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

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Abstract. Foreland fold-and-thrust belts record long-lived tectono-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). Three regional tectonic phases are recognized in the middle Eocene-Pliocene interval: (1) pre-orogenic faulting at 48.4 ± 1.5 and 44.7 ± 2.6 Ma associated to the far-field effect of the Alpine or Pyrenean compression, (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 the formation of the Jura fold-and-thrust belt with possible in-sequence thrust propagation, and (3) syn-orogenic tear faulting at 10.5 ± 0.4, 9.1 ± 6.5, 5.7 ± 4.7, and at 4.8 ± 1.7 Ma including the reactivation of a pre-orogenic fault at 3.9 ± 2.9 Ma. Previously unknown faulting events at 48.4 ± 1.5 and 44.7 ± 2.6 Ma predate by ~10 Ma the reported late Eocene age for tectonic activity onset in the Alpine

foreland. In addition, we date the previously inferred re-activation of pre-orogenic strike-slip faults as tear faults during Jura imbrication. The U-Pb ages document a minimal time frame for the evolution of the Jura FTB wedge by possible in-sequence thrust imbrication above the low-friction basal décollement consisting of evaporites.

1. Introduction

Foreland fold-and-thrust belts develop at the external edges of orogens and are characterized by a multiphase tectono-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.

This issue is addressed by dating syn-tectonic sediments and, more recently, better constrained through dating of fault activity with K-Ar, $^{40}Ar/^{39}Ar$, and U-Pb and U-Th methods (Van der Pluijm et al., 2009; Vrolijk et al., 2018). In particular, calcite U-Pb and U-Th geochronology (Roberts et al., 2020) is the unique method for dating syntectonic calcite mineralizations. This technique has been applied for dating single 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 faults at the regional scale across a foreland fold-and-thrust belt remains rare (Beaudoin et al., 2018; Looser et al., 2021).

In this study, 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 laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) U-Pb dating. We reconstructed three tectonic phases having occurred in the middle Eocene-Pliocene period, documenting a long-lived polyphase tectonic history of the northwestern Alpine foreland system along the convergent boundary between European and African plates.

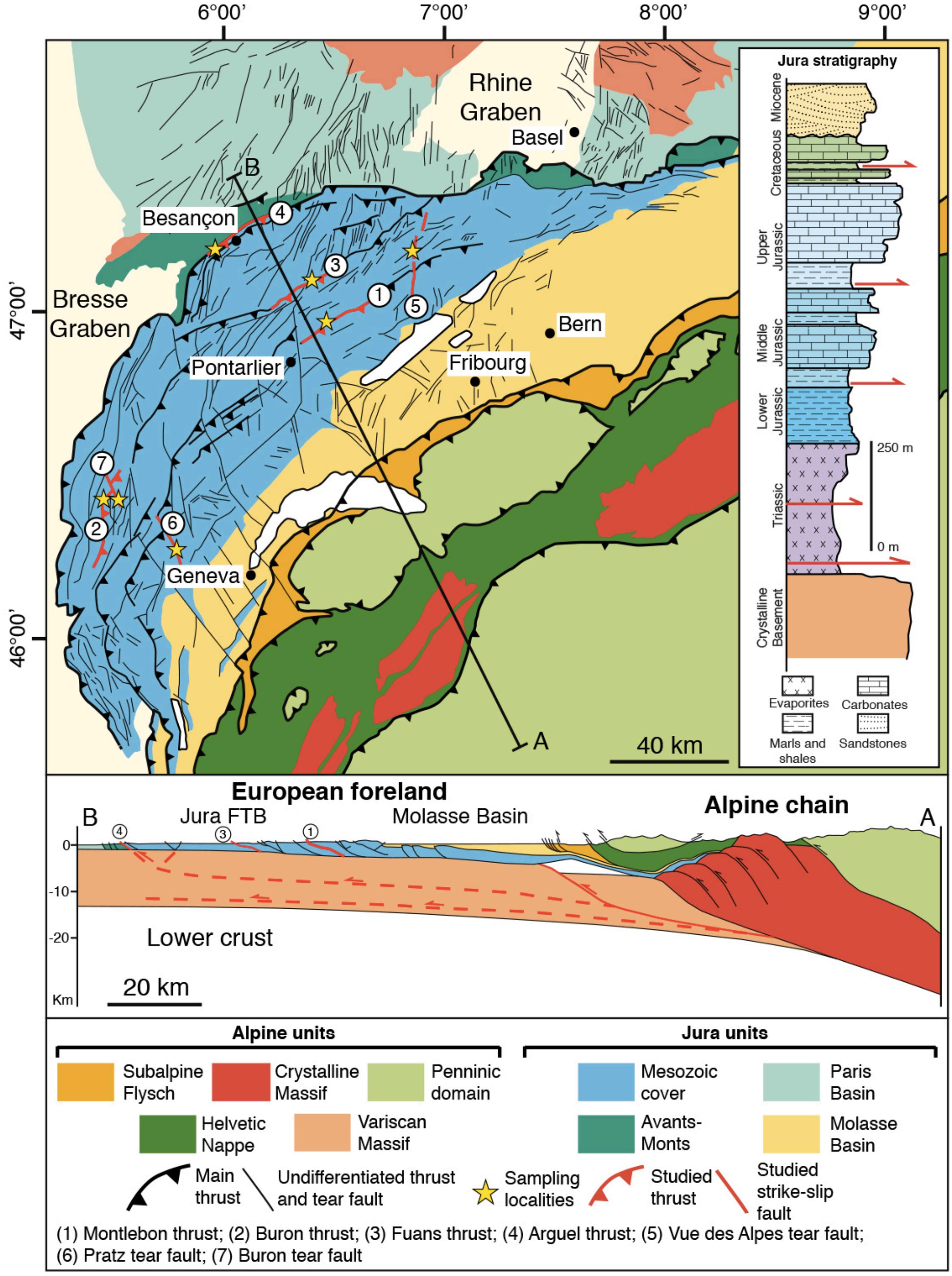

Figure 1. Geological map of the northwestern Alpine foreland and surrounding areas and stratigraphic column of the main lithological units of the Jura area. Map modified from Rime et al. (2019), cross-section modified from Von Hagke et al., 2014.

2. Tectonic setting

Located in the Western Alps foreland, the Jura FTB formed by the ongoing continental collision of the Eurasian plate with the African plate (Sommaruga, 1997; Mosar, 1999; Lacombe and Mouthereau, 2002; Affolter and Gratier 2004; Bellahsen et al., 2014) (Fig. 1). Shortening affected the Triassic-late Miocene sedimentary succession deposited on the European passive margin above the Hercynian crystalline basement and caused brittle-ductile deformation at several levels (Fig. 1) (Philippe et al., 1996; Homberg et al., 2002; Ustaszewski and Schmid, 2006). The sedimentary succession starts with Triassic shales and evaporites overlain by Jurassic-Cretaceous shales, marls, and limestones (Fig. 1) (Sommaruga et al., 2017). 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 are available. Based on structural analyses and calcite U-Pb ages, three phases of normal faulting during the Late Eocene, Oligocene, and Miocene in the distal parts of the Molasse Basin in northern Switzerland and in the Jura area have been documented (Lacombe et al., 1993; Homberg et al., 2002; Mazurek et al., 2018; Radaideh and Mosar, 2021). Normal faulting during the Late Eocene-Oligocene is associated to crustal extension due to the opening of the Rhine Graben (Lacombe et al., 1993; Homberg et al., 2002; Mazurek et al., 2018; Radaideh and Mosar, 2021) or to the coeval onset of Alpine collision (Merle and Michon, 2001), while normal faulting during the middle Miocene has been related to crustal tilting associated to uplift of the Black Forest Highlands and subsidence of the northern part of the Molasse Basin (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., 2021 and references therein) and is still active (Mosar, 1999; Becker, 2000;

Lacombe and Mouthereau, 2002; 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). The main décollement level of the thrust system developed along Triassic evaporites (Jordan, 1992; Pfiffner, 2014; Gruber, 2017; Sommaruga et al., 2017). Therefore, there is a common agreement in considering the Jura FTB mainly as the product of thin-skinned tectonics (Sommaruga, 1997). However, thick-skinned tectonics occurred in the late stage of deformation, mostly in the external part (Lacombe and Mouthereau, 2002; Ustaszewski and Schmid, 2006, 2007; Madritsch et al., 2008; Lacombe and Bellahsen, 2016).

Field cross-cutting relationships and U-Pb ages of syntectonic calcite mineralizations show that tear faults were synchronously active with thrusting and folding (Sommaruga, 1997; Looser et al., 2021) and their movement continued after thrusting. In fact, in some cases, tear faults are still seismogenic (Thouvenot et al., 1998). 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, direct dating of this fault reactivation is so far not available.

3. Methods

The following methods were used: (1) field structural analyses and vein/slickenfiber 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). In particular, we measured the orientation of sampled veins and the rake of sampled slickenfibers in order to combine U-Pb ages from veins and slickenfibers with structural measurements; (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. In most cases, the U-Pb analyses were performed on calcite crystals showing a homogenous color or undisturbed growth-zoning under cathodoluminescence light, indicating no open-system alteration after calcite precipitation by late fluid infiltration and/or recrystallization (Figs. S1-S3). Analytical details are described in the Supplementary Material.

4. Results

4.1 Structural and microstructural observations

The Montlebon, Buron, Fuans, and Arguel thrusts are NNE-SSW- to SW-NE striking and N- to NW-verging thrusts (Madritsch et al., 2008; Rime et al., 2019; Smeraglia et al., 2020) (Fig. 2a-d). More precisely, the Montlebon thrust is characterized by E to ESE-dipping (30-90°) thrust planes with slickenfibers showing left-lateral transpressional movements with N to NNW tectonic transport directions (Fig. 2a). The Buron thrust is characterized by E to SE-dipping (20°-30°) thrust planes with slickenfibers showing left-lateral transpressional movements with NW tectonic transport directions (Fig. 2b). The Fuans thrust is characterized by E to SE-dipping (20°-40°) thrust planes with slickenfibers showing left-lateral transpressional movements with NNW to NW tectonic transport directions (Fig. 2c). The Arguel thrust is characterized by S-dipping (10-30°) thrust planes with slickenfibers showing right-lateral transpressional movements with NNW tectonic transport directions (Fig. 2d).

The subvertical Vue des Alpes, Pratz, and Buron tear faults show sinistral strike-slip displacements (Sommaruga, 1997) (Fig. 2de-g). More precisely, the Vue des Alpes strike-slip fault is characterized by NE-SW-striking subvertical fault planes with slickenfibers showing sinistral movements and associated NW-SE-striking subvertical fault planes with slickenfibers showing dextral movements (Fig. 2e). Both the Pratz and Buron strike-slip faults are characterized by NE-SW-striking subvertical fault planes with slickenfibers showing sinistral movements (Fig. 2f-g).

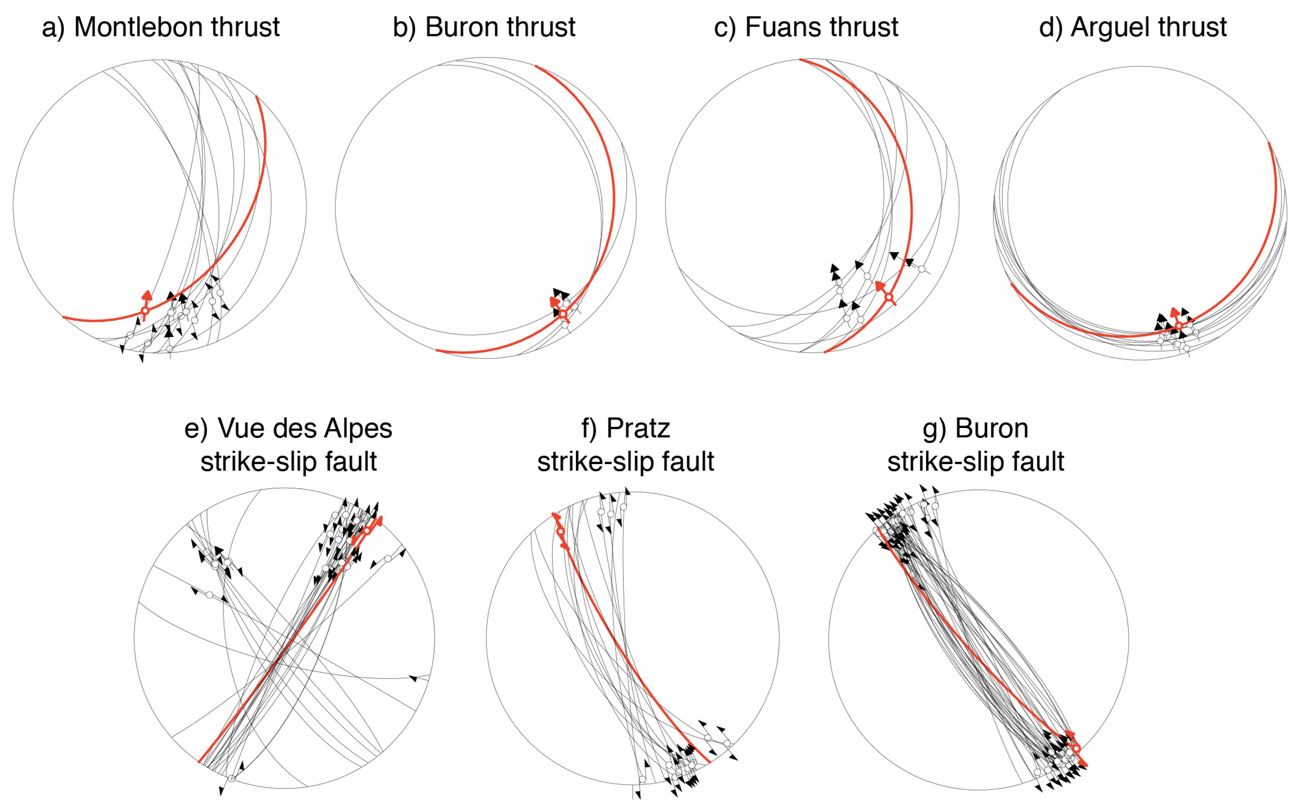

Figure 2. Lower Schmidt hemisphere projection of fault-slip data and slip vectors for thrust and strike-slip faults. Dated faults in red. **(a)** Montlebon thrust. **(b)** Buron thrust. **(c)** Fuans thrust. **(d)** Arguel thrust. **(e)** Vue des Alpes strike-slip fault. **(f)** Pratz strike-slip fault. **(g)** Buron strike-slip fault-

Both thrusts and strike-slip 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. 3a-d). Breccia lenses are developed in the Buron thrust core (Fig. 4d). Calcite mineralizations in extensional veins (Buron, Arguel, Montlebon, Vue des Alpes, and Pratz) and in slickenfibers (Fuans, Vue des Alpes, and Pratz) were sampled.

Extensional veins occur in limestone fragments of foliated fault rocks (Fig. 3e,g) and in clasts from breccias (Figs. 3f and 4g). In limestone fragments of foliated fault rocks, extensional veins are oriented perpendicularly to stylolites (Fig. 3e,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. 3f). Extensional veins are filled by blocky to elongated-blocky calcite crystals and show syntaxial growth (Figs. 3i-k, 4g, S1a-d, S2a,b,g,h, S3a-h).

The fault planes are coated by slickenfibers (Figs. 3d,h and 4e,f). At the microscale, slickenfibers occur in dilational jogs along shear planes (Fig. 3h) and are filled by fibrous calcite crystals bounded by sharp shear planes (Figs. 3j, 4i, S1e-h, and S2c-f) and/or by blocky calcite crystals (Figs. 3l and 4h). Fibrous crystals are oriented parallel to shear planes.

Most of the studied veins and slickenfibers show homogeneous cathodoluminescence colors, ranging from bright to dull red, and/or show cathodoluminescence zoning on the same crystal (Figs. 3i-l, 4g-i, S1a,c,e,g, S2a,c,e,g, and S3a,c,e,g). In places, slickenfibers and extensional veins are cross-cut by extensional veins showing black to dull red luminescence colors (Figs. S1e-h, S2c-f, and S3a,b,g,h)

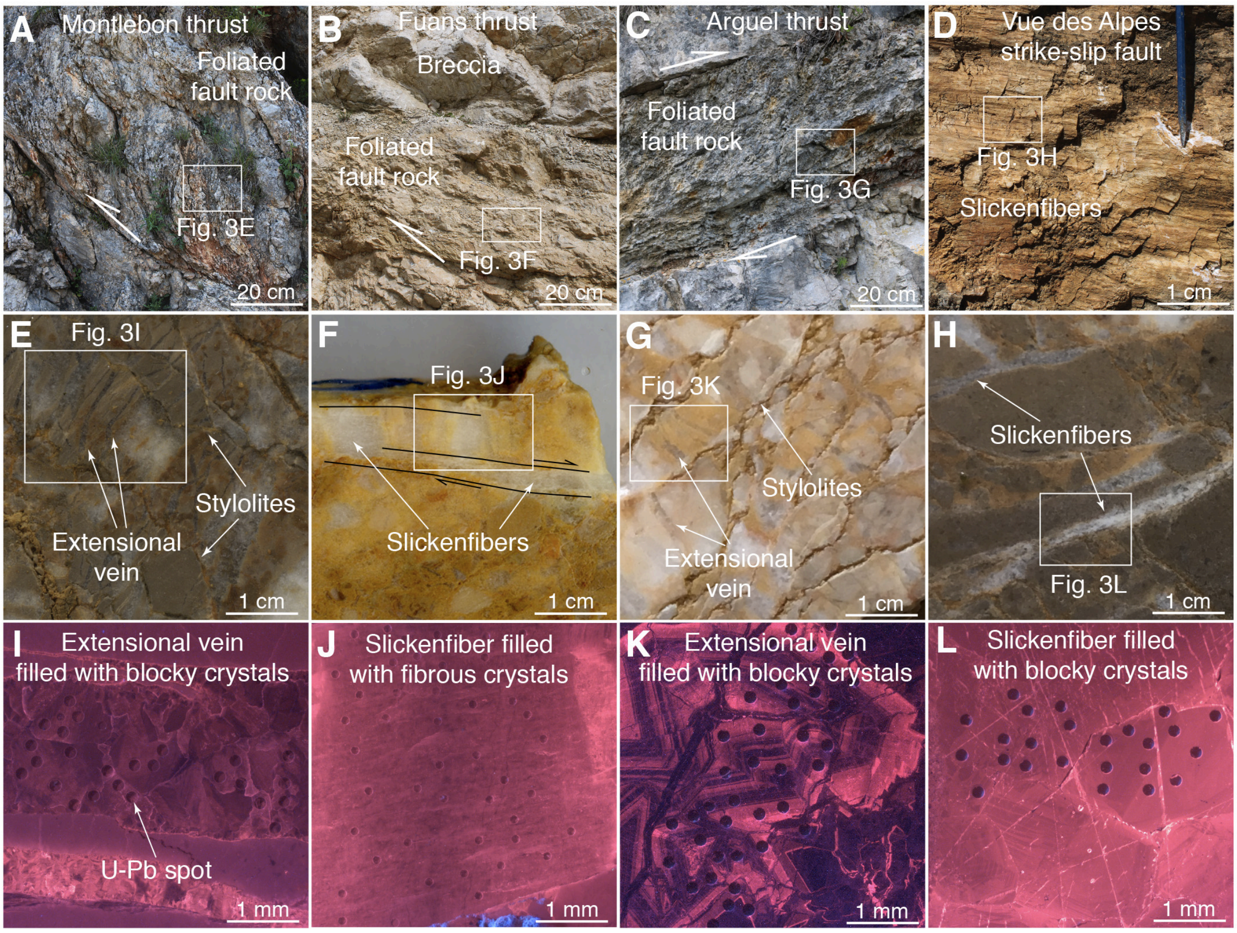

Figure 3. Foliated fault rocks in the fault core of the Montlebon thrust **(a)**, Arguel thrust **(b)**, and **(c)** Fuans thrust. **(d)** Detail of minor fault plane along the Vue des Alpes strike-slip fault showing calcite slickenfibers. **(e)** Hand sample from the Montlebon thrust showing host rock sigmoids bounded by stylolites and extensional veins perpendicular to stylolites. **(f)** Hand sample from the Fuans thrust showing host rock sigmoids bounded by stylolites and extensional veins

perpendicular to stylolites. **(g)** Hand sample from the Arguel thrust showing extensional veins with crackle-like texture. **(h)** Hand sample from a minor fault plane along the Vue des Alpes strike-slip fault showing slickenfibers developed along dissolution planes. **(i-l)** Cathodoluminescence microphotographs of thin sections showing extensional veins and slickenfibers from the studied faults with ablation craters of the U-Pb analyses.

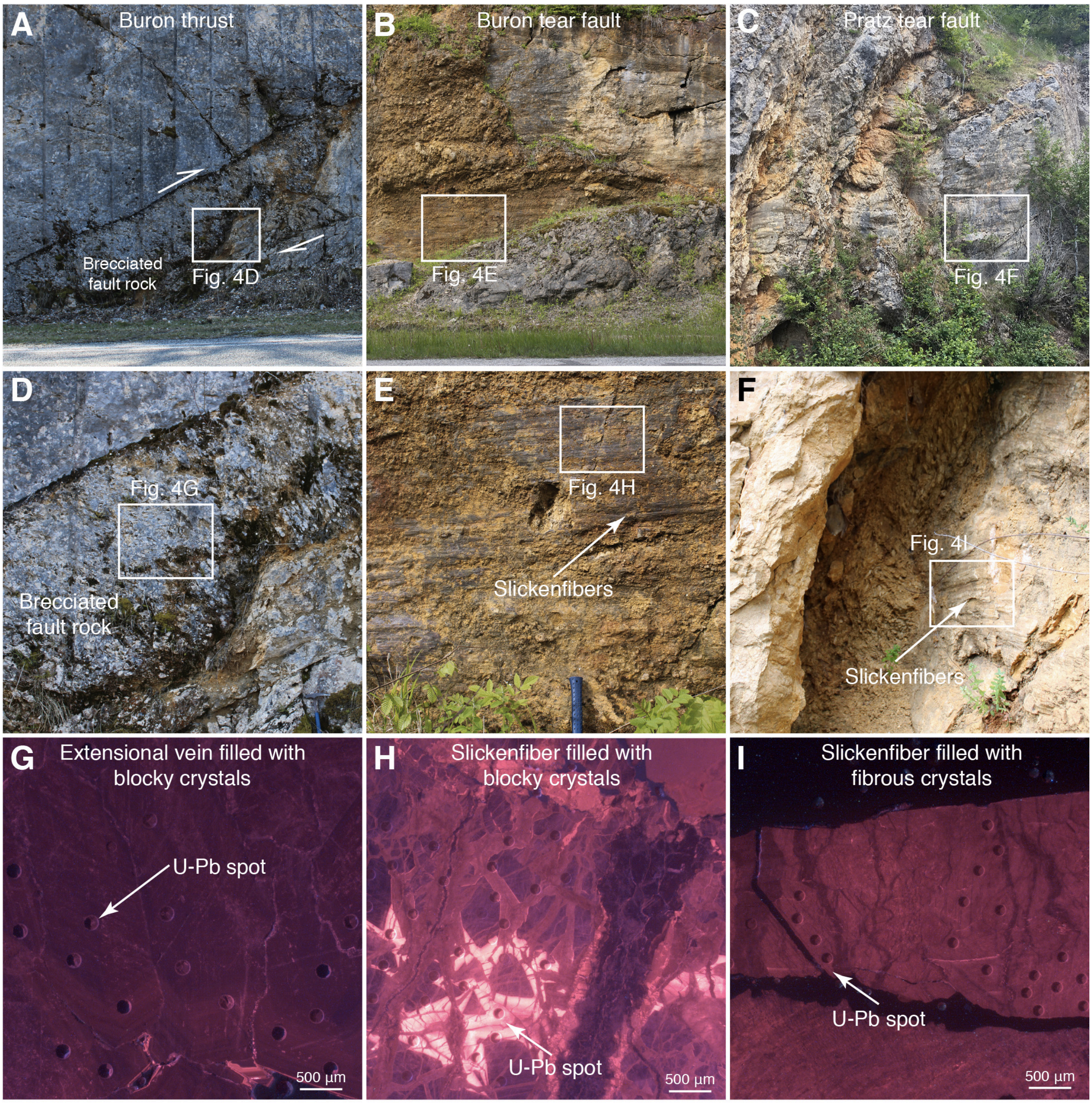

Figure 4. (a) Buron thrust. **(b)** Buron tear fault. **(c)** Pratz tear fault. **(d)** Brecciated fault rocks in the fault core of the Buron thrust. **(e)** Brecciated fault rocks cut by sharp fault planes in the fault core of the Buron tear fault. **(f)** Foliated fault rock cut by sharp fault planes in the fault core of the Pratz tear fault. **(g-i)** Cathodoluminescence microphotographs of

thin sections showing extensional veins and slickenfibers from the studied faults with ablation craters of the U-Pb analyses.

4. 2 U-Pb dating

A total of 12 reliable lower intercept ages (Figs. 5 and 6) out of 19 analyses (rejected age data is presented in Fig. S4) are reported with uncertainties at 2σ absolute including counting statistics uncertainties, uncertainty of the primary reference material and inter-session variations (Guillong et al., 2020). The U-Pb ages indicate different phases of tectonic activity and related calcite precipitation in the middle Eocene to Pliocene period and also multiple precipitation ages along the same fault (Supplementary Information Table 1).

An extensional vein from the Montlebon thrust shows a Serravallian age of 11.4 ± 1.1 Ma (Fig. 5a). An extensional vein from the Buron thrust shows a Tortonian age of 10.6 ± 0.5 Ma (Fig. 5b). Two slickenfibers from the Fuans thrust yield Tortonian ages indistinguishable from each other of 9.7 ± 1.4 Ma and 9.6 ± 0.3, respectively (Fig. 5c,d). An extensional vein from the Arguel thrust shows a Tortonian-Messinian age of 7.5 ± 1.1 Ma (Fig. 5e). Along the Vue des Alpes strike-slip fault, two slickenfibers yield Ypresian-Lutetian ages of 44.7 ± 2.6 and 48.4 ± 1.5 Ma (Fig. 6a,b), while an extensional vein shows a Pliocene age of 3.9 ± 2.9 Ma (Fig. 6c). An extensional vein from the Buron strike-slip fault shows a Messinian age of 5.7 ± 4.7 Ma (Fig. 6d). One slickenfiber and one extensional vein from the Pratz strike-slip fault show Tortonian-Messinian ages of 10.5 ± 0.4 and 9.1 ± 6.5 Ma (Fig. 6f-g), while one slickenfiber shows a younger age of 4.8 ± 1.7 Ma (Fig. 6e). Because of the common-lead rich $^{207}Pb/^{206}Pb$ compositions, the U-Pb ages of the samples DA2, BUS1, PR1-A, PR2-2 of the strike-slip faults have larger uncertainties than those of the thrusts.

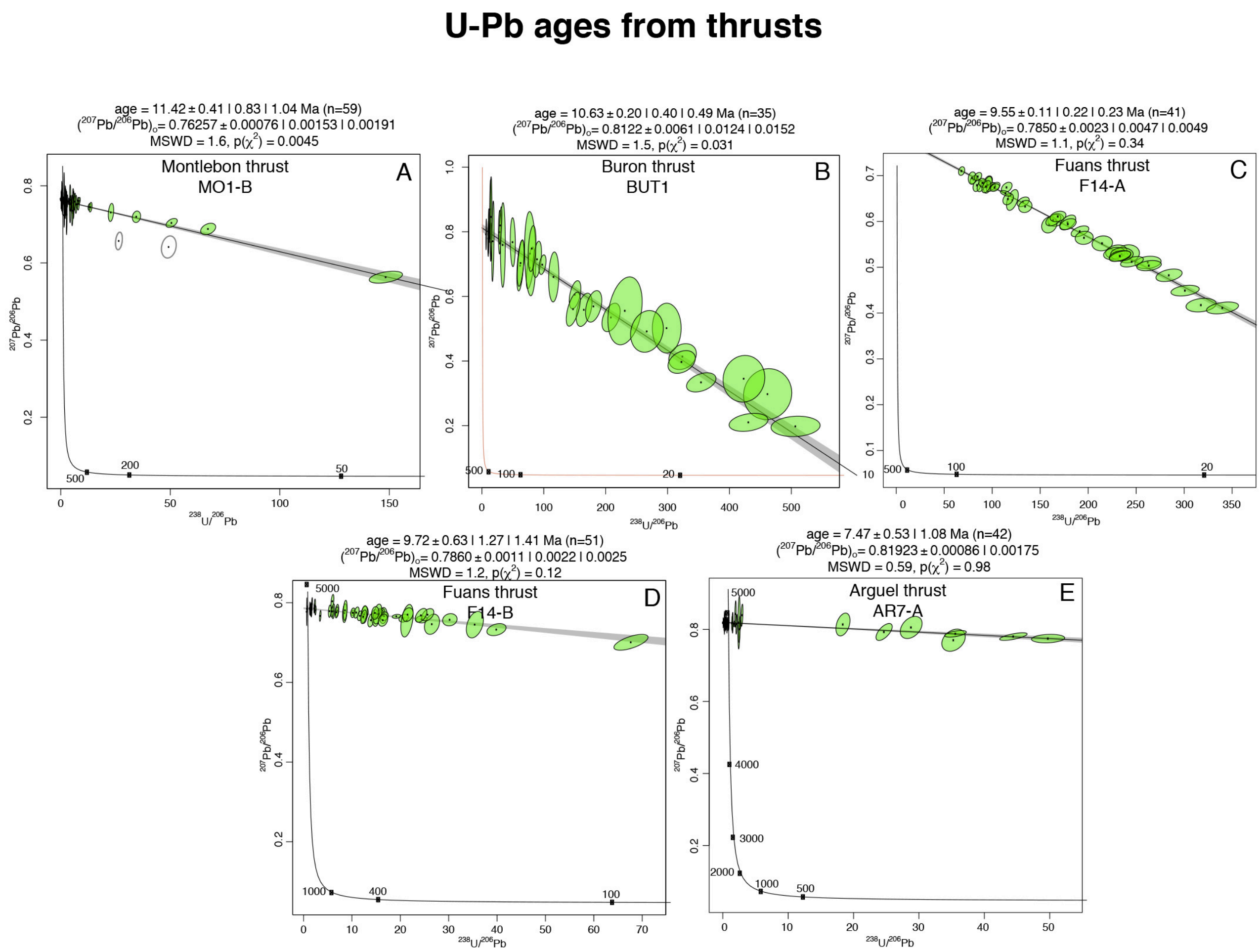

Figure 5. Tera-Wasserburg concordia diagrams of thrust faults. **(a)** Montlebon thrust. **(a)** Buron thrust. **(c,d)** Fuans thrust. **(e)** Arguel thrust.

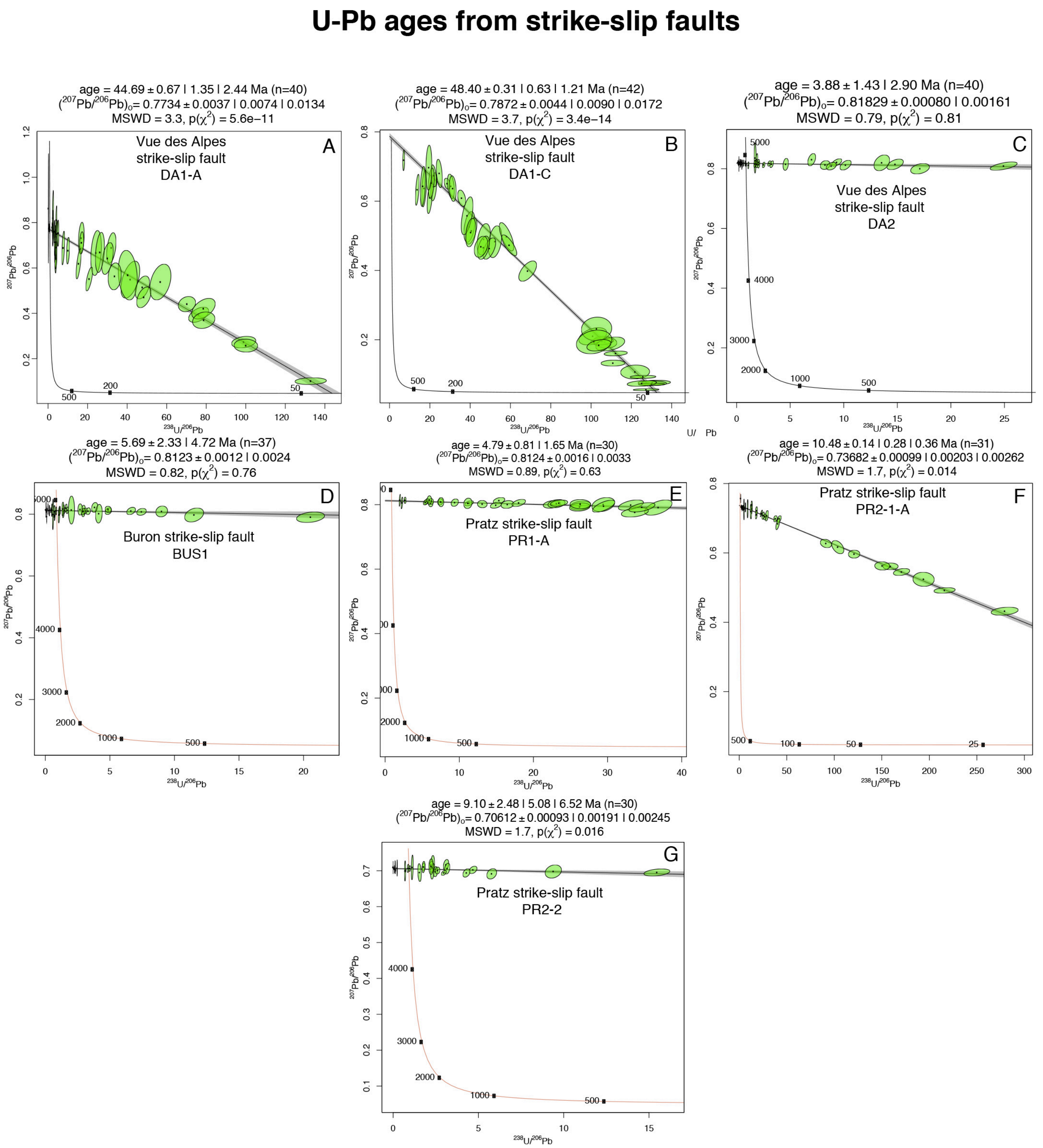

Figure 6. Tera-Wasserburg concordia diagrams of strike-slip faults. **(a-c)** Vue des Alpes strike-slip fault. **(d)** Buron strike-slip fault. **(e-g)** Pratz strike-slip fault.

5. Discussion and conclusions

Slickenfibers on sharp fault planes are clear evidence of tectonic slip along faults (Figs. 3j-l, 4i, S1e-h, and S2c,f). In particular, blocky and fibrous crystals indicate respectively fast and slow vein opening rates associated with fault slip. Within slickenfibers, calcite crystal precipitated during syn- to early post-slip fluid influx in newly formed dilational sites formed along undulated and sharp slip planes (Gratier and Gamond, 1990; Urai et al., 1991; Holland and Urai, 2010; Fagereng et al., 2010; Bons et al., 2012; Woodcock et al., 2014). Extensional veins oriented perpendicular to stylolites (Fig. 3e,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 three regional tectonic phases between the middle Eocene and the Pliocene (Figs. 7 and 8), which are linked to the long-lived tectonic activity of the Alpine foreland evolution. The presented ages should be regarded as minimum ages for the onset of deformation at the studied faults or as maximum ages for its termination as potentially older or younger deformation phases recorded by other veins and slickenfibers not sampled and analyzed here may have been missed. As commonly done in carbonate LA-ICP-MS U-Pb dating, no disequilibrium correction for initial $^{234}U/^{238}U$ and ^{230}Th was applied. This may cause underestimation of young (<10 Ma) samples (Roberts et al. 2020) and accordingly, they should be regarded to reflect maximal ages.

The U-Pb ages are regionally consistent in terms of the tectonic evolution of the Jura FTB, and the microstructures of the analyzed veins and slickenfibers indicate precipitation during syn- to early post-slip fluid influx. However, although U-Pb dating was performed on crystals with no indication of later open-system alteration based on CL-microscopy, possible late fluid infiltration and calcite recrystallization cannot be excluded as previously suggested by other studies (Beaudoin et al., 2018; Hoareau et al., 2021; Roberts et al., 2020, 2021).

Sample BUS1 clearly shows multiple calcite phases indicating vein re-opening and potentially different ages (Fig. 4h). However, the Tera-Wasserburg diagram of BUS1 shows a single age trend with a low MSWD of 0.82 (Fig. 6d). This would not be observed in a sample that experienced crystallization at significantly different times. Therefore, sample BUS1 reflects calcite precipitation within a time interval smaller than what would result in multiple age trends.

The oldest tectonic phase is recorded by two horizontal slickenfibers 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. 7). 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; Mazurek et al. 2018). The strike-slip faulting in Eocene times is consistent with fault-slip data of Homberg et al. (1997). We propose that the Ypresian-Lutetian tectonic activity can be related to the late Mesozoic-Eocene far field tectonic shortening in the European plate foreland due to the advancing Alpine orogen (Mazurek et al., 2006; Timar-Geng et al., 2006) (Fig. 8a). However, previous studies suggested that middle Eocene strike-slip faulting in the Jura area can be also related to the far-field effect of the Pyrenean compression (Bergerat, 1987; Homberg et al., 2002). The Pyrenean far field effect is also recognized in the Paris Basin (e.g., Lacombe et al., 1990; Lacombe and Mouthereau, 1999; Lacombe and Obert, 2000), in eastern France (Lacombe et al., 1993), and even in the United Kingdom (Hibsch et al., 1995) where Pyrenean-related calcite veins were dated by U-Pb (ages between 55 and 25 Ma; Parrish et al., 2018). Therefore, we cannot fully distinguish if the strike-slip fault activity during Ypresian-Lutetian times is related to the Pyrenean or to the Alpine shortening. Further studies are necessary to better constrain the origin of pre-Miocene fault activity in the European foreland.

Structural analyses of the studied thrusts highlight N to NW oriented tectonic transport directions (Fig. 4a-d) consistent with the regional NW-SE to N-S compressional phase that has affected the Jura fold and thrust belt since the Miocene (Philippe et al, 1996; Becker, 2000; Homberg et al., 2002; Ustaszewski and Schmid, 2006; Madritsch et al., 2008; Looser et al., 2021). Although age uncertainties do not allow a distinction beyond doubt and the limited numbers of U-Pb ages and studied thrusts provide a limited picture, the Jura imbrication seems to have occurred by in-sequence thrusting. The oldest observed thrusts ages are Serravallian-Messinian and become progressively younger moving from the inner (SE) toward the external (NW) part, from 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, in the Montlebon, Buron, Fuans, and Arguel thrusts (Figs. 7 and 8b). 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 references therein) and from calcite U-Pb ages of thrust activity in the eastern Jura FTB (Looser et al., 2021) (Fig. 7).

Previous studies interpreted the subvertical strike-slip faults in the Jura FTB as tear faults, with activity during thrusting and folding (Sommaruga, 1997; Looser et al., 2021). Our structural analyses and U-Pb ages from the studied strike-slip faults support this interpretation. In particular, strike-slip faults are subvertical and are roughly parallel or oblique to the regional transport directions inferred from thrust kinematics (compare tectonic transport directions of Fig. 4a-d with those of Fig. 4f,g), a common feature of tear faults (Twiss and Moores, 1992).

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. 7 and 8c). The Pratz tear fault was active at 10.5 ± 0.4 and 9.1 ± 6.5 Ma, indicating tear faulting generation during coeval thrust propagation, and further late-orogenic re-activation at 4.8 ± 1.7 Ma (Figs. 7 and 8b). These data indicate that tear faulting occurred during syn- to late-orogenic times (Fig. 8b,c). In addition, a late-orogenic phase is recorded by an extensional vein from the Vue des Alpes strike-slip fault showing a Pliocene age of 3.9 ± 2.9 Ma (Fig. 7). This age has been measured on an extensional vein that cannot be directly related to fault slip. Therefore, we cannot completely exclude that this age represents a late alteration event not directly linked to fault slip during the Pliocene. However, the 3.9 ± 2.9 Ma age is consistent with late orogenic deformation between 4.2 and 2.9 Ma documented in the frontal part of the Jura FTB (Madritsch et al., 2008 and references therein). The 3.9 ± 2.9 Ma age from the Vue des Alpes strike-slip fault is ~40 Ma younger than the middle Eocene ages (44.7 ± 2.6 and 48.4 ± 1.5 Ma) measured on the same fault, suggesting the reactivation of the Vue des Alpes strike-slip fault during late Jura shortening. This inference is also consistent with field cross-cutting relationships indicating re-activation of pre-existing strike-slip faults as tear faults (Homberg et al., 1997).

We consider the retrieved age as fault re-activation of the Vue des Alpes strike-slip fault 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 initiating only after ~4.5 Ma (Looser et al., 2021 and references therein), which led to an increase in the principal vertical stress (sigma 3) and a switch between sigma 3 and sigma 2 (Ferril et al., 2021). Shortening is still active in the Jura FTB and tear faults (also re-activated tear faults) are seismogenic (Thouvenot et al., 1998).

The presented tectonic reconstruction depicts a stable evolution of the Jura FTB wedge by possible in-sequence thrusting consistent with thrust imbrication above the low-friction décollement consisting of evaporites (Fig. 8a-c). Contrarily, out-of-sequence thrusting occurred as late as in Messinian-early Pliocene times in the proximal Molasse Basin (Von Hagke et al., 2012, 2014) and in the Alps (Bellahsen et al., 2014). This tectonic framework suggests a stable topographic evolution of the critical taper and topographic profile of the Jura fold-and-thrust belt. Finally, this study constrains a long-lived polyphase tectonic history of the northwestern Alpine foreland system along the convergent boundary between European and African plates from the middle Eocene to the Pliocene.

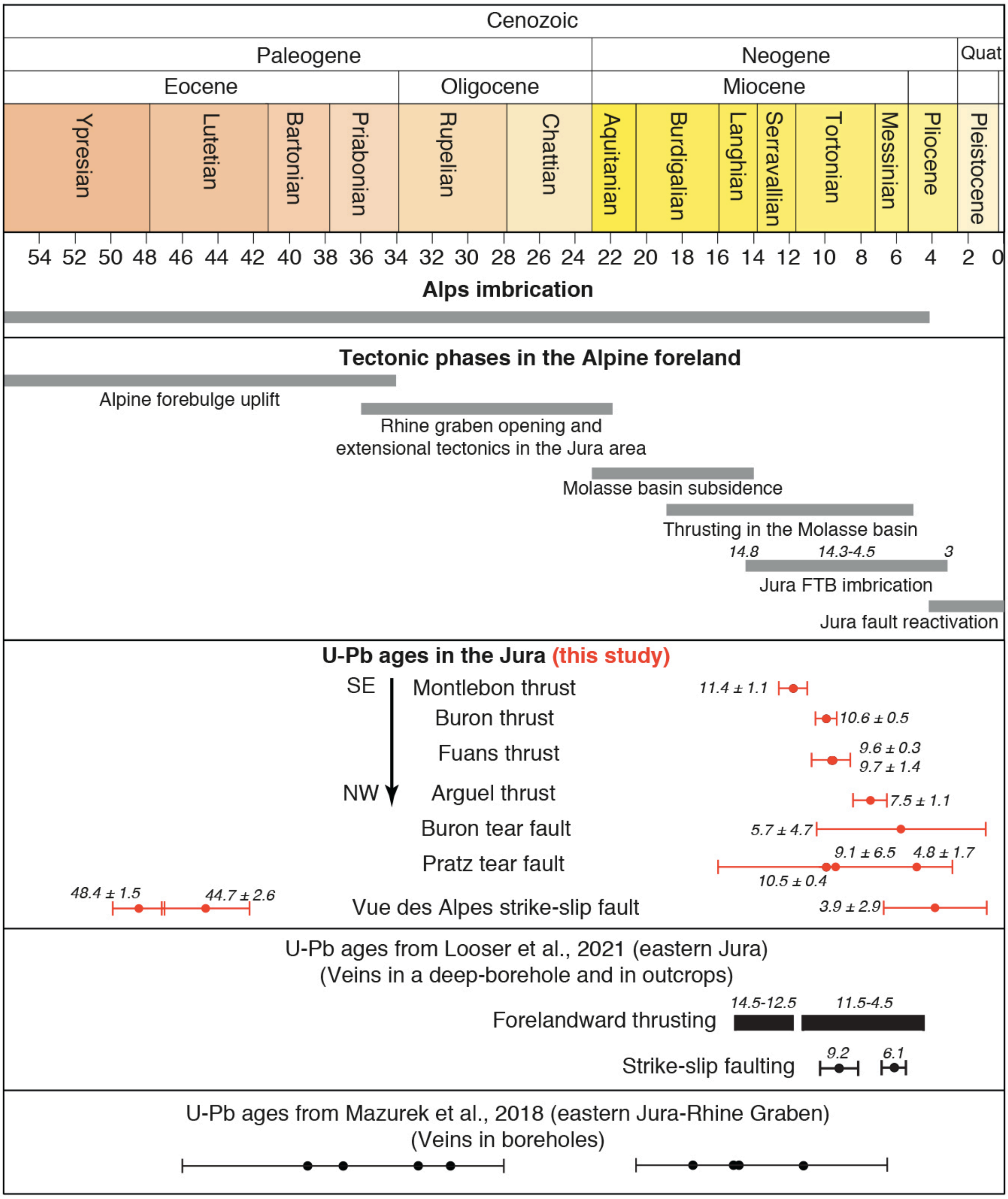

Figure 7. Main tectonic phases in the Alps and in the Alpine foreland. Age constraints shown as grey bars are from Burkhard and Sommaruga (1998), Ustaszewski et al. (2006), Madritsch et al. (2008), Bellahsen et al. (2014), and Von Hagke et al. (2014). For calcite U-Pb data, all uncertainties are represented as 2σ.

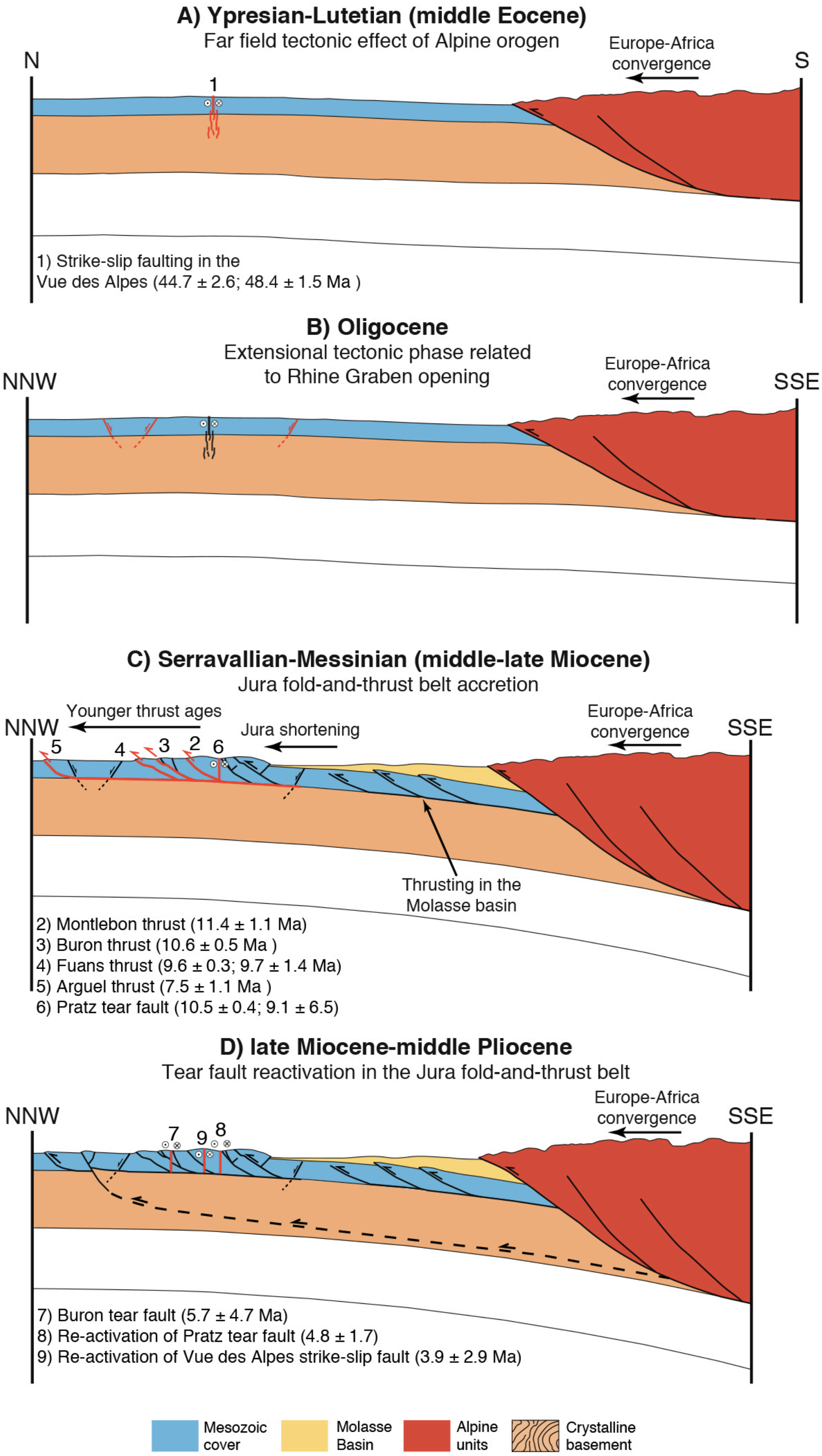

Figure 8. (a-d) Schematic reconstruction of the main tectonic phases dated in the Jura area in the regional context of the Alpine foreland system evolution.

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