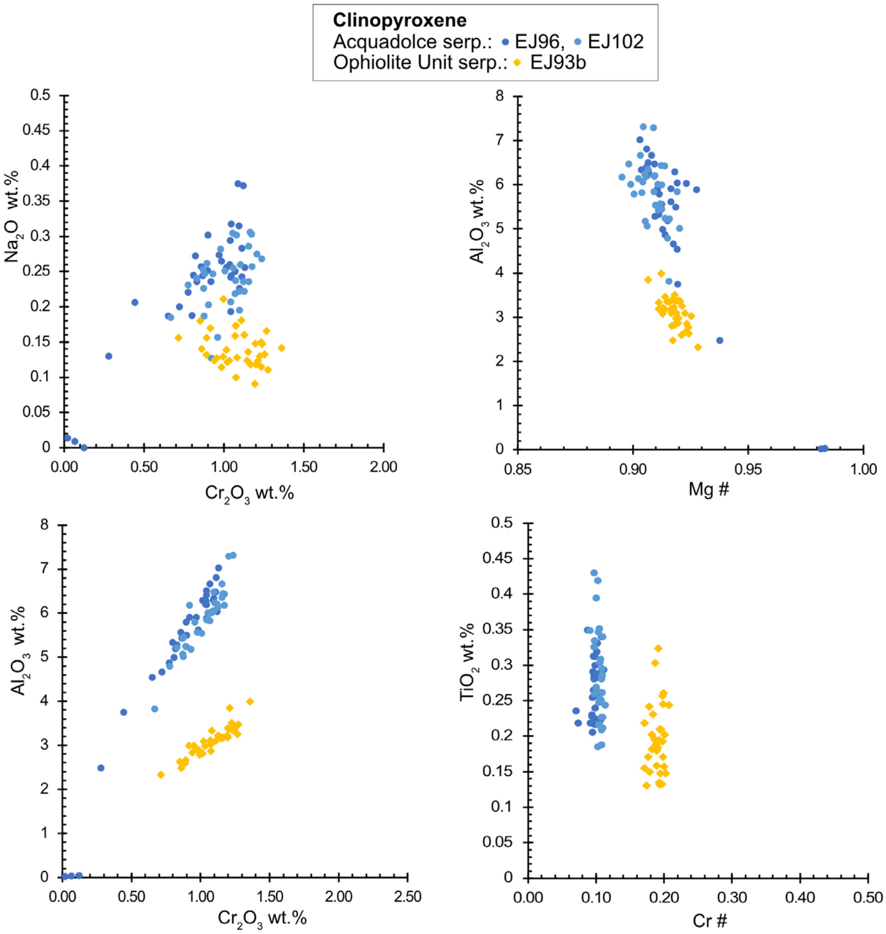

FIGURE 10 | Selected major element distributions of clinopyroxene of representative samples of the two different groups of serpentinites showing significant differences in Na_2O, Al_2O_3, TiO_2, Cr# (molar Cr/(Cr + Al)).

is characterised by a major Pan-African age peak, along with minor age peaks at 1000 and 1800–2200 Ma. However, neither significant Variscan nor Ordovician age peaks are recorded. Thus, a typical African/Adria provenance is inferred (Sirevaag et al. 2016; Paoli et al. 2017). The youngest detrital U–Pb zircon age of 279 Ma defines the maximum deposition age of the shales. The large age gap of ca. 150 Ma between the youngest detrital zircon age and the biostratigraphically oldest Palombini shales indicates that the source lacked post Variscan erosional products. As our Palombini shale sample does not show much of a Corsica/Europe fingerprint, we infer that our Palombini shale sample was most likely sourced from the East, that is, Adria-Africa. Palombini shales with siltstone layers, such as those we dated, are typical for the lower, early Cretaceous part of the succession on mainland Tuscany (Perilli 1997).

There are no other published detrital zircon studies of the Palombini shales that our data could be compared with. The only other available provenance information is from geochemical data of the shales, but these are from distinctly different regions of the Ligurian Ocean (Bracciali et al. 2007; Marroni, Meneghini, and Pandolfi 2017).

In search of a comparative provenance match of our sample, the age spectra of the Palaeozoic units from the Adria-Africa side of the western Ligurian Ocean branch has been considered. Close-by on Elba Island, the Calamita schists of the Porto Azzurro Unit (Sirevaag et al. 2016), and on mainland Italy, the Buti phyllites-quartzites from Monti Pisani, as well as the Upper and Lower quartzites-phyllites from Alpi Apuane are potential sources (Paoli et al. 2017). All these units lack zircons with Variscan or Ordovician ages (except for a group of Ordovician zircons found in Calamita Schists by Musumeci et al. (2011)) and at the same time have dominant Pan-African age peaks (ca. 500–600 Ma), along with a minor Grenville-age age peak at ca. 1000 Ma, comparable to the Palombini shale sample (Figure 11). The relative proportions of zircon age spectra of our Palombini shale sample are most similar with those of the Buti phyllites-quartzites, whilst the lack of Cryogenian ages observed in the Palombini shales is found only in the Upper quartzites-phyllites (Figure 11). The latter are inferred to have a distinct source region in central-eastern northern Africa, whilst the Calamita schists and Buti phyllites-quartzites were rather sourced form NW Africa (Paoli et al. 2017). No matter what, our new Palombini shales data most likely point at an Adria-Africa source with a most likely deposition in proximity to westernmost Adria (Extensional Allochthons/AlKaPeCa), in the eastern part of the western branch of the Ligurian Ocean (Figure 2).

The LO serpentinites have an oceanic setting, similar to classic Internal Ligurian ophiolites. Their very low Na_2O, $TiO_2 < 0.2$ wt.% (clinopyroxene) indicate that they most likely originated from

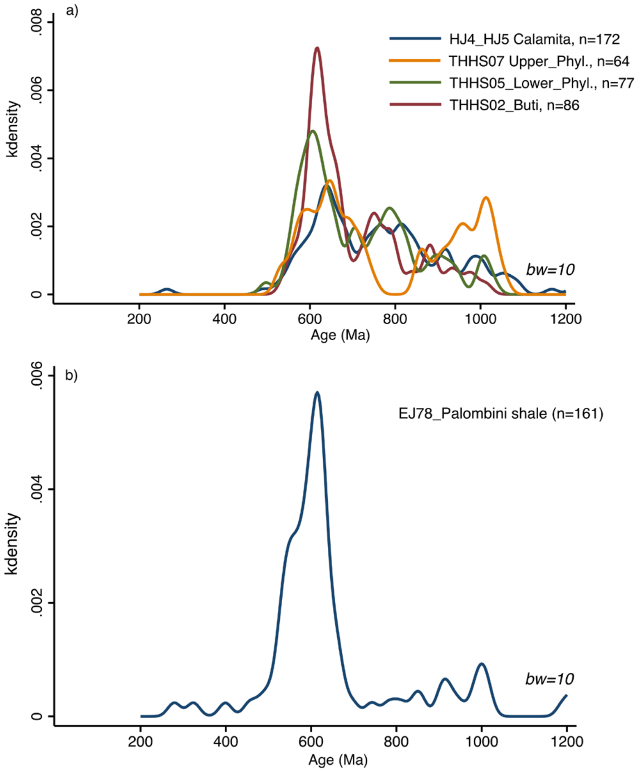

FIGURE 11 | Comparison of U–Pb zircon age distribution of Palombini shales (b) with those of the Calamita schists (HJ4, HJ5 Elba Island) and typical basement rocks of the Monti Pisani and Alpi Apuane area, Tuscany (a) (Paoli et al. 2017; Sirevaag et al. 2016). Kernal densities shown at bandwidth (bw) of 10 Ma.

mature abyssal oceanic lithosphere, similarly to that of the Monte Maggiore ophiolite, Corsica (e.g. Rampone, Borghini, and Basch 2020). They equilibrated in plagioclase peridotite facies. Negative ∂Cl-isotopes are interpreted to indicate low-angle extensional mantle exhumation and subsequent serpentinization in the presence of sedimentary pore fluids (Barnes, Selverstone, and Sharp 2006). The sedimentary pore water likely derived from the Palombini shales, as they form the most frequent contact to the serpentinites in the study area. This supports the interpretation of an overall extensional tectonic setting of this serpentinite–sediment assemblage within the western branch of the Ligurian Ocean, with a most likely Late Jurassic/Early Cretaceous serpentinization age of the LO mantle rocks. The ophiolite retained an uppermost structural level, with no evidence for later metamorphic overprint and no major ductile deformation. The accretion age of the ophiolite is only loosely constrained. The ingredients of the tectonic mélange at the ophiolite base involve solely lithologies of Internal Liguride units, with no involvement of lithologic units of continental origin.

6.1.2 | Provenance of AD Serpentinite–Sediment Association (Complex II), Including Pseudomacigno Sediments

The detrital age distribution of Pseudomacigno sample EJ81 has many similarities with our previously dated samples of the AD phyllites and metasiltstones (Jacobs et al. 2018). As the samples of the AD Unit, they show a major Cenozoic age component, though the Cenozoic age maximum of the Pseudomacigno samples is slightly older. In the age range from 200 to 1200 Ma, the samples of the two different units are largely indifferentiable, with both lithologies showing major Variscan, Ordovician and Pan-African age components (Figure 12a,b). This confirms that the general source region of both units is likely the same in northern Adria, with the difference being that the source of Alpine igneous rocks differs. Whilst in the Pseudomacigno sediments more than 50% of all ages are young, Cenozoic ages in the AD samples contribute only ca. 20% of the entire age population. The AD sediments have a broader young age distribution ranging from 29 to 41 Ma with a pronounced positive skewness and a major age peak at 31.6 Ma. The Pseudomacigno has a narrow and symmetric age distribution from 36 to 42 Ma with an age peak at 38 Ma.

Potential Late Eocene-early Oligocene zircon sources on the Adria plate/margin are linked to Alpine magmatism that is almost exclusively confined to the Periadriatic line (Figure 13) (Lustrino, Duggen, and Rosenberg 2011; Tiepolo et al. 2014; von Blanckenburg and Davies 1995). Igneous activity largely coincides with the termination of Alpine subduction underneath Adria around 35 Ma and may relate to slab break-off (Handy et al. 2010; von Blanckenburg and Davies 1995) or slab steepening and corner flow (Ji et al. 2019). Today, remnants of this magmatism are, from west to east, the post-collisional intrusions of Traversella, Biella, Novate, Bergell, Adamello and other minor easternmost bodies plus numerous scattered dykes (Lustrino, Duggen, and Rosenberg 2011). Additional potential sources located just south of the Periadriatic line include the early Oligocene calc-alkaline Mortara volcano that has been found buried under ~5000 m thick sediments under the westernmost Po Plain (Mattioli, Di Battistini, and Zanzucchi 2002) as well as the Veneto Volcanic Province that has intraplate magmatic affinity (Brombin et al. 2021). Whilst the AD Unit with its distinct age peak at 31.6 Ma was likely sourced from the western-central Alps (Traversella, Bergell, Biella plutons) (Jacobs et al. 2018), the Eocene zircons of the Pseudomacigno sample of this study have a single and precise age match in the central portion of the Adamello pluton (Ji et al. 2019), where ages of 38 Ma predominate (Figure 12c). As the plutons themselves were not exhumed until ca. 10 Ma (Malusà et al. 2011), their volcanic counterpart must have been the main source. Indeed volcanic rocks with equivalent ages are widespread in both the northern and southern Alpine foreland basins (Brugel, Dunkl, Frisch, Kuhlemann, Balogh 2000; Lu et al. 2019, 2018; Macera and Martin 2014; Ruffini et al. 1997). The southern foreland basin records volcaniclastic zircons ranging from 47 to 29 Ma in age. The late Eocene plagioclase arenites of the Molveno (Trento) area have zircons ranging from 39 to 33 Ma, which most likely derive from the Adamello area (Lu et al. 2018) and which match ages of Pseudomacigno zircons best. The source of the AD sediments was activated after the reorganisation of the drainage pattern at the Eocene–Oligocene boundary (34 Ma) (Lu et al. 2019, 2018), when Adamello sources stopped, the Alpine water divide had moved to the west, and Bergell (and Biella)-related volcanics started to feed the southern foreland basin (conglomeratic Gonfolite Lombarda Unit) (Lu et al. 2019) (Figure 2).

The AD serpentinites have striking differences with respect to the LO serpentinites. They have a continental setting, as they are now sandwiched in between two continental units. The

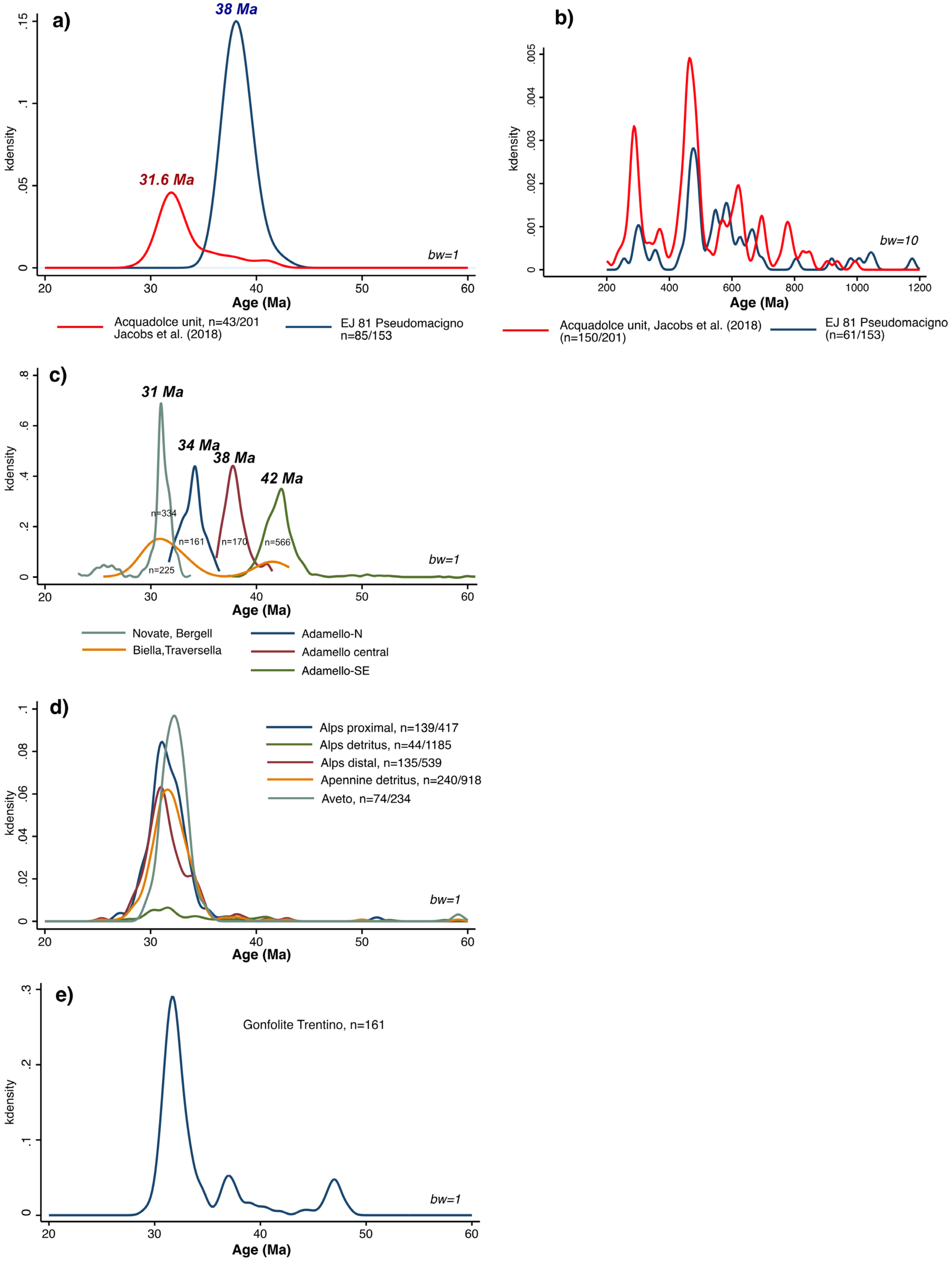

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FIGURE 12 | (a, b) Comparison of Pseudomacigno sample EJ81 with published data of the AD sediments (Jacobs et al. 2018). The Pseudomacigno sample has a significantly higher proportion of Cenozoic ages compared to the sample of the AD Unit and the two units have slightly different Alpine age peaks at 38 and 31.6 Ma respectively. In the older age range from 200 to 1200 Ma, the samples are very similar. (c) Compilation of available U–Pb zircon age data ($n = 1241$) of Alpine igneous activity along the Periadriatic line indicates four igneous pulses at 42, 38, 34 and at 31 Ma. Whilst the major source of the AD Unit appears to be the western-central Alps (Bergell, Novate, Biella and Traversella), the Pseudomacigno sediments appear to derive from the central Alps (central portion of the Adamello). Data sources: Broderick et al. (2015), Ji et al. (2019), Romer, Schärer, and Steck (1996), Samperton et al. (2015), Schaltegger et al. (2009), Schoene et al. (2012), Tiepolo et al. (2014) and Tiepolo, Tribuzio, and Langone (2011). (d) Comparison of various published Alps-derived detritus following the compilation of Jacobs et al. (2018). Whereas the AD detritus is comparable to the general Alpine Cenozoic detritus, the Pseudomacigno detritus is special and can be traced back to the central Adamello massif (c). (e) The zircon record in detrital material of volcanic origin (Lu et al. 2019, 2018) includes ages from 47 to 29 Ma, with dominant ages peaking at ca. 32 Ma for the Gonfolite sediments, and minor peaks at ca. 47 and 38 Ma, the latter from the late Eocene plagioclase arenites of the Molveno (Trento) area, compatible with the ages of Pseudomacigno zircons. Kernal densities shown at bandwidth (bw) of 1 or 10 Ma.

widespread ophicalcites that characterise the LO serpentinite–sediment assemblage are missing. The spinel-lherzolites lack plagioclase, are less intensely serpentinised and show high-T dynamic recrystallisation and mylonitisation. Neocrystallised metamorphic olivine is oriented parallel to the mylonitic foliation, requiring deformation temperatures in excess of 400°C. They are depleted, however with higher Na_2O, TiO_2 (ca. 0.2–0.45 wt.%, clinopyroxene) and show a significantly lower Cr# when compared to the LO serpentinites. The AD serpentinites show an overall more protracted history when compared to LO serpentinites and have evolved at significantly greater depth. They could relate to deeper, depleted SCML (e.g. Picazo et al. 2016) and as such have similarities with the Civrari ophiolite in the Alps (McCarthy and Müntener 2015). As the AD serpentinites are now sandwiched in between continental units and are juxtaposed in the hanging wall and in contact to high-P rocks of Complex II, it is tempting to interpret their source and exhumation as resulting from subduction-exhumation (e.g. Brun and Faccenna 2008) of the eastern branch of the Ligurian Ocean during E-directed rollback of a W-dipping slab. Thus, the AD serpentinite–sediment assemblage evolved in an overall contractional setting in Oligocene-Miocene times.

6.2 | Tectonic Significance of the Different Serpentinite–Sediment Assemblages

Previous tectonic studies infer that the two studied serpentinite units are the same and that their repetition resulted from out-of-sequence thrusting or a megafold (e.g. Keller and Pialli 1990; Bianco et al. 2015; Bortolotti et al. 2001; Massa et al. 2016). This study questions this assumption.

A general challenge in the study area and over large parts of the Apennines is to unequivocally date and differentiate key Alpine-Apennine tectonic events, as significant age records have been obliterated by superimposed later tectonism and significant thermal effects of the Miocene Thyrrenean igneous province. Neither the age of the Ligurian oceanic crust formation is well constrained (e.g. Frasca, Manatschal, and Chenin 2024), nor LO obduction. K-Ar dating of illite fractions of mylonites have been applied to date ophiolite obduction and deformation of the Apenninic subduction channel (Viola et al. 2018). However, these apparent ages could rather relate to structural reworking or thermal overprinting and could miss records of major earlier tectonism.

Furthermore, the age dating of the serpentinization of ultramafic rocks in general is challenging and this also accounts for our study, where the serpentinization age of the two differing serpentinites are unknown but critical for the differentiation of available models. Moreover, whilst there is generally good data coverage for mantle compositions of Alpine Tethys (e.g. Picazo et al. 2016; Piccardo et al. 2004; Rampone and Piccardo 2000; Rampone and Sanfilippo 2021), improving data coverage specifically for the southwestern part of the North Apennines would significantly enhance our understanding of this complex tectonic region.

With these limitations in mind, we would like to reflect on selected controverse tectonic problems that the study of the two different serpentinite–sediment assemblages came upon.

6.2.1 | Age of LO Serpentinite–Sediment Assemblage and Tectonic Relevance

The LO serpentinite–sediment assemblage roots in the western branch of the Ligurian Ocean and probably represents a typical LO that originates in the continental margin transition zone of Adria (e.g. Saccani et al. 2015). Our new and first zircon provenance data of the Palombini shales supports this view. Their provenance matches those of the Alpi Apuane Upper quartzites-phyllites on mainland Italy and shows that they most likely derived from local sources and not too far from the western continental margin of Adria. However, the origin and tectonic significance of the LO serpentinite–sediment assemblage, as part of the tectonic mélange at the base of the LO, is controversial. It is unclear whether it initially formed in extension or contraction and when. In principle, the LO tectonic mélange could relate to Apenninic contraction, but also to cryptic Alpine tectonism or even in extension following opening of Alpine Tethys. At present, field relationships alone do not allow for assigning the main mélange forming process to one of these three major regional tectonic events, as the mélange ingredients are restricted to rocks of the Internal Ligurides (i.e., western Ligurian Ocean branch) with the Palombini shales as the youngest rocks involved. The LO tectonic mélange lacks regional metamorphism but varying Miocene contact metamorphism related to the Tyrrhenian igneous province is widespread. The view of an Apenninic origin of the LO tectonic mélange is based

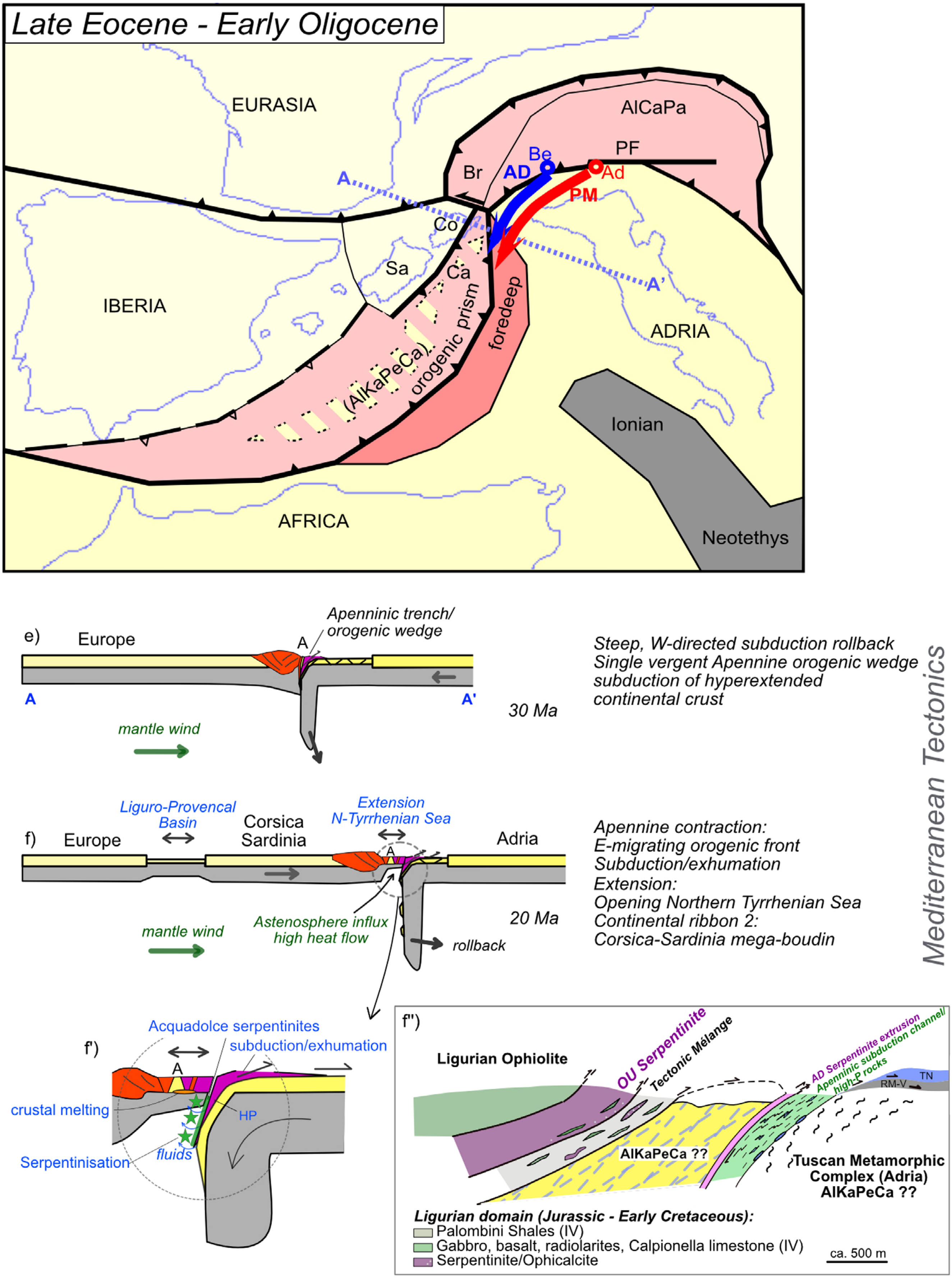

FIGURE 13 | Legend on next page.

FIGURE 13 | Closure of the Ligurian Ocean (Alpine Tethys) and development of the Apennines as a retreating, single vergent, accretionary orogen. Subduction–accretion of the western part of the Ligurian Ocean, followed by the subduction of the hyper-extended continental margin of the eastern part (e) (e.g. Handy et al. 2021). The LO serpentinites are related to accretion of the western branch of the Ligurian Ocean, whilst the AD serpentinites may relate to subduction-exhumation of the eastern branch (f, f"), as the two studied serpentinites are fundamentally different. The proposed provenance path of the Pseudomacigno sediments (PM) and the AD phyllites/metasiltstones (AD) are indicated by red and blue arrows. The tentative consideration of AlKaPeCa in the study area is hypothetical. Labelling of the profiles continues from Figure 2. Redrawn after published geodynamic reconstruction (Handy et al. 2010; Le Breton et al. 2021; Molli and Malavieille 2011; Stampfli and Borel 2002). Ad, Volcanic rocks associated to Adamello pluton; AlKaPeCa, Alboran-Kabylia-Peloritani-Calabria continental ribbon; Be, Volcanic rocks associated to Bergell pluton; Br, Briançonnais; Ca, Possible position of the continental fragment represented by the Calamita Schists of Elba Island; Co, Corsica; PF, Periadriatic Fault; RM-V, Rio Marina and Verruca formations; Sa, Sardinia; TN, Tuscan Nappe.

on illite dating of mylonitic shear zones (e.g. Viola et al. 2018; Papeschi et al. 2022) with all its limitations it has in high heat flow regimes as outlined above.

The LO tectonic mélange could primarily originate in extension during opening of Alpine Tethys (see also Frassi et al. 2017). Jurassic rifting was highly asymmetric, ultraslow and poorly volcanic and led to Alpine Tethys between c. 170 and 130 Ma, with Adria forming the lower plate margin (e.g. Handy et al. 2010; Marroni, Meneghini, and Pandolfi 2010; Marroni et al. 1998) (Figure 2a). In this tectonic setting, the LO tectonic mélange could have originated along a W-dipping extensional oceanic detachment that tectonically juxtaposed mantle rocks to various oceanic sedimentary rocks. The extensive occurrence of ophicalcites indicates sea floor serpentinization of mantle rocks in a slow-ultraslow spreading environment. The ∂Cl isotope values of some LO serpentinites confirm that they formed in direct contact with Ligurian sedimentary rocks and underpin the interpretation of abyssal Jurassic mantle serpentinization (Barnes, Selverstone, and Sharp 2006). Thus, a primary sedimentary contact of the Palombini shales and mantle rocks is feasible and may be best explained within an oceanic core complex setting (e.g. Whitney et al. 2013).

The LO tectonic mélange could also have originated during cryptic early Alpine contraction of Alpine Tethys that started at c. 85 Ma. Although it is undisputed that Elba Island is part of the east-vergent Northern Apennines, the existence of an earlier contractional Alpine imprint is debated. Many authors tend to relate the entire accretionary tectonic evolution of Elba Island to Apenninic west-only subduction–accretion (e.g. Bortolotti et al. 2001; Papeschi et al. 2020, 2021; Principi and Treves 1984; Rossetti et al. 2001; Ryan et al. 2021; Viola et al. 2018), whilst others view much of the Northern Apennines as having evolved from successive Alpine and Apennine tectonic processes (e.g. Boccaletti, Elter, and Guazzone 1971; Carminati, Lustrino, and Doglioni 2012; Doglioni 1991; Marroni, Meneghini, and Pandolfi 2010, 2017; Molli 2008). The different views and uncertainties again reflect the difficulty to 'see through' the pervasive late Apenninic tectonothermal evolution that is dominated by a late high-T imprint. It should be kept in mind that Alpine convergence is recognised throughout much of the Mediterranean realm, as it relates to large-scale convergence of the two major plates Africa and Iberia-Europe (*Tethyan Tectonics*, Jolivet et al. 2021). In contrast, Apennine convergent tectonics affected a single plate margin, driven by slab-pull of the subducting remaining parts of Alpine Tethys (*Mediterranean Tectonics*, Jolivet et al. 2021). Thus, a possible early Alpine signature within the predominantly Apenninic accretionary prism of eastern Elba should not be excluded and awaits further critical assessment (Figure 2c,d).

The common interpretation is that the LO tectonic mélange originated from a W-directed, retreating Apenninic subduction zone (e.g. Papeschi et al. 2022). Here, the question arises, why the LO tectonic mélange is restricted to Ligurian ocean ingredients with neither records of younger components nor lithologies that could derive from the consumption of the eastern branch of the Ligurian Ocean, nor the foredeep. The particularly little coupled and steep Apenninic subduction, governed by roll-back may have led to an effective total subduction of both younger lithologies as well as components of the east Ligurian Ocean branch. In fact, the apparent subduction of significant volumes of continental material is documented by modern tomography of the region (Sun et al. 2019; Handy et al. 2021). On the other hand, whether possible remnants of the Eastern Allochthons and/or AlKaPeCa that escaped subduction are exposed in eastern Elba is debatable (s. below).

6.2.2 | AD Serpentinite–Sediment Assemblage, Tectonic Relevance

The original fundamental tectonic studies of the region (e.g. Trevisan 1950; Bortolotti et al. 2001; Bortolotti, Pandeli, and Principi 2016; Deino et al. 1992) were unaware of the unexpected young Oligocene maximum deposition age of the structurally upper part of the AD sedimentary rocks (Jacobs et al. 2018) and their high-P mineralogy (Bianco et al. 2015). The present study demonstrates that also the AD serpentinites may require a reinterpretation, as the structural, compositional, textural and petrologic differences of the AD and LO serpentinites do not allow for their straightforward correlation. Based on the new data it is unlikely that the two serpentinite bands simply resulted from structural repetition by either out of-sequence-thrusting or megafolding of the same serpentinite body (e.g. Bortolotti et al. 2001; Bortolotti, Pandeli, and Principi 2016; Bianco et al. 2015; Massa et al. 2016). The available data of the AD serpentinite–sediment assemblage point to a joint high-strain structural evolution in a subduction environment. Subduction is bracketed by the Oligocene maximum deposition age (Jacobs et al. 2018) of the high-P rocks of the AD sediments (Bianco et al. 2015) and a Miocene Ar-Ar phyllosilicate cooling age of these rocks (Deino et al. 1992).

This time window was immediately preceded by the collision of Adria with Corsica-Europe and the complete consumption of the western branch of the Ligurian Ocean by the end of the Eocene (35 Ma) (Figure 13). Prior to Alpine continental collision, the SE-directed subduction underneath Adria was moderate to shallow and lacked magmatism/volcanisms due to strong plate coupling (e.g. Doglioni et al. 2015). Alpine continental collision then triggered the first extensive Alpine magmatism along the Periadriatic line, after the subducting slab had delaminated (e.g. Handy et al. 2010; Handy, Ustaszewski, and Kissling 2014; Lustrino, Duggen, and Rosenberg 2011). The central Adamello records the earliest related igneous source along the Periadriatic line (c. 38 Ma) and its volcanic counterparts form a significant provenance for the lithostratigraphically uppermost Pseudomacigno sediments on Elba Island as our new data show. The slightly older AD sediments have their main source in slightly younger volcanic equivalent igneous rocks in the western Alps (c. 32 Ma). Thus, the source of the AD and Pseudomacigno sediments are successively sourced from first the upper, thereafter the lower volcanic successions of the Alpine foreland.

Characteristic large-scale *Tethyan Tectonics* between Africa and Adria-Europe from 110 to 35 Ma terminated with Alpine collision (e.g. Jolivet et al. 2021; Romagny et al. 2020) and was followed back-to-back by the development of the Apennines on its western margin after 35 Ma (Figure 13e). The NW-directed subduction of the remaining eastern branch of the Ligurian Ocean underneath Europe (and AlKaPeCa?) formed a typical retreating accretionary orogen, characterised by steep and fast subduction, hinge-retreat roll-back and the subduction of substantial quantities of the hyperextended western continental margin of Adria (e.g. Handy et al. 2021) (Figure 13e,f). The *Mediterranean tectonics* described by Jolivet et al. (2021) resulted in an orogen with relatively low topography. The foredeep, which migrated eastward over time, continued to receive sediment from the high-standing Alpine region to the north (AD and Pseudomacigno sediments) (Figure 13a).

At the end of the Oligocene (23–20 Ma), subduction roll-back accelerated, leading to deep subduction of trench sediments (e.g. Ryan et al. 2021), with fluids of the downgoing slab hydrating the subcontinental lithospheric mantle wedge of the eastern branch of the Ligurian Ocean and thus forming the AD serpentinite–sediment assemblage at that time. The inference would be that the serpentinization age of the AD serpentinites would postdate that of the LO serpentinites by more than 100 Ma. The associated volume increase initiated tectonic exhumation of the AD serpentinite–sediment assemblage by synorogenic subduction-extrusion (e.g. Brun and Faccenna 2008) by c. 20 Ma (Deino et al. 1992). Continued roll-back led to a high heat flow province and ultimately crustal melting, generating the Tyrrhenian igneous province by late Miocene times.

As the eastern branch of the Ligurian Ocean was closing and large quantities of continental crust were subducted, some continental crust probably remained in the overriding plate or were tectonically incorporated into it. The question arises, whether remnants of this continental crust (Extensional Allochthons and/or AlKaPeCa) are present on Elba Island. The AD serpentinite–sediment assemblage is structurally overlain by Complex III, which indeed could be underlain by remnants of the Extensional Allochthons and/or AlKaPeCa (Figure 13f′,f″). Alternatively, the Calamita schists (Garfagnoli et al. 2005; Sirevaag et al. 2016) of the Porto Azzurro Unit (Figure 1) to the south of the study area may represent remnants of the External Allochthons and/or AlKaPeCa.

7 | Concluding Remarks

The Apenninic wedge of eastern Elba Island hosts two different types of serpentinite–sediment associations, most likely representing two contrasting processes during opening and closure of Alpine Tethys.

The LO serpentinite–sediment association is linked to a typical Internal LO, representing a remnant of the western branch of the Ligurian Ocean. The tectonic significance and age of a major tectonic mélange at the base of the ophiolite is questionable and could relate to either opening of Alpine Tethys, or to Alpine or Apennine contraction. As the mélange ingredients are entirely oceanic and lack metamorphism and major deformation, the tectonic mélange probably initially formed in extension, and was later subjected to reactivation during Alpine-Apennine contraction. Mantle serpentinization probably formed during slow-ultraslow Jurassic spreading and the contact to the Palombini shales could at least in part be a primary sedimentary contact. However, more structural work is needed to better constrain a primary extensional nature of the tectonic mélange at the base of the ophiolite.

In contrast, the AD serpentinite–sediment association formed in a high-strain, ductile environment, involving a highly tectonised serpentinite sliver in contact to highly deformed high-pressure metasedimentary rocks that record Oligocene maximum deposition ages and early Miocene ^{40}Ar–^{39}Ar mica ages. These serpentinites probably formed by Oligocene-Miocene hydration of the subcontinental mantle lithosphere in the wake of steep Apenninic subduction of the remaining eastern branch of the Ligurian Ocean at significant depth. Their subsequent rapid exhumation can be explained by the hydration of the mantle wedge that led to rapid Miocene tectonic extrusion of the AD serpentinite–sediment association. Thus, the two different serpentinite units do not correlate and this needs to be accounted for in any tectonic model of the study area.

The subduction of the eastern branch of the Ligurian Ocean evidently involved the subduction of significant amounts of continental crust (Sun et al. 2019; Handy et al. 2021) and the question arises, whether remnants of these are found in the accretionary wedge of Elba Island. In the study area, Complex III, located in the hanging wall of the AD serpentinite–sediment assemblage, might be underlain by remnants of Extensional Allochthons and/or AlKaPeCa. Alternatively, the Calamita schists (Garfagnoli et al. 2005; Sirevaag et al. 2016) of the Porto Azzurro Unit (Figure 1), situated to the south of the study area, could represent these remnants, though this hypothesis remains to be tested.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

All the data is part of the submission.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.