Clinopyroxene–rutile phyllonites from the East Tenda Shear Zone (Alpine Corsica, France): pressure–temperature–time constraints to the Alpine reworking of Variscan Corsica

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Clinopyroxene–rutile phyllonites from the East Tenda Shear Zone (Alpine Corsica, France): pressure–temperature–time constraints to the Alpine reworking of Variscan Corsica

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Abstract: The East Tenda Shear Zone is the regional structure that marks the Alpine overthrusting of the Ligurian–Piedmontese ocean onto the Variscan Corsica. We present the first report of a Na-pyroxene (acmite)–rutile-bearing assemblage from a phyllonitic shear zone that occurs within the gneissic lithologies of the East Tenda Shear Zone. Acmite hosts inclusions of Na-ampibole and titanite, and is rimmed by retrogressive biotite. Forward modelling of the shear zone assemblages in the NCKFMASHTO chemical system indicates a cold burial–exhumation path (paleogeothermal gradient <10 °C/km–1) and a metamorphic climax with minimum pressure of 1.2 GPa and temperatures of 350–400 °C. U–Pb thermal ionization mass spectrometry analyses on synkinematic rutile yield a 3D array with an age of 48±8 Ma (MSWD 7.3), whereas coexisting acmite–phengite and coatings of oxides or sulphides provide an intercept at 54±8 Ma (MSWD=48). The scatter of the arrays is considered to reflect secondary disturbances of the system and the age provided by acmite–phengite and the coatings at 54±8 Ma is considered the most reliable estimate for shear zone formation. Implications of these new metamorphic and geochronological data are discussed in the regional framework of the Alpine geology and integrated in the plate-tectonic scenario of the central Mediterranean.

Shear zones in the middle and lower crust exert an important control on the metamorphic processes and tectonic reworking in orogenic belts (e.g. Austrheim 1987; Selverstone et al. 1991; Imber et al. 1997; Jolivet et al. 2005). The systematic spatial association between zones of ductile deformation and zones of fluid infiltration has led many researchers to suggest that deformation, fluid flow, metamorphic reactions and changes in the bulk rheology are mutually reinforcing processes (e.g. Austrheim 1987; Dipple & Ferry 1992; Jolivet et al. 2005; John et al. 2009). Furthermore, enhanced fluid–rock interaction in shear zones may cause major changes in mineralogy and bulk-rock chemistry via metasomatism, including the resetting of radiogenic as well as stable isotopes (e.g. Selverstone et al. 1991; Clark et al. 2005). Such pervasive changes are useful for determining the conditions and timing of deformation, which otherwise may be subtle and barely detectable in the unreacted rock mass. This is particularly relevant at depth within continental basement complexes reactivated during orogenic events, as granitoids and high-grade metamorphic or other mostly ‘dry’ rocks are the dominant lithology (e.g. Labrousse et al. 2010).

In this paper we present new petrological and geochronological data from the East Tenda Shear Zone of Alpine Corsica (Fig. 1). This shear zone is the deformation zone that marks the Alpine overthrusting of the Ligurian–Piedmontese oceanic domain (Schistes Lustrés unit) onto the basement rocks of the Variscan Corsica (see Gueydan et al. 2003; Molli & Malavieille 2010; Fig. 1b). Despite the regional significance, the pressure–temperature–time (P–T–t) evolution of this shear zone is still poorly constrained, particularly concerning the timing of the Alpine metamorphic climax. We report the first occurrence of clinopyroxene (acmite)–rutile assemblages from the East Tenda Shear Zone and fix the time of the Alpine high-pressure stage in the Early Eocene (54±8 Ma) by U–Pb isotope dilution thermal ionization mass spectrometry (ID-TIMS) dating of the synkinematic assemblage. The implications of these new metamorphic and geochronological data, which are coupled to fabric development within the East Tenda Shear Zone, are discussed in the regional framework of the Alpine geology of the central Mediterranean.

Regional geological setting

The island of Corsica is located in the centre of the western Mediterranean, between the Liguro-Provençal and Tyrrhenian back-arc basins (Fig. 1a). The island consists mostly of a variably deformed Variscan crystalline basement with a Permian–Eocene sedimentary cover, which constituted part of the European foreland domain of the Alpine orogeny (e.g. Rossi et al. 2003; Malasoma & Marroni 2007). Alpine Corsica forms the northeastern parts of the island, and is made up of a nappe stack largely composed of ophiolitic rocks with associated (meta-)sedimentary cover and slivers of continental basement, composed of rocks originally formed within the Neothethyan Ligurian–Piedmontese oceanic basin and along the Tethyan ocean–continent transition (see Vitale Bravarone et al. 2011a; Fig. 1b). The structural architecture of Alpine Corsica consists of a lower nappe system (the Schistes Lustrés nappe) affected by subduction zone metamorphism and an upper, low-grade metamorphosed nappe complex comprising the Balagne, Nebbio and Macinaggio units (e.g. Mattauer et al. 1981; Dallan & Nardi 1984; Durand-Delga 1984; Waters 1990; Fournier et al. 1991; Dallan & Pulcinelii 1995; Daniel et al. 1996; Malavieille et al. 1998; Rossi et al. 2003; Molli & Malavieille 2010). During the Alpine orogeny the continental European basement, the ophiolitic rocks of the Ligurian–Piedmontese basin and their deep-marine sedimentary
cover were affected by the subduction-related blueschist- to eclogite- and lawsonite-eclogite-facies metamorphism (e.g. Essene 1968; Caron et al. 1981; Lahondère & Guerot 1997; Tribuzio & Giacomini 2002; Chopin et al. 2008; Ravna et al. 2010; Vitale Brovarone et al. 2011a, b).

The transition between the Variscan and the Alpine domains occurs along the Tenda Massif, in a deformation zone that formerly constituted the extended continental margin of the European basement (see Molli & Malavieille 2010), known as the East Tenda Shear Zone. This portion of the Variscan crust was strongly reworked during the Alpine orogeny, synkinematically with epidote- to blueschist-facies metamorphism (Gibbons & Horak 1984; Daniel et al. 1996; Tribuzio & Giacomini 2002; Gueydan et al. 2003; Molli et al. 2006). The fabrics of the East Tenda Shear Zone are composite, recording both the overthrusting and the subsequent exhumation of the Schistes Lustrés nappe. Contrasting kinematic and tectonic interpretations have previously been proposed to explain these fabrics. Molli et al. (2006) emphasized the top-to-the-west compressional shearing as the dominant structural grain in the East Tenda Shear Zone, whereas others considered top-to-the-east ductile-to-brittle extensional reactivation along the contact with the Schistes Lustrés to be the dominant fabric (Jolivet et al. 1990; Gueydan et al. 2003; Daniel et al. 1996).

The age of the HP–LT Alpine deformation and metamorphism in Corsica is still poorly constrained (see recent summary by Martin et al. 2011). The earliest and coldest metamorphic stage, which produced lawsonite-bearing eclogites near the ‘forbidden zone’ in parts of the Schistes Lustrés units (Ravna et al. 2010; Vitale Brovarone et al. 2011b) is believed to be late Cretaceous (e.g. Molli & Malavieille 2010, and references therein), based on the available Sm–Nd whole-rock (garnet–glaucophane–clinopyroxene) isochron age of 84±5 Ma (Lahondère & Guerot 1997) and the c. 90 Ma 40Ar/39Ar glaucophane ages (Maluski 1977) from eclogite lenses within the Schistes Lustrés. Lawsonite eclogites were synkinematically decompressed at both blueschist and later greenschist facies, and have therefore experienced a protracted structural and metamorphic history. Recent U–Pb zircon ages from continental-derived granulite slivers found within the Schistés Lustres gave an age of 34.4±0.8 Ma that is considered to date the Alpine pressure peak during reactive fluid infiltration in Alpine Corsica (Martin et al. 2011). This Tertiary age is in line with the biostratigraphic constraints provided by the nummulite-bearing sedimentary sequences of the Alpine foreland involved in the Alpine nappe construction, which suggests a post Middle Eocene orogenic construction and metamorphism at the expense of the Corsica–Europe continental margin (Bezert & Caby 1988; Egal 1992; Brunet et al. 2000; Malasoma & Marroñi 2007). In the Schistes Lustrés, Tertiary metamorphic ages are provided by 40Ar/39Ar geochronology (Maluski 1977; Amaudric Du Chaffaut & Saliot 1979; Brunet et al. 2000). In particular, discordant 40Ar/39Ar phengite ages ranging from 65 to 55 Ma and from 55 to 37 Ma are derived from eclogite and blueschist units, respectively (Brunet et al. 2000). In the East Tenda Shear Zone, 40Ar/39Ar phengite dating provided ages between 45 and 30 Ma (Brunet et al. 2000), whereas earlier Rb–Sr whole-rock data point to a Middle Cretaceous (108±5 Ma) age (Cohen et al. 1981).

Structures and petrography

Deformation is heterogeneously distributed within the East Tenda Shear Zone, with zones of localized ductile-to-brittle shearing (SZ) that wrap around lens-shaped massive lenses (ML) with a prominent gneissic texture (Figs 2 and 3a). The main foliations in the East Tenda Shear Zone and the overlying Schistes Lustrés are nearly concordant and strike NW–SE and dominantly dip shallowly towards the NE (Fig. 2). In the following, mineral abbreviations follow Whitney & Evans (2010).

The mineralogy of the ML consists of a high-variance assemblage of Qz, Ph and relic igneous Fsp with Ep, Fe-oxides, relic Zrn and Aln as accessory phases. The SZ mineralogy is invariably dominated (40–60 vol%) by highly substituted Ph (Si4+ = 3.5–3.7 a.p.f.u.), modally abundant Qz (30–50 vol%), Ab (10–20 vol%), Ep (5–10 vol%) and Mc (5–10 vol%). Locally, Na-Amp (10–20 vol%) also occurs in the SZ assemblage to form mostly thin (up to 0.5 mm thick) dark bluish mylonitic layers (Fig. 3a and b). Stretching lineations trend WSW–ENE to east–west (Fig. 2) and are provided by aggregates of Qz–Ph–Ab in the ML and of Qz–Ph–Ab ± Na-Amp in the SZ. Kinematic indicators, at outcrop and thin-section scale, systematically indicate top-to-the-west ductile shear sense in both ML and SZ (Fig. 3b and c). Semi-brittle to brittle top-to-the-east shear bands locally reactivate the main top-to-the-west ductile shear fabrics. This late deformation is mostly localized within the phyllonitic shear zones (Fig. 3d).
Approximately 200 m structurally below the main contact with the Schistes Lustrés (i.e. normal to the main foliation), a 10 cm thick, discontinuous clinopyroxene (acmite–rutile (Cpx–Rt) phyllonitic shear zone was found in sharp contact with the host ML (Fig. 3g and f). Geographical coordinates 42°39′23.34″N, 9°16′20.74″E. Stretching lineations are provided by Ph–Qz–Cpx–Rt aggregates ± Fsp (Fig. 3g). The modal composition of the phyllonitic consists of Ph (>60 vol%), Cpx (20–25 vol%), Qz (2–5 vol%), Rt (2–5 vol%) and alkaline Fsp (Ab and Mc) ± Ep + relic Zrc (<5 vol%) as minor phases (Fig. 4a). The Cpx crystals host inclusions of Na-Amp and Ttn and are rimmed by retrogressive Bt; Rt forms porphyroblasts along the main phyllonitic foliation (Fig. 4b and c). Microprobe data and back-scattered electron (BSE) images indicate a rather homogeneous composition both for the Ph (3.6–3.7 Si4+ a.p.f.u.) and Cpx (average composition Acm2.67Jd1.31Hed2.61, Opx0.05) (Table 1; Fig. 5). In contrast, Ph in the host rocks shows a strong core-to-rim zonation (Si4+ content ranging from 3.3 a.p.f.u. in the core to 3.6 a.p.f.u. in the rim) (Table 1; Figs 4d and 5a). The phengite compositions of rims and in the Cpx–Rt shear zone significantly deviate from the ideal Tschermak’s substitution line, suggesting that some of the iron is ferric (Fig. 5a).

Thermobarometry of the Cpx–Rt shear zone

Because of the high-variance shear zone assemblage (Ph–Cpx–Rt–Qz ± Fsp (Ab and Mc) ± Ep), the inverse (conventional and multi-equilibrium) thermobarometry is not applicable. Accordingly, we adopted a forward modelling technique to infer the pressure–temperature (P–T) conditions of formation of the Cpx–Rt shear zone. The P–T–X modelling was computed using the Perple_X software (Connolly 2005; http://www.perplex.ethz.ch/) in the NKFMASHTO (Na2O–K2O–FeO–MgO–Al2O3–SiO2–H2O–TiO2–O2) chemical system, for bulk-rock compositions as calculated from mineral modal compositions and electron microprobe data. We used the thermodynamics dataset of Holland & Powell (1998; updated in 2002) for minerals and aqueous fluids, integrated with those of Massonne & Willner (2008) for low-grade metamorphic Fe3+-bearing phases (Cpx and Na-Amp). In particular, the following solution models offered by Perple_X were chosen: Bio(HP) for Bt, Chl(HP) for Chl, Ep(HP) for Ep, GlTrTsMr for Na-Amp, Acm(M) for Cpx, Gt(HP) for Grt, and fsp11 for Fsp. Water content was considered to be always in excess.

A representative pseudosection is shown in Figure 6. The synkinematic Rt–Cpx–Ph–Qz ± Na-Amp assemblage occurs in a narrow, highly shear zone development with low-strain domains corresponding to the gneissic (massive) lenses wrapped by high-strain domains consisting of mylonitic to phyllonitic shear zones. The kinematics relative to the main compressional fabric development (D1) and the later extensional reaction (D2) are also indicated. 1, protolith rocks; 2, East Tenda Shear Zone units (2a, massive lenses; 2b, shear zones); 3, Schistes Lustrés units; 4, compressional shear senses; 5, extensional shear reactivation. (b, c) Representative stereoplots (Schmidt net, lower hemisphere projection) showing the plano-linear shear fabrics at regional (b) and outcrop (c) scale.
of the used bulk composition, particularly of the $O_2$ content; (2) variation of the bulk-rock composition induced by fluid–rock interaction during progressive shearing; (3) significant uncertainty of the thermodynamic dataset in the low $T$ range. Accordingly, forward modelling of the Cpx–Rt shear zone can be considered as tentative only and $P$–$T$ estimates as semi-quantitative. Nevertheless, trial calculations with variations of $O_2$ content, as well as using different bulk compositions, did not result in significant modification of the general aspects of the derived $P$–$T$ path, which was dominantly constrained by the positive slope of the Ph isopleths in the $P$–$T$ interval of interest. In addition, the obtained results are compatible with the previous $P$–$T$ estimates on the Alpine metamorphic climax along the East Tenda Shear Zone, which collectively document epidote- to blueschist-facies peak metamorphism (Tribuzio & Giacomini 2002; Molli et al. 2006).

**TIMS U–Pb geochronology**

To establish the age of shearing along the East Tenda Shear Zone, we analysed Rt and coexisting Cpx, Ph, and oxide or sulphide coatings on Qz. The minerals used for analysis were extracted from the schist by crushing, pulverizing and enrichment on a Wilfley table, and by using magnetic separators and heavy liquid. The selected minerals were dissolved in concentrated HF (+ $HNO_3$); the Rt in
**Table 1. Representative mineral compositions of the Cpx–Rt shear zone samples**

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Sample:</th>
<th>Phengite</th>
<th>Clinopyroxene</th>
<th>Biotite</th>
<th>Na-amphibole (inclusion in Cpx)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Host rock</td>
<td>Cpx–Rt shear zone</td>
<td>Cpx–Rt shear zone</td>
<td>Cpx–Rt shear zone</td>
</tr>
<tr>
<td>Analysis:</td>
<td>core 1</td>
<td>rim 3</td>
<td>core 5</td>
<td>rim 7</td>
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<tr>
<td>SiO₂</td>
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<td>50.20</td>
<td>49.85</td>
<td>50.72</td>
<td>51.88</td>
</tr>
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<td>0.53</td>
<td>0.03</td>
<td>0.62</td>
<td>0.12</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>27.83</td>
<td>23.51</td>
<td>27.99</td>
<td>22.19</td>
<td>19.00</td>
</tr>
<tr>
<td>FeO⁴⁺</td>
<td>3.87</td>
<td>6.33</td>
<td>3.48</td>
<td>6.02</td>
<td>6.28</td>
</tr>
<tr>
<td>MnO</td>
<td>0.24</td>
<td>0.12</td>
<td>0.23</td>
<td>0.17</td>
<td>bdl</td>
</tr>
<tr>
<td>MgO</td>
<td>1.85</td>
<td>2.49</td>
<td>1.96</td>
<td>2.42</td>
<td>5.18</td>
</tr>
<tr>
<td>CaO</td>
<td>bdl</td>
<td>bdl</td>
<td>bdl</td>
<td>0.01</td>
<td>0.03</td>
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<tr>
<td>Na₂O</td>
<td>0.01</td>
<td>0.06</td>
<td>0.01</td>
<td>0.26</td>
<td>0.25</td>
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<tr>
<td>K₂O</td>
<td>11.71</td>
<td>11.42</td>
<td>11.65</td>
<td>10.41</td>
<td>10.00</td>
</tr>
<tr>
<td>BaO</td>
<td>0.04</td>
<td>0.04</td>
<td>0.01</td>
<td>0.24</td>
<td>0.05</td>
</tr>
<tr>
<td>Total</td>
<td>95.12</td>
<td>94.70</td>
<td>95.21</td>
<td>93.06</td>
<td>93.20</td>
</tr>
</tbody>
</table>

The analyses are normalized to fixed oxygen: phengite, O = 11; biotite, O = 11; amphibole, O = 23; total cations without K = 15; pyroxene, O = 6; total cations ~ 4.

bombs at c. 190°C, and the other minerals in Savillex vials on a hotplate at around 100°C. Chemical separation was performed with a two-stage anion exchange procedure using HBr for Pb and HNO₃ + HCl for U on AG 1-X8, 200–400 mesh resin. The samples were spiked with a ²⁰²Pb–²⁰⁵Pb–²³⁵U spike. Other details of the procedure and measurement have been given by Corfu (2004). The decay constants are those of Jaffey et al. (1971). Plotting and regressions employed the program Isoplot of Ludwig (2003). Results are listed in Table 2 and shown in Figure 7.

Rt consists largely of tabular twinned prisms containing 5–15 ppm U and 0.3–4 ppm initial Pb. Cpx has mostly about 0.5 ppm U and half as much initial Pb. One fraction of Cpx was selected among grains full of Rt inclusions, the Cpx was dissolved at low temperature, and the residual Rt was recovered and dissolved separately. In this case the Cpx analysis yielded much higher U (11 ppm) and initial common Pb (5 ppm) contents; the liberated Rt consisted of very small and fragile pieces that could not be weighed. The data for all these minerals are all relatively unradiogenic, hence the age calculation is strongly dependent on the common Pb correction. The least radiogenic composition was found in the coatings of oxide or sulphide on Qz, although these values are clearly more radiogenic than normal crustal values (²⁰⁶Pb/²⁰⁴Pb of 20.5). Such elevated initial values, however, are provided independently by regression lines through the various datasets. Use of the 3D concordia plot provides the means to deal with these types of data without exerting over-strong external controls by choosing specific compositions to correct the initial Pb (Fig. 7). The data define separate arrays for Rt (the low precision of this array reflecting the very small amount of Pb available for analysis) and the other minerals, although both lines are variously scattered. The intercepts with concordia, however, are similar, giving 53.7 ± 7.7 Ma for the Cpx–Pb–oxide regression and 48 ± 18 Ma for Rt (except for one of the Rt analyses, which plots very far from the line, but the significantly higher U content...
suggests that the fraction may have had inclusions of Zrn, which in this sample is very U-rich and discordant). The difference between the two arrays could be interpreted in two ways. One is that Rt formed after the Cpx, but that seems unlikely given their close paragenetic association. The alternative is that Rt remained open for the diffusion of Pb, or was affected by younger Pb loss that shifted the data towards younger ages. Interestingly, the very same age relationship is observed for the rutile inclusions liberated from the Cpx. In conclusion, the age provided by Cpx–Ph and the coatings at 53.7 ± 7.7 Ma is considered the most reliable estimate for development of these minerals.

Discussion

The new data integrating information on the fabrics and kinematics with geochronology and metamorphic petrology show that the Variscan basement along the East Tenda Shear Zone of Corsica underwent prograde high-pressure blueschist metamorphism in the Early Eocene (c. 50 Ma) during top-to-the-west-directed shearing. This shear sense is consistent with the kinematics of the Schistes Lustrés units overthrusting onto the European foreland (see Daniel et al. 1996; Molli & Malavieille 2010). Late reworking of the early-formed top-to-the-west ductile shear fabric by east-directed shear senses is also documented.

The Early Eocene timing of the Alpine peak metamorphism and the fabric-forming events reconstructed from the East Tenda Shear Zone confirms a Tertiary age for the Alpine metamorphism in Corsica. In particular, the U–Pb Rt ages presented herein are compatible with the maximum, discordant ⁴⁰Ar/³⁹Ar ages (46.6 ± 1.2 Ma) obtained from the East Tenda Shear Zone (Brunet et al. 2000), but older than the Late Eocene–Early Oligocene ages reported both from the East Tenda Shear Zone (Brunet et al. 2000) and the Schistes Lustrés nappe (Brunet et al. 2000; Martin et al. 2011). We emphasize here that the shape of the P–T path reconstructed for the

<table>
<thead>
<tr>
<th>Properties</th>
<th>Weight (µg)</th>
<th>U (ppm)</th>
<th>Pbc (ppm)</th>
<th>Pbcom (pg)</th>
<th>238/204* 2σ%</th>
<th>206/204* 2σ%</th>
<th>235/204* 2σ%</th>
<th>207/204* 2σ%</th>
<th>238/206* 2σ%</th>
<th>207/206* 2σ%</th>
<th>204/206* 2σ%</th>
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<td>R</td>
<td>5</td>
<td>15.19</td>
<td>0.31</td>
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<td>3141</td>
<td>198</td>
<td>29</td>
<td>74</td>
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<td>446</td>
<td>13</td>
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<tr>
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<td>0.497</td>
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<td>0.61</td>
<td>15.774</td>
<td>0.30</td>
<td>0.00</td>
<td>1.0</td>
</tr>
</tbody>
</table>

R, rutile; A, acmite; P, phengite; C, oxide or sulphide coatings on quartz; incl, inclusions. Pbc, initial amount of common Pb. Pbcom, total amount of common Pb (initial + blank).

*Corrected for fractionation, spike and blank; error calculated by propagating the main sources of uncertainty.
framed within the Tertiary plate-tectonic framework of the central and the Variscan Corsica, the activity of this shear zone can be convergence boundary between the Ligurian–Piedmontese ocean East Tenda Shear Zone.

required to describe the polyphase deformation history along the collectively document a Middle Eocene–Early Miocene timespan (see Cpx–Rt shear zone suggests that the 40Ar–39Ar phengite ages from the East Tenda Shear Zone probably record the continuous exhumation of this shear zone, as highly substituted phengite compositions persisted down to lower P–T conditions along a cooling–exhumation path (Fig. 6). This cooling–exhumation path can then provide a reason for the staircase geometry of the phengite argon release spectra obtained from the East Tenda Shear Zone samples (Brunet et al. 2000). A protracted history of deformation along this shear zone is also derived from stratigraphic data from the Alpine foreland (Egal 1992; Malasoma & Marroni 2007) and from the 40Ar–39Ar phengite ages (Brunet et al. 2000), which collectively document a Middle Eocene–Early Miocene timespan (see Molli et al. 2006). Consequently, a revised tectonic scenario is required to describe the polyphase deformation history along the East Tenda Shear Zone.

Assuming the East Tenda Shear Zone marks the major Alpine convergence boundary between the Ligurian–Piedmontese ocean and the Variscan Corsica, the activity of this shear zone can be framed within the Tertiary plate-tectonic framework of the central Mediterranean, estimating the expected convergence from plate kinematics reconstruction. To evaluate the relative motion between Adria and Eurasia, we adopt the Dewey et al. (1989) rotation pole for the Africa–Eurasia convergence and assume that the Adria motion was coherent with that of Africa (Van Der Voo 1993). The coherent motion of Adria with Africa during most of the Cenozoic is well established by palaeomagnetic data and palaeogeographical evidence (Channell et al. 1979; Muttoni et al. 2001). From this reconstruction it is possible to derive the direction and the amount of plate convergence expected along the main plate boundary in Corsica; that is, along the future East Tenda Shear Zone (Jolivet & Faccenna 2000; Piromallo & Faccenna 2004). We note that, for the time frame crucial for this tectonic reconstruction (Eocene), different velocity models converge towards the same solution (Savostin et al. 1986; Jolivet & Faccenna 2000; Rosenbaum et al. 2002; Capitanio & Goes 2006), which has been recently confirmed by new kinematic reconstructions (Cande & Stegman 2011).

The results are shown in Figure 8. Prior to 67 Ma, the convergence between Africa and Eurasia had a NE–SW trend, parallel to the East Tenda Shear Zone (Fig. 8a). In this scenario, the net convergence along the East Tenda Shear Zone was probably very minor, being dominated by a sinistral strike-slip component (Fig. 8c). Between c. 67 and c. 45 Ma, the motion changed sharply towards an east–west-striking convergence direction (Dewey et al. 1989; Jolivet & Faccenna 2000; Piromallo & Faccenna 2004). This significant kinematic change, well documented also in the recent kinematic model of Cande & Stegman (2011), probably had a profound influence on the tectonic evolution of the central Mediterranean and western Alps (Malusà et al. 2011). Decomposing the convergence vector into components parallel and perpendicular to the East Tenda Shear Zone, we expect a net convergence perpendicular to the East Tenda Shear Zone of about 80–90 km and a right lateral strike-slip component of the order of 0.40–50 km (Fig. 8c). From c. 45 to c. 30–35 Ma, the plate convergence was NNE–SSW directed, and hence parallel to the East Tenda Shear Zone, probably producing significant left-lateral deformation (Fig. 8b). At c. 30–35 Ma, the dynamics of the system again changed and the roll-back of the Apennines subduction system commenced. Rifting in the Provençal–Ligurian basin started during the latest Eocene–Early Oligocene (34–28 Ma) and ended in Aquitanian (21 Ma) (Séranne 1999). Subsequently, the central oceanic portion of the basin was generated between the late Aquitanian and late Burdigalian (21–16 Ma), associated with the counterclockwise rotation of the Corsica–Sardinia Block (Speranza et al. 2002) and the onset of the Tyrrhenian back-arc extension (Jolivet et al. 1998). The East Tenda Shear Zone therefore may have been active as a major thrust in the period from c. 67 to 40–45 Ma. It is expected to have been subsequently reactivated as an extensional shear zone at c. 30–20 Ma when the high-pressure core of the Alpine orogen in Corsica was finally exhumed during post-orogenic extension (Jolivet et al. 1990).

The Early Eocene timing of the Alpine peak metamorphism and the fabric-forming events in the East Tenda Shear Zone reconstructed in this study imply that net convergence in Corsica may have lasted slightly more than 20 Ma (between ca. 67 and 45–40 Ma; Early–Middle Eocene), and that a large part of the expected 80–90 km of shortening was mostly accommodated along the East Tenda Shear Zone to produce underthrusting of the Variscan basement to a minimum depth of c. 40 km (assuming an average density for the basement rocks of 2800 kg m−3 along a 30°-dipping thrust zone (Fig. 8c). This pulse of convergence was probably mostly accommodated along the former continent–ocean transition zone (Vitale Brovarone et al. 2011b) with final shear strain localization along the East Tenda Shear Zone. This process caused the compressional reactivation of the former continental passive margin, which resulted in overthrusting of the
subducted tracts of the Ligurian–Piedmontese Ocean onto the Variscan Corsica. The recent zircon U–Pb dating of eclogite metamorphism in continental-derived slivers embedded within the Schistes Lustrés nappe (Martin et al. 2011) suggests that convergence and related subduction metamorphism affected the Ligurian–Piedmontese oceanic up to Late Eocene time. This long-lasting compressional tectonism is also recorded by post-37Ma thrusting in the Alpine foreland of Corsica (Egal 1992; Brunet et al. 2000; Malasoma & Marroni 2007), which also suggests that East Tenda Shear Zone rocks were exhumed and entered brittle deformation environments at that time.

In the timespan relevant for this study (Eocene), correlation with the tectono-metamorphic evolution of the Western Alps may contribute to elucidate the sequence of deformation events along the Corsica–Europe active margin of the Alpine chain. In particular, two points deserve consideration. First, the main phase of exhumation of the Schistes Lustrés accretionary complex in the Western Alps (Agard et al. 2002) occurred concurrently with the Early Eocene climax of Alpine metamorphism in the Variscan basement of Corsica documented in this study. Second, as for Alpine Corsica (see Martin et al. 2011), the climax of subduction-zone metamorphism in the Western Alps occurred later, during the Middle–Late Eocene (from c. 45 to 35Ma; e.g. Rubatto & Hermann 2003; Meffan-Main et al. 2004; Di Vincenzo et al. 2006; Malasú et al. 2011), in a scenario there dominated by the continuous subduction of the European margin and collision with the Adria plate (see Schmid et al. 1996). A polyphase evolution can be thus envisaged: (1) the Alpine activation of the East Tenda Shear Zone within the Variscan basement of Corsica occurred synchronously with exhumation of the oceanic–derived Schistes Lustrés accretionary complex, and the East Tenda Shear Zone may be thus interpreted as the basal thrust of the early structured Schistes Lustrés accretionary complex; (2) shortly after achievement of the Alpine metamorphic climax (Middle–Late Eocene), exhumation of the high-pressure core of the orogen occurred; Corsica was disconnected from the Alpine system and incorporated in the back-arc domain of the Apennine subduction system, which accommodated the overall plate convergence at least from the Late Eocene onward (e.g. Facenna et al. 2001; Lustrino et al. 2009). This evolutionary scenario requires an along-strike space–time transition in the mode and regimes of oceanic subduction along the Alpine–Apennine junction (see, e.g. Vignaroli et al. 2008; Argnani 2010).

### Conclusion

The finding of a clinopyroxene–rutile-bearing shear zone within the East Tenda Shear Zone and definition of its P–T–t evolution provide new constraints on the metamorphic regimes and timing of the Alpine reworking of the Variscan crust in Corsica. We document an Early Eocene phase of orogenic construction that can be linked to the general scenario of plate convergence in the central Mediterranean during the Palaeogene. Evidence is provided for a polyphase evolution of the East Tenda Shear Zone, which was first activated as a major thrust to exhume the fossil Schistes Lustrés accretionary complex of the Western Alps during the Eocene and then reactivated as an extensional shear zone in Oligocene–Miocene times at the back of the eastward retreating Apennine subduction system.

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