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U-Pb dating of middle Eocene-middle Pleistocene multiple tectonic pulses in the Alpine foreland

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Abstract. Foreland fold-and-thrust belts record long-lived tectonic-sedimentary activity, from passive margin sedimentation, flexuring, and further involvement into wedge accretion ahead of an advancing orogen. Therefore, dating fault activity is fundamental for plate movement reconstruction, resource exploration, or earthquake hazard assessment. Here, we report U-Pb ages of syntectonic calcite mineralizations from four thrusts and three tear faults sampled, at the regional scale, across the Jura fold-and-thrust belt in the northwestern Alpine foreland (eastern France). Four regional tectonic phases are recognized in the middle Eocene-middle Pleistocene interval: (1) pre-orogenic faulting at 44.7 ± 2.6 and 48.4 ± 1.5 Ma associated to the uplift of the Alpine forebulge, (2) syn-orogenic thrusting at 11.4 ± 1.1, 10.6 ± 0.5, 9.7 ± 1.4, 9.6 ± 0.3, and 7.5 ± 1.1 Ma associated to possible in-sequence thrust propagation, and (3) syn-orogenic tear faulting at 10.5 ± 0.4, 9.1 ± 6.5, 7.3 ± 1.9, 5.7 ± 4.7, 4.8 ± 1.7, and at 0.7 ± 4.2 Ma including the reactivation of a pre-orogenic fault as tear fault at 3.9 ± 2.9 Ma. Previously unknown faulting events at 44.7 ± 2.6 and 48.4 ± 1.5 Ma predate by ~10 Ma the accepted late Eocene age for tectonic activity onset in the Alpine foreland. In addition, we dated the previously inferred strike-slip faults re-activation as tear fault. The U-Pb ages demonstrate the long-lived tectonic history at the plate boundary between European and African plates and that the deformation observed in the foreland is directly linked to continental collision.

1 Introduction

Foreland fold-and-thrust belts develop at the external edges of orogens and are characterized by a multiphase tectonic-sedimentary history including: pre-orogenic sedimentation, uplift at the peripheral bulge of the advancing orogen, progressively accelerating subsidence followed by syn-tectonic sedimentation, and accretion of the sedimentary cover into the foreland fold-and-thrust belt (Lacombe et al., 2007). Unraveling the timing of these tectonic events is fundamental for plate kinematic modelling, natural resource exploration, paleoseismicity, and topography evolution studies (Vergés et al., 1992; Craig and Warvakai, 2009). However, deciphering the different tectonic phases is complicated by the overprinting of inherited structures by progressively younger tectonic events.

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This issue was initially addressed by dating syn-tectonic sediments and, more recently, through dating of fault activity with K-Ar, 40Ar/39Ar, and U-Pb methods (Van der Pluijm et al., 2009; Vrolijk et al., 2018). In particular, calcite U-Pb geochronology (Roberts et al., 2020) is the unique method for dating syntectonic calcite mineralizations developed in carbonate-hosted faults. This technique has been applied for dating single carbonate faults in extensional, strike-slip, and compressional settings (Goodfellow et al., 2017; Nuriel et al., 2017; Hansman et al., 2018; Smeraglia et al., 2019; Carminati et al., 2020). So far, the dating of multiple carbonate faults at the regional scale across a foreland fold-and-thrust belt remains rare (Beaudoin et al., 2018; Looser et al., 2020).

To fill this gap, we dated syntectonic calcite mineralizations from four thrusts and three tear faults sampled across the Jura fold-and-thrust belt (Jura FTB, eastern France, Fig. 1) by LA-ICP-MS U-Pb dating. We dated four tectonic phases having occurred in the middle Eocene-Late Miocene period, thus demonstrating a long-lived polyphase tectonic history of the Alpine chain-foreland system along the convergent boundary between European and African plates. We point out that dating fault activity in foreland fold-and-thrust belts can record the far field tectonic effects of continental collision, with direct implication in understanding the late stage evolution of orogens.

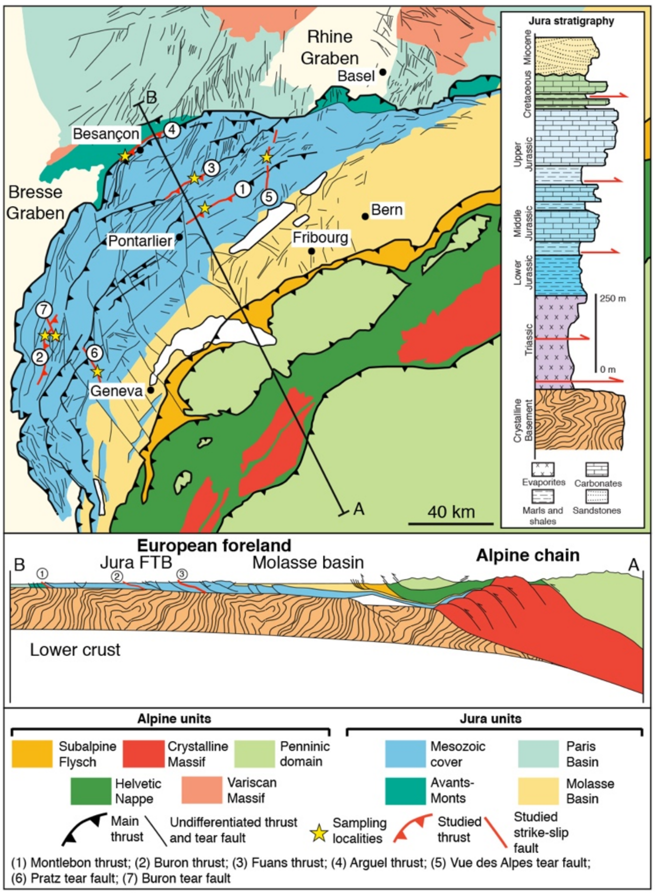

Figure 1: Geological map of the northwestern Alpine foreland and surrounding areas and stratigraphic column of the main lithological units of the Jura area. Modified from Rime et al. (2019).

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2 Tectonic setting

The Jura FTB is located in the foreland of the Western Alps and formed by the ongoing continental collision of the Eurasian plate with the African plate (Sommaruga, 1997; Bellahsen et al., 2014) (Fig. 1). Shortening affected the ~3 km-thick Triassic-late Miocene sedimentary succession deposited in the European passive margin above the Hercynian crystalline basement13 (Fig. 1). The sedimentary succession starts with Triassic shales and evaporites overlain by Jurassic-Cretaceous shales, marls, and limestones (Fig. 1). Following a Late Cretaceous-Eocene regional unconformity, Oligocene-Miocene shallow marine to continental clastic deposits of the Molasse Basin were deposited above Cretaceous limestones (Fig. 1).

The post-Mesozoic tectonic history of the Jura area is assumed to have started in the middle Eocene with N-S shortening related to the far field effect of the "Pyrenean orogeny" generating strike-slip faults (Bergerat, 1987). However, no absolute ages of this tectonic phase were available. Subsequent normal faulting during the Oligocene in the western and northern parts of the Jura area based on calcite U-Pb ages is related to the opening of the Rhine Graben and associated crustal extension (Mazurek et al., 2018).

Biostratigraphic dating of syn-orogenic deposits, geomorphological observations, interpretation of seismic reflection profiles, and syntectonic calcite U-Pb ages of fault activity in the eastern tip of Jura FTB indicate that orogenic shortening started ~14.5 Ma ago (Langhian times) at the latest (Looser et al., 2020) and is still active (Becker, 2000; Madritsch et al., 2008). Shortening was accomodated by N to NE-verging and NE-SW-striking thrusts and by NW-SE to N-S trending sinistral tear faults (Sommaruga, 1997) (Fig. 1). Field cross-cutting relationships and U-Pb ages of syntectonic calcite mineralizations show that tear faults, which are seismogenic (Thouvenot et al., 1998), occurred synchronously or posteriously to thrusting (Sommaruga, 1997; Madritsch et al., 2008; Looser et al., 2020). Several authors suggested that pre-orogenic strike-slip and normal faults were reactivated in early Pliocene, respectively as tear and transpressional faults (Madritsch et al., 2008; Homberg et al., 1997; Ustaszewski and Schmid, 2006). Overall, no direct dating of this fault re-activation is available.

3 Methods

The following methods were used: (1) geological field mapping and fault rock sampling from four major thrusts (From SE to NW: Montlebon, Buron, Fuans, and Arguel thrusts) and three NNE-SSW tear faults (Vue des Alpes, Pratz, and Buron) moving from the internal (most deformed) to the external (less deformed) parts of the Jura FTB (Fig. 1); (2) microstructural analyses with optical microscope and cathodoluminescence to unravel different phases of calcite precipitation; (3) calcite U-Pb LA-ICP-MS dating on veins and slickenfibers to date fault activity. Analytical details are described in the Supplementary Material.

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4 Results

4.1 Structural and microstructural observations

The Montlebon, Buron, Fuans, and Arguel thrusts are SW-NE striking and NW-verging thrusts (Madritsch et al., 2008; Rime et al., 2019; Smeraglia et al., 2020) (Fig. 2a-c and 3a). The Vue des Alpes, Pratz, and Buron tear faults are NNE-SSW strike-slip fault with sinistral displacement (Sommaruga, 1997) (Fig. 2d and 3b,c). These faults cut through Middle-Upper Jurassic and Lower Cretaceous limestones. The fault core zones are characterized by foliated fault rocks cut by sharp fault planes (Fig. 1a-d). Breccia lenses are developed in the Buron thrust core (Fig. 3d). Calcite mineralizations in extensional veins (Buron, Arguel, Montlebon, Vue des Alpes, and Pratz) and in shear veins (Fuans, Vue des Alpes, and Pratz) were sampled.

Extensional veins occur in limestone fragments of foliated fault rocks (Fig. 2e,g) and in clasts from breccias (Figs. 2f and 3g). In limestone fragments of foliated fault rocks, extensional veins are oriented perpendicularly to stylolites (Fig. 2e,g), which occur along S- and C-planes. Extensional veins in clasts from breccias show a crackle-like texture and mutually cross-cutting relationships (Fig. 2f). Extensional veins are filled by blocky to elongated-blocky calcite crystals and show syntaxial growth (Figs. 2i-k and 3g).

The fault planes are coated by slickenfibers, which develop on the surface of shear veins (Figs. 2d,h and 3e,f). At the microscale, shear veins occur in dilational jogs along shear planes (Fig. 2h) and consist of multiple layers bound by sharp shear planes filled by fibrous to blocky calcite crystals (Figs. 2l and 3h,i). Fibrous crystals are oriented parallel to shear planes (Fig. 2l).

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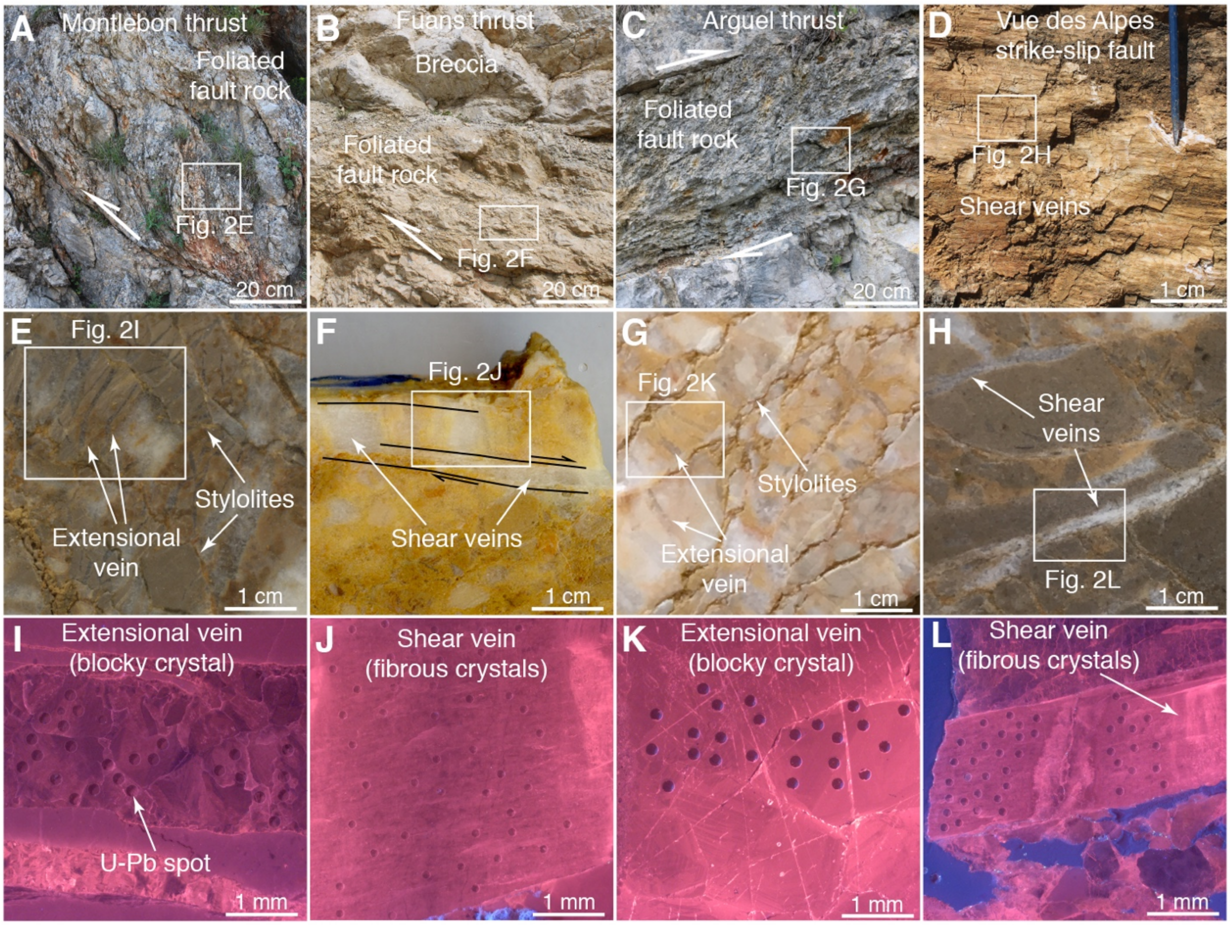

95 **Figure 2: Foliated fault rocks in the fault core of the Montlebon thrust (a), Arguel thrust (b), and (c) Fuans thrust. (d) Detail of minor fault plane along the Vue des Alpes strike-slip fault showing calcite slickenfibers. (e) Hand sample of foliated fault rock from the Arguel thrust showing host rock sigmoids bounded by stylolites and extensional veins perpendicular to stylolites. (f) Hand sample of foliated fault rock from the Arguel thrust showing host rock sigmoids bounded by stylolites and extensional veins perpendicular to stylolites. (g) Hand sample of breccia clast from the Fuans thrust showing extensional veins with crackle-like texture. (h) Hand**
100 **sample from a minor fault plane along the Vue des Alpes strike-slip fault showing shear veins developed along dissolution planes. (i-l) Cathodoluminescence microphotographs of thin sections showing extensional and shear veins from the studied faults with ablation craters of the U-Pb analyses.**

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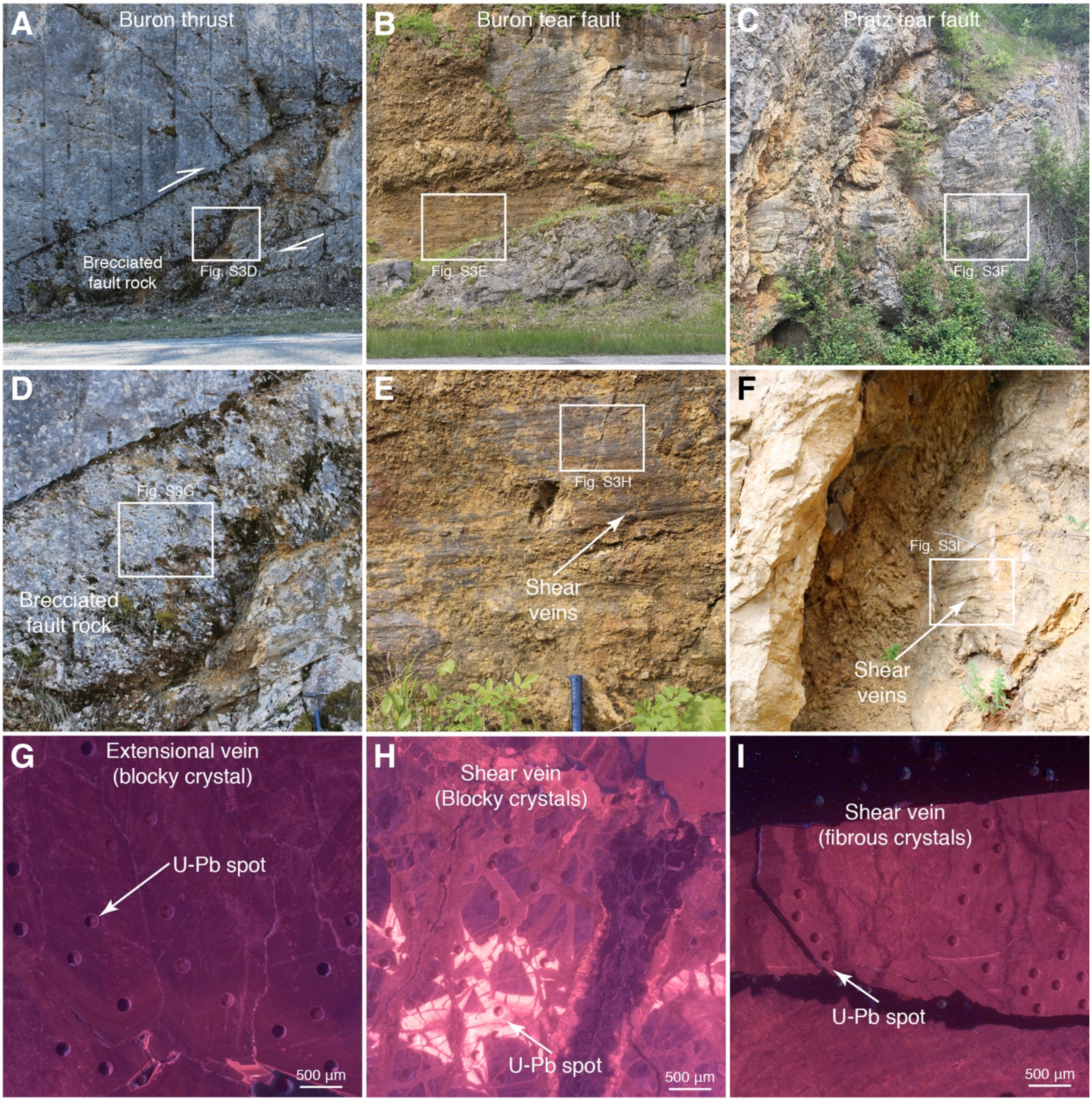

105 **Figure 3: (a) Buron thrust. (b) Buron tear fault. (c) Pratz tear fault. (d) Brecciated fault rocks in the fault core of the Buron thrust. (e) Brecciated fault rocks cut by sharp fault planes in the fault core of the Buron tear fault. (f) Foliated fault rock cut by sharp fault planes in the fault core of the Pratz tear fault. (g-i) Cathodoluminescence microphotographs of thin sections showing extensional and shear veins from the studied faults with ablation craters of the U-Pb analyses.**

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4.2 U-Pb dating

A total of 14 reliable lower intercept ages (see Data Repository) are reported with uncertainties at 2σ absolute including counting statistics uncertainties, uncertainty of the primary reference material and inter-session variations. The U-Pb ages indicate different phases of tectonic activity and related calcite precipitation in the middle Eocene to late Miocene period and also multiple precipitation ages along the same fault (Supplementary Information Table 1 and Figs. 1 and 2).

An extensional vein from the Arguel thrust shows a Tortonian-Messinian age of 7.5 ± 1.1 Ma. An extensional vein from the Buron thrust shows a Tortonian age of 10.6 ± 0.5 Ma. Two shear veins from the Fuans thrust yield Tortonian ages of 9.6 ± 0.3 and 9.7 ± 1.4 Ma, respectively. An extensional vein from the Montlebon thrust shows a Serravallian age of 11.4 ± 1.1 Ma. Along the Vue des Alpes tear fault, two shear veins yield Ypresian-Lutetian ages of 44.7 ± 2.6 and 48.4 ± 1.5 Ma, while an extensional vein shows a Pliocene age of 3.9 ± 2.9 Ma. An extensional vein from the Buron tear fault shows a Messinian age of 5.7 ± 4.7 Ma. Three extensional veins from the Pratz tear show Tortonian-Messinian ages of 10.5 ± 0.4, 9.1 ± 6.5, and 7.3 ± 1.9 Ma, while two shear veins show younger ages of 4.8 ± 1.7 and of 0.7 ± 4.5 Ma.

5 Discussion and conclusions

Shear veins (i.e. slickenfibers) on striated fault planes and crackle-like texture of extensional veins are clear evidence of tectonic slip along faults (Fig. 2j-l). In particular, blocky and fibrous crystals indicate respectively fast and slow calcite precipitation in dilation sites associated with fault slip, with calcite crystal precipitation having occurred during syn- to early post-slip fluid influx in newly formed dilational sites (Gratier and Gamond, 1990; Fagereng et al., 2010; Woodcock et al., 2014). Extensional veins oriented perpendicular to stylolites (Fig. 2e,g) are linked to syn-thrusting shortening (Gratier et al., 2013). The studied veins are therefore interpreted as the product of tectonic fault slip and their U-Pb ages are considered as representative of faulting activity.

We recognize four regional tectonic phases between middle Eocene and late Miocene times (Fig. 4). These phases are linked to the long-lived tectonic activity of the Alpine chain-foreland evolution. The oldest tectonic phase is recorded by two horizontal shear veins dated at 44.7 ± 2.6 and 48.4 ± 1.5 Ma in Ypresian-Lutetian times (middle Eocene) along the Vue des Alpes strike-slip fault (Fig. 4). These ages are ~10 Ma older than the onset of the extensional tectonic activity in Priabonian (late Eocene) related to Rhine Graben opening (Sissingh, 1998). The strike-slip faulting in Eocene times is consistent with fault-slip data of Homberg et al. (1997). We interpret the Ypresian-Lutetian tectonic activity as related to the late Mesozoic-Eocene forebulge uplift and shortening in the European plate foreland due to the advancing Alpine orogen (Mazurek et al., 2006; Timar-Geng et al., 2006) (Fig. 5a). Our interpretation is in contrast with previous studies suggesting that middle Eocene strike-slip faulting in the Jura area was related to the far-field effect of the Pyrenean compression (Bergerat, 1987; Homberg et al., 2002). This inference was drawn only through analogies with coherent fault-slip data in Southern France. However, we suggest that the Pyrenean orogen, located ~650 km in the SW, was likely too distant to have any effect on the Jura area.

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Although age uncertainties do not allow a precise distinction beyond doubt, the Jura FTB imbrication seems to have occurred by in-sequence thrusting in the Serravallian-Messinian interval as testified by progressively younger ages, moving from the inner (SE) toward the external (NW) part, of 11.4 ± 1.1, 10.6 ± 0.5, 9.7 ± 1.4 and 9.6 ± 0.3 on the same thrust, and 7.5 ± 1.1 Ma, respectively, measured in the Montlebon, Buron, Fuans, and Arguel thrusts (Figs. 4 and 5b). These ages are consistent with the time interval of ~14.5-3.3 Ma suggested for thrusting activity from biostratigraphic dating of syn- to post-tectonic sediments (Becker, 2000) and from calcite U-Pb ages of fault activity in the eastern Jura FTB (Looser et al., 2020) (Fig. 4).
The Buron thrust, active at 10.6 ± 0.5 Ma, was cross-cut by the Buron tear fault ~5 Ma later, at 5.7 ± 4.7 Ma (Figs. 4 and 5c). The Pratz tear fault was active at 10.5 ± 0.4, 9.1 ± 6.5, and 7.3 ± 1.9 Ma, indicating tear faulting generation during coeval thrust propagation, and further late-orogenic re-activations at 4.8 ± 1.7 and at 0.72 ± 4.5 Ma (Figs. 4 and 5b). These data indicate that tear faulting occurred during syn- to late-orogenic times (Fig. 5b,c), including very recent activity in middle Pleistocene. In addition, a late-orogenic phase is recorded by an extensional vein from the Vue des Alpes strike-slip fault showing a Lower Pliocene age of 3.9 ± 2.9 Ma (Fig. 4), consistent with late orogenic deformation between 4.2 and 2.9 Ma in the frontal part of the Jura FTB (Madritsch et al., 2008). This age is ~40 Ma younger than the middle Eocene ages (44.7 ± 2.6 and 48.4 ± 1.5 Ma) measured on the same fault, indicating the reactivation of the Vue des Alpes strike-slip fault as a tear fault during Jura shortening. This is consistent with field cross-cutting relationships indicating re-activation of pre-existing strike-slip faults as tear faults (Homberg et al., 1997). However, for the first time we directly dated such fault reactivation and relate it to a stress change from pure compression to strike-slip state of stress coupled with the occurrence of an inherited strike-slip fault favorably oriented with respect to the regional stress field. This stress change associated with tear fault development can be related to progressive fold-and-thrust belt thickening and low erosion, initiating only after ~4.5 Ma (Looser et al., 2020) and leading to an increase in the maximum vertical stress (sigma 3) and a switch between sigma 3 and 2. Shortening is still active in the Jura FTB and tear faults (also re-activated tear faults) are seismogenic (Thouvenot et al., 1998). In particular, the 0.72 ± 4.5 Ma age calculated on the Pratz tear fault suggests future U-Pb and U-Th dating of tear faults in order to better constrains the early Pliocene-onward earthquake recurrence time.
The presented tectonic reconstruction depicts a stable evolution of the Jura FTB wedge by possible in-sequence thrusting consistently with thrust imbrication above a low-friction décollement consisting of evaporites (Fig. 5a-c). Contrarily, out-of-sequence thrusting occurred as late as in Messinian-early Pliocene times in the Molasse Basin (Von Hagke et al., 2012, 2014) and in the Alps (Bellahsen et al., 2014). In the Jura FTB no out-of sequence thrusting has been dated so far (Looser et al., 2020), suggesting low erosion rates and a stable topographic evolution of the chain. Higher erosion rate would have led to out-of sequence thrusting to balance the critical taper and topographic profile.

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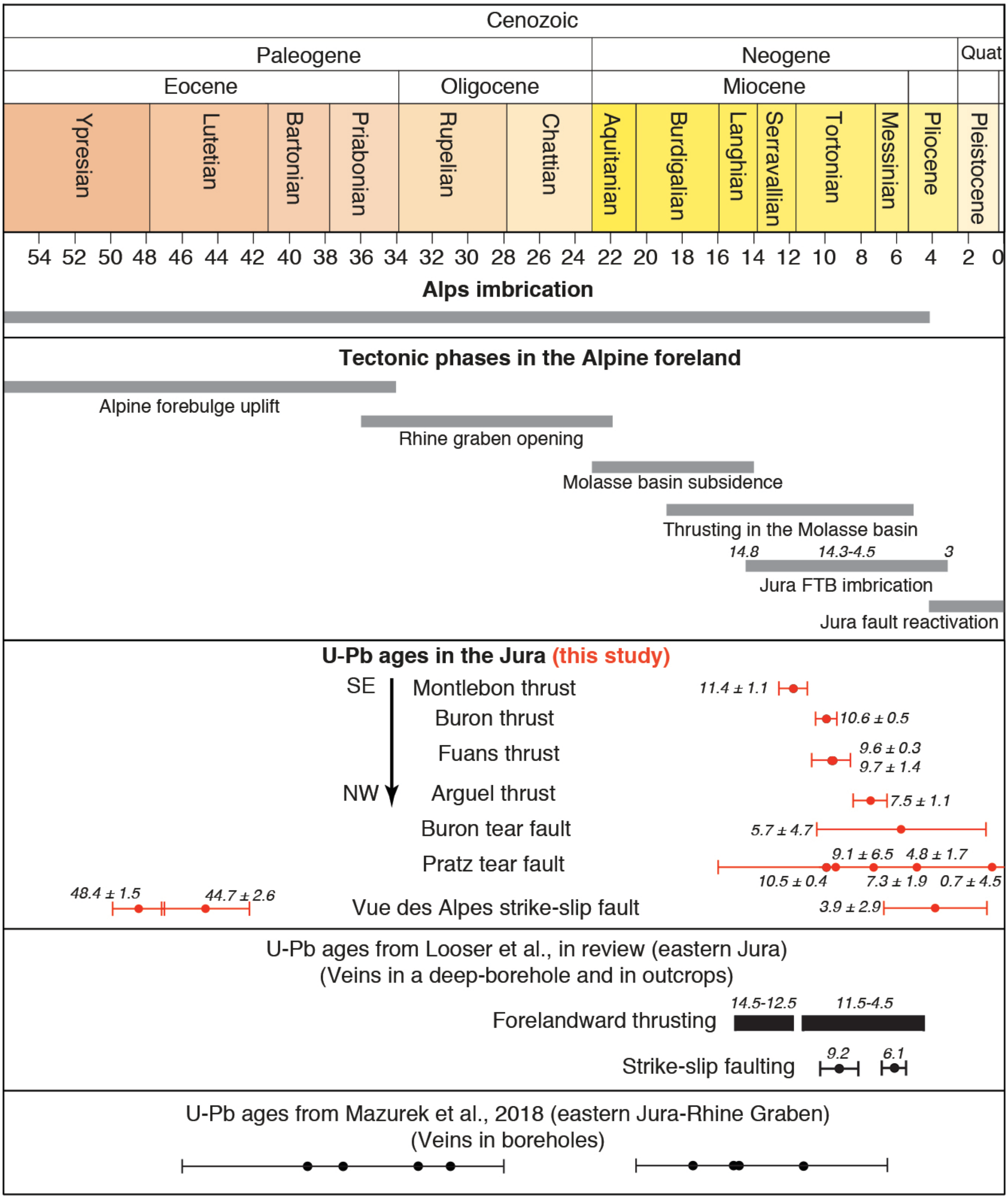

Figure 4: Main tectonic phases in the Alps and in the Alpine foreland. Age constraints shown as grey bars are from Burkhard and Sommaruga (1998), Ustaszewski et al. (2006), Madritsch et al. (2008), Bellahsen et al. (2014), and Von Hagke et al. (2014). For calcite U-Pb data, all uncertainties are represented as 2σ.

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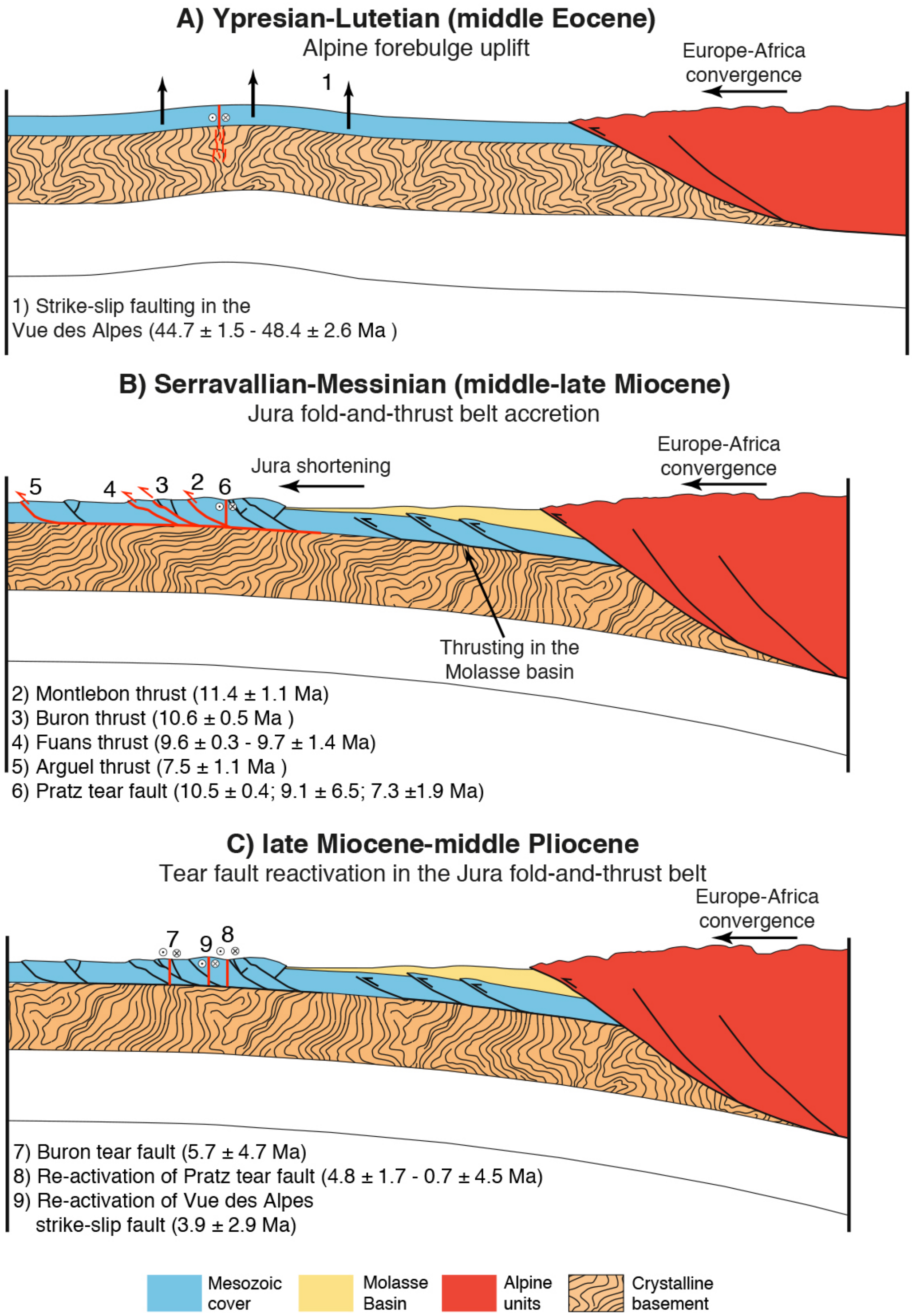

175 **Figure 5 (a-d) Schematic reconstruction of the main tectonic phases dated in the Jura area in the regional context of the Alpine chain-foreland system evolution.**

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