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Foreland exhumation controlled by crustal thickening in the Western Alps

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ABSTRACT

In alpine-type collision belts, deformation of the foreland may occur as a result of forward propagation of thrusting and is generally associated with thin-skinned deformation mobilizing the sedimentary cover in fold-and-thrust belts. Locally, foreland deformation can involve crustal-scale thrusting and produce large-scale exhumation of crystalline basement resulting in significant relief generation. In this study, we investigate the burial and exhumation history of Tertiary flexural basins located in the Western Alpine foreland, at the front of the Digne thrust sheet (southeast France), using low-temperature apatite fission-track and (U-Th)/He thermochronology. Based on the occurrence of partially to totally reset ages, we document 3.3–4.0 km of burial of these basin remnants between ca. 12 Ma and 6 Ma, related to thin-skinned thrust-sheet emplacement without major relief generation. The onset of exhumation is dated at ca. 6 Ma and is linked to erosion associated with significant relief development. This evolution does not appear to have been controlled by major climate changes (Messinian crisis) or by European slab breakoff. Rather, we propose that the erosional history of the Digne thrust sheet corresponds to basement involvement in foreland deformation, leading to crustal thickening. Our study highlights the control of deep-crustal tectonic processes on foreland relief development and its erosional response at mountain fronts.

INTRODUCTION

Interactions between tectonics, erosion, and climate in shaping mountain ranges and adjacent foreland basins have been discussed for the past two decades (e.g., Whipple, 2009, and references therein); the timing of uplift and erosion are critical in this respect but in many cases remain a matter of debate. In situ thermochronological databases suggest a significant increase in exhumation rates in the Western Alps during the past ~2–8 m.y., argued to be controlled by lithospheric slab breakoff and/or climate change (e.g., Cederbom et al., 2011; Fox et al., 2015). Rapid exhumation is focused on the External Crystalline Massifs (ECMs), which constitute the topographic backbone of the Alpine arc. However, these massifs crop out discontinuously, separated by structural saddles that expose the sedimentary cover and are characterized by lower elevations. The processes leading to these variations in topographic and structural relief reflect a competition between thin- and thick-skinned deformation (Mouthereau et al., 2013). In the westernmost Alps, the Digne thrust sheet (southeast France) fills one of these saddles, between the Pelvoux and Argentera ECMs (Fig. 1). It has overthrust the Tertiary foreland basin, remnants of which currently crop out in a regional-scale erosional half-window, suggesting recent uplift and exhumation (e.g., Hippolyte and Dumont, 2000). Here, we present new low-temperature apatite fission-track (AFT) and (U-Th)/He (AHe) thermochronology data and thermal-history inversion for samples from these foreland basin remnants in order to constrain the amount and timing of burial and exhumation in this part of the Alpine foreland, and to test whether they are controlled by crustal, lithospheric, or climatic processes.

GEOLOGICAL SETTING

The study area is located in the foreland of the southwestern French Alps (Fig. 1A) and corresponds to the external deformation front (Fig. 1B). The development of Tertiary foreland basins reflects the progressive westward propagation of deformation related to the Alpine collision, which began at ca. 34–32 Ma with the development of the Penninic frontal thrust (Ford et al., 2006). As a result of westward propagation of deformation, the Pelvoux and Argentera ECMs (Fig. 1B) have been exhumed by thick-skinned deformation processes since ca. 20 Ma, with a possible acceleration at ca. 8 Ma (van der Beek et al., 2010, and references therein). Between these ECMs, this propagation is recorded by the emplacement of the Digne thrust sheet, which contains an ~5-km-thick Triassic to Eocene sedimentary sequence (Figs. 1B and 1C). These series overthrust a deformed and reduced Mesozoic succession and overlying syntectonic Tertiary sediments in a thin-skinned tectonic regime.

The Tertiary basins were underthrust below the Digne thrust sheet and nowadays crop out within an erosional half-window (Fig. 1C). Based on stratigraphic and tectonic analysis of the underthrust Tertiary sediments, emplacement of the Digne thrust sheet is proposed to have started between ca. 15 and 13 Ma (Gidon and Pairis, 1992; Fournier et al., 2008; see the GSA Data Repository[1]), followed by ~10 km of southwestward tectonic transport during the late Miocene (Lickorish and Ford, 1998). At the front of the Digne thrust sheet, the Mio-Pliocene Valensole conglomerates (Fig. 1C) were tilted toward the west during the Quaternary (Hippolyte and Dumont, 2000). However, the precise amount of mid- to late Miocene burial, the timing of subsequent exhumation, and the controlling tectonic processes have not been documented previously.

The present-day geometry of the top of the basement is irregular (Fig. 1C), deepening to ~7000 m and ~3000 m in front of the northern (Pelvoux) and the southern (Argentera) ECMs, respectively (Rangin et al., 2010). Beneath the Digne thrust sheet, the top of the basement lies at only 1000 m depth and crops out north of the Faucon-du-Caire area (Fig. 1C). This irregular basement morphology is partly inherited from Tethyan passive margin development during the Jurassic, which also controls the thickness variations of the Mesozoic series (e.g., Lickorish and Ford, 1998).

TIMING OF BURIAL AND EXHUMATION

We dated eight sandstones from two sites in the Tertiary basins exposed in the half-window

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[1] GSA Data Repository item 2017035, details on sampling, mineral separation, AHe and AFT dating methods, and thermal-history modeling; Digne thrust-sheet burial and thickness estimation; Table DR1 (sample description); Table DR2 (AHe data); Table DR3 (AFT data); Figure DR1 (stratigraphic logs); Figure DR2 (AHe age versus effective U content); and Figure DR3 (AFT radial plots), is available online at www.geosociety.org/pubs/ft2017.htm or on request from editing@geosociety.org.

Data Repository item 2017035 | doi:10.1130/G38561.1

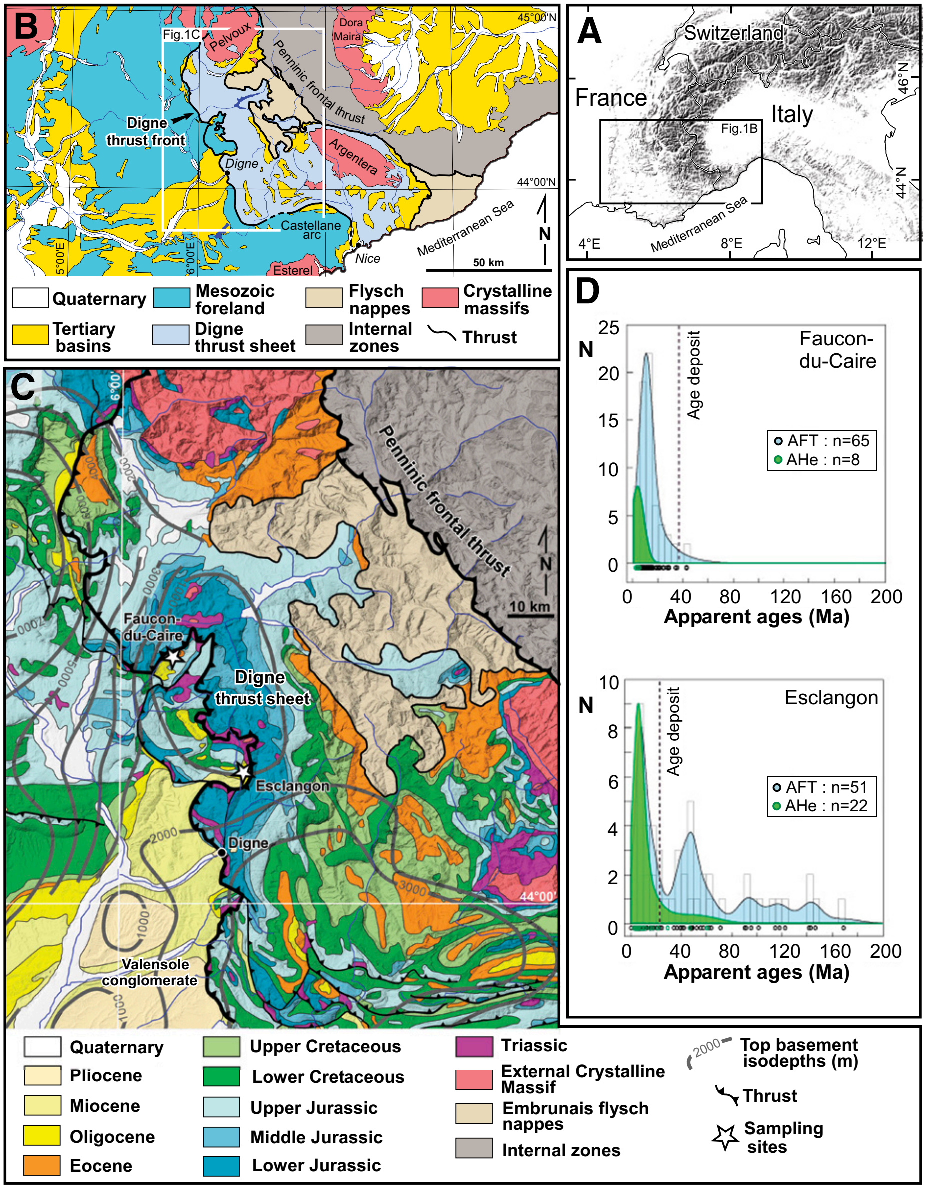

Figure 1. A: Location of study area in European Alps. B: General tectonic framework of Western Alps. C: Geological map of Digne thrust-sheet area centered on erosional half-window. Sample sites in Tertiary basins at Faucon-du-Caire and Esclangon are indicated. D: Apatite fission-track (AFT) and (U-Th)/He (AHe) single-grain age histograms for both sampling sites.

of the Digne thrust sheet (Figs. 1, 2A, and 2B): at Faucon-du-Caire in the north (samples DIG14-9, DIG14-10A, and DIG14-10B) and Esclangon ~30 km to the southeast (samples DIG13-1, DIG13-3, DIG14-4, DIG14-5, and DIG14-8). Samples were collected along altitudinal profiles between 810 m and 1175 m (Table DR1 in the Data Repository). They include upper Eocene to lower Oligocene fluvial and Miocene marine molasse deposits, constituted by detrital material, and pre-depositional AFT and AHe ages are expected to range from Triassic to Oligocene (e.g., Schwartz et al., 2012; see the Data Repository).

Both AFT and AHe data were obtained for most of the samples, except for DIG14-9, which did not yield apatite of sufficient quality for AHe dating (Fig. 1D). Data and methodological details are given in the Tables DR2 and DR3.

Low-Temperature Thermochronology Data

The Esclangon samples present dispersed AHe and AFT ages due to partial resetting of both thermochronometers (Figs. 1D and 2D). AHe ages range from 3.1 ± 0.3 Ma to 60 ± 5 Ma, and AFT central ages from 11 ± 2 Ma to 62 ± 16 Ma (Fig. 1D). In contrast, the Faucon-du-Caire samples present homogeneous AHe ages ranging from 1.9 ± 0.2 Ma to 4.7 ± 0.4 Ma, with AFT central ages ranging from 10 ± 1 Ma to 12 ± 1 Ma (Figs. 1D and 2C). Thus, all samples are either partially or totally reset, implying significant heating after sediment deposition.

Thermal History Modeling

We use QTQt inverse modeling (http://www.iearth.org.au/codes/QTQt/) to quantify the thermal history of these Tertiary basin sediments (see the Data Repository), as this code takes into consideration the vertical relations between samples (Gallagher, 2012). It is important to note that, because of the limited thermal resolution of thermochronological data, the inversion results will only record heating and cooling of several tens of degrees, linked to kilometer-scale burial and exhumation signals. Due to partial to total resetting of the thermochronological signal, the pre-burial thermal history is only weakly constrained for both sites. The timing of thrusting-related burial is bracketed to the mid- to late Miocene by the preserved stratigraphic sequence (providing a maximum age constraint) and the reset AFT ages (providing a minimum constraint). We impose that the samples remained close to the surface from deposition until 14 Ma at Faucon-du-Caire and 13 Ma at Esclangon (black boxes in Figs. 2E and 2F; see the Data Repository), when they were buried due to emplacement of the Digne thrust sheet. The inverse models provide new constraints on the timing and amount of burial as well as on the onset of final exhumation (Figs. 2E and 2F). The independently obtained thermal histories for Faucon-du-Caire and Esclangon show similar shapes, attesting to the common history of both sites. Ages predicted by the best-fit thermal history are reported in the age-elevation plots (Figs. 2C and 2D).

DISCUSSION AND CONCLUSIONS

Digne Thrust-Sheet Dynamics from Burial to Exhumation

Our two thermal history models evidence heating up to 110 ± 5 °C between ca. 12 and 6 Ma and between ca. 9 and 6 Ma for the Faucon-du-Caire and Esclangon areas, respectively, followed by rapid cooling from 6 Ma onward (Figs. 2E and 2F). The heating phase recorded at Faucon-du-Caire and Esclangon shows a ~30 km regional extent that cannot be explained by local hydrothermal circulation (Haccard et al., 1989). Moreover, the late Miocene–Pliocene sediment cover (Valensole conglomerates) is only 1 km thick (Graham et al., 2012) and cannot be responsible for the ~100 °C heating that we observe in our samples. Consequently, we infer that heating of our samples, leading to total or partial resetting of both thermochronometers, resulted from burial of the Tertiary sediments due to underthrusting below the Digne thrust sheet. For a mean surface temperature of 10 °C and geothermal gradient ranging from 25 to 30 °C/km (Cederbom et al., 2011, and references therein), our data show that the samples were buried to a depth of 3.3–4.0 km, consistent with the thickness of the Digne thrust sheet prior to

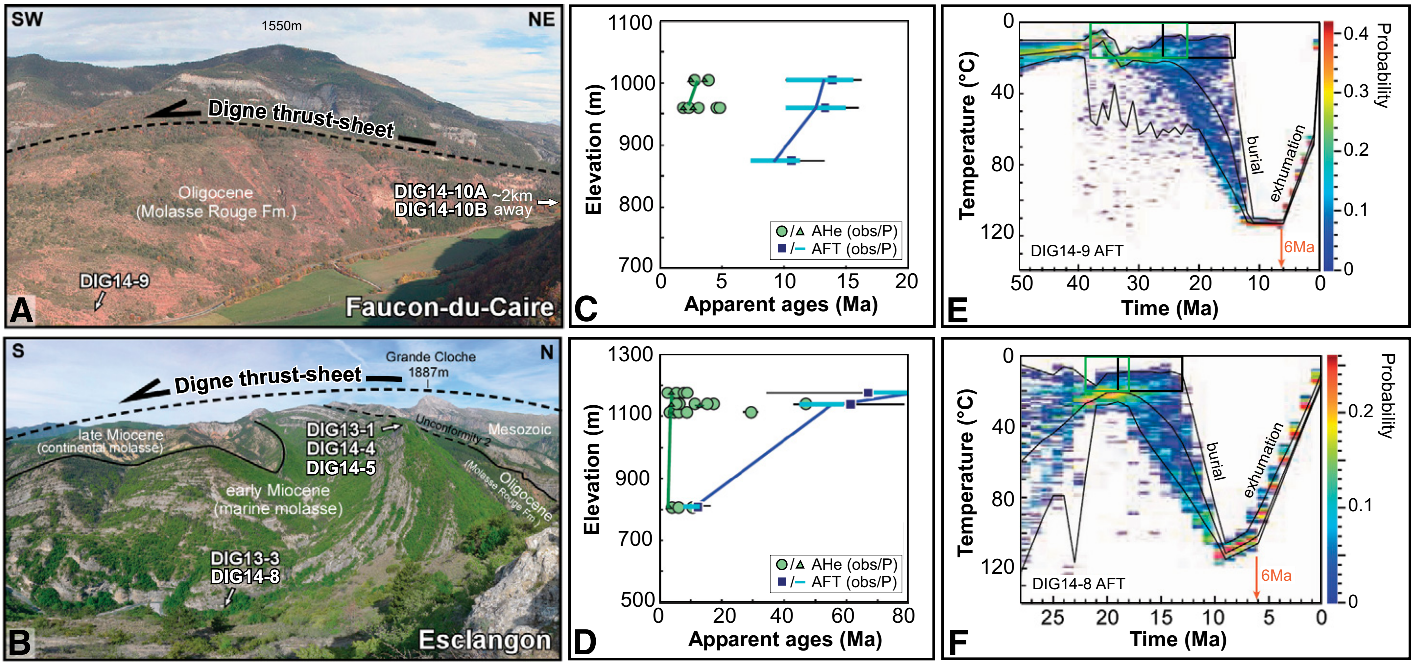

Figure 2. A: Location of Faucon-du-Caire samples on panoramic view of Digne (France) nappe thrust over Oligocene deposits (Molasse Rouge Formation). B: Location of Esclangon samples on panoramic view of "Vélodrôme" recumbent syncline, involving Miocene marine molasse sampled in footwall of Digne thrust. C,D: Apatite fission-track (AFT) and (U-Th)/He (AHe) age-elevation profiles and modeled ages. obs—observed age ; P—predicted age. E,F: Thermal-history paths of lowest-elevation samples (DIG14-9 and DIG14-8, respectively) deduced from inverse thermal-history modeling of combined data set. Black line is the expected model, and color represents the path probability. Green box represents the time of deposit, and black box a constraint. See the Data Repository (see footnote 1) for modeling.

erosion at both sites (Figs. 2A and 2B; thickness estimates for the Digne thrust sheet are detailed in the Data Repository).

Evolution of the Western Alpine Foreland

Digne thrust-sheet emplacement reflects the westward propagation of compressive deformation in the Alpine foreland, but little is known about relief development in the foreland. Pollen data suggest an absence of significant relief at the southwestern Alpine front prior to 15 Ma (Fauquette et al., 2015). We interpret the lag between burial and exhumation (both locations remaining at 110 ± 5 °C until 6 Ma; Figs. 2E and 2F) as reflecting the absence of significant regional erosion from ca. 12 to 6 Ma, implying no significant relief generation during Digne thrust-sheet emplacement.

The exhumation dynamics recorded by our thermochronological data reflect a significant, regional-scale erosional event at ca. 6 Ma. The final folding phase (post–6 Ma) affecting the Digne thrust sheet may have participated in, but cannot have been responsible for, the ~3–4 km erosion observed in both the Faucon-du-Caire and Esclangon areas. The magnitude of the erosive response implies crustal-scale dynamics. A recent geophysical profile across the Western Alps (Zhao et al., 2015) shows crustal thickening below the Digne half-window, reflecting thick-skinned deformation of the European crust. Our data suggest that such crustal thickening is responsible for the large-scale (30-km-long) erosional window

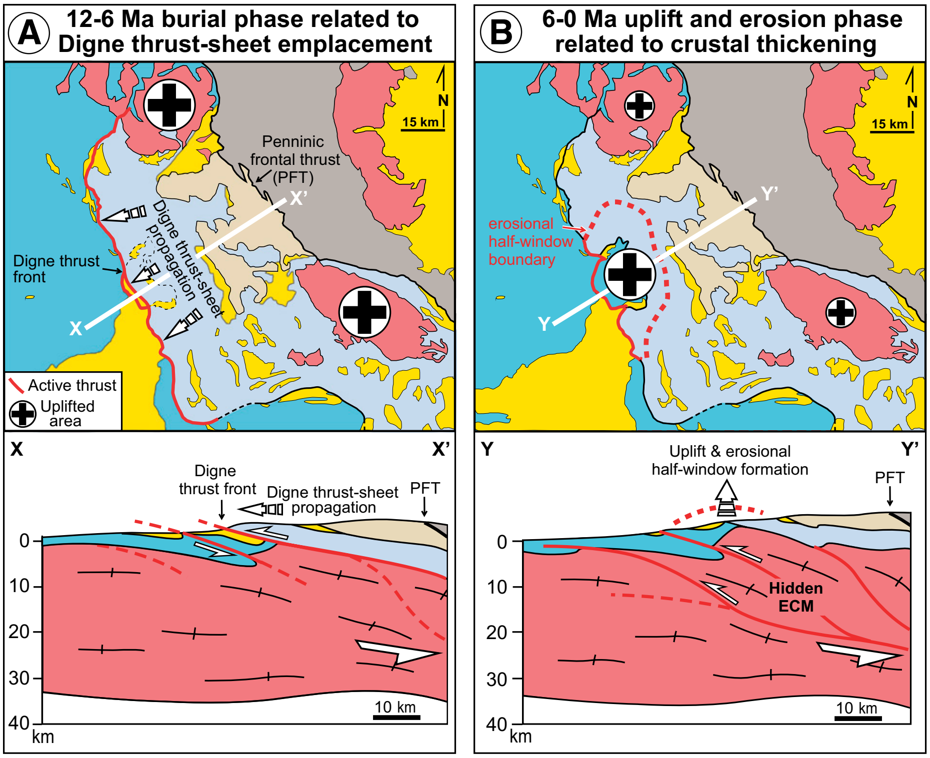

Figure 3. Tectonic sketch maps and northeast-southwest cross sections illustrating evolution of French Alpine foreland, from 12 Ma to present day, constrained by our thermochronological data. Same colors are used as in Figure 1B; cross symbols illustrate the deformation of the crystalline basement. A: Burial of reduced Mesozoic series and overlying Tertiary basins under Digne thrust sheet related to thin-skinned deformation. B: Large-scale uplift and erosion centered on erosional half-window related to thick-skinned deformation. ECM—External Crystalline Massif.

in the Digne thrust sheet and started developing at ca. 6 Ma. The shape and regional size of the erosional half-window is similar to the shape of the top of the basement that locally reaches the surface (Figs. 1C and 3), although this is partly controlled by inherited Tethyan margin structures (Lickorish and Ford, 1998).

In the Western Alps, published thermochronological data (e.g., van der Beek et al., 2010, and references therein) record exhumation of the European foreland in response to propagation of deformation toward the external domain since ca. 20 Ma, accelerating at ca. 8 Ma. This major exhumation phase is related to thick-skinned basement underthrusting in the Argentera and Pelvoux ECMs (van der Beek et al., 2010). At the same time, our study sites, located west of and between these two ECMs, record sedimentation and burial associated with thin-skinned deformation (Fig. 3A). Erdös et al. (2015) suggested a strong link between front-range cover thickness and the initiation of crustal-scale thick-skinned deformation. In our study area, crustal-scale deformation may thus be controlled by the variation of sediment thickness and occurs later and more externally with respect to the Argentera and Pelvoux ECMs (Fig. 3B). We propose that formation of the erosional half-window corresponds to the incipient exhumation of a new and late ECM (“hidden ECM” in Fig. 3B).

Implications for Alpine Tectonics

The results of this study integrated at the scale of the European Alps have several important implications. Exhumation of the Eastern and Central Alpine foreland since ca. 5 Ma has been interpreted as the result of European slab breakoff (e.g., Baran et al., 2014; Fox et al., 2015). However, this hypothesis is difficult to apply to such a short-wavelength erosional window (~30 km), and slab breakoff may have taken place much earlier, at 30–35 Ma, in the Western Alps (Piromallo and Faccenna, 2004). In contrast to earlier results (Lippitsch et al., 2003), recent high-resolution seismic-tomography images (Zhao et al., 2016) document lateral and downdip (>400 km) continuity of the European slab from the Western to the Central Alps, inconsistent with recent slab breakoff.

We rather suggest that the onset of kilometer-scale exhumation recorded in the Digne thrust sheet is the consequence of basement involvement in shortening and outward propagation of foreland deformation at 6 Ma. Exhumation is synchronous with the Messinian Salinity Crisis (MSC; 5.96–5.33 Ma; Krijgsman et al., 1999). Erosion associated with the MSC is known to have produced narrow incision features like canyons but did not generate large-scale erosion as observed. The climatic change related to the MSC might have enhanced erosion of the Digne thrust-sheet half-window but cannot be considered as the first-order control on exhumation. Moreover, our results indicate active basement deformation at the southwestern Alpine front, contradicting the hypothesis that deformation stepped back to the internal part of the orogen in response to a climatically induced increase in erosional efficiency in Messinian times (Willett et al., 2006).

The erosional signature documented here highlights the control of thick-skinned crustal tectonic processes on foreland relief development and its erosional response at mountain fronts. Spatially and temporally variable basement involvement in fold-and-thrust belt development may be controlled by structural inheritance and sedimentary cover thickness. Late-stage foreland exhumation therefore does not necessarily require either deep-mantle or climatic drivers.

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REFERENCES CITED

Baran, R., Friedrich, A.M., and Schlunegger, F., 2014, The late Miocene to Holocene erosion pattern of the Alpine foreland basin reflects Eurasian slab unloading beneath the Western Alps rather than global climate change: Lithosphere, v. 6, p. 124–131, doi:10.1130/L307.1.

Cederbom, C.E., van der Beek, P., Schlunegger, F., Sinclair, H., and Oncken, O., 2011, Rapid, extensive erosion of the North Alpine foreland basin at 5–4 Ma: Climatic, tectonic and geodynamic forcing on the European Alps: Basin Research, v. 23, p. 528–550, doi:10.1111/j.1365-2117.2011.00501.x.

Erdös, Z., Huismans, R.S., and van der Beek, P., 2015, First-order control of syntectonic sedimentation on crustal-scale structure of mountain belts: Journal of Geophysical Research: Solid Earth, v. 120, p. 5362–5377, doi:10.1002/2014JB011785.

Fauquette, S., et al., 2015, Quantifying the Eocene to Pleistocene topographic evolution of the southwestern Alps, France and Italy: Earth and Planetary Science Letters, v. 412, p. 220–234, doi:10.1016/j.epsl.2014.12.036.

Ford, M., Duchêne, S., Gasquet, D., and Vanderhaeghe, O., 2006, Two-phase orogenic convergence in the external and internal SW Alps: Journal of the Geological Society, v. 163, p. 815–826, doi:10.1144/0016-76492005-034.

Fournier, M., Agard, P., and Petit, C., 2008, Microtectonic constraints on the evolution of the Barles half-window (Digne nappe, southern Alps): Implications for the timing of folding in the Valensole foreland basin: Bulletin de la Société Géologique de France, v. 179, p. 551–568, doi:10.2113/gssgfbull.179.6.551.

Fox, M., Herman, F., Kissling, E., and Willett, S.D., 2015, Rapid exhumation in the Western Alps driven by slab detachment and glacial erosion: Geology, v. 43, p. 379–382, doi:10.1130/G36411.1.

Gallagher, K., 2012, Transdimensional inverse thermal history modeling for quantitative thermochronology: Journal of Geophysical Research, v. 117, B02408, doi:10.1029/2011JB008825.

Gidon, M., and Pairis, J.L., 1992, Relations entre le charriage de la Nappe de Digne et la structure de son autochtone dans la vallée du Bès (Alpes de-Haute-Provence, France): Eclogae Geologicae Helvetiae, v. 85, p. 327–359.

Graham, R., Jackson, M., Pilcher, R., and Kilsdonk, B., 2012, Allochthonous salt in the sub-Alpine fold–thrust belt of Haute Provence, France, *in* Alsop, G.I., et al., eds., Sat Tectonics, Sediments and Prospectivity: Geological Society of London Special Publication 363, p. 595–615, doi:10.1144/SP363.30.

Haccard, D., Beaudoin, B., Gigot, P., and Jorda, M., 1989, Notice explicative, carte géologique de la France à 1/50 000, feuille 918: La Javie: Orléans, France, Bureau de Recherches Géologiques et Minières, 152 p.

Hippolyte, J.C., and Dumont, T., 2000, Identification of Quaternary thrusts, folds and faults in a low seismicity area: Examples in the Southern Alps (France): Terra Nova, v. 12, p. 156–162, doi:10.1046/j.1365-3121.2000.00287.x.

Krijgsman, W., Hilgen, F.J., Raffi, I., Sierro, F.J., and Wilson, D.S., 1999, Chronology, causes and progression of the Messinian salinity crisis: Nature, v. 400, p. 652–655, doi:10.1038/23231.

Lickorish, W.H., and Ford, M., 1998, Sequential restoration of the external Alpine Digne thrust system, SE France, constrained by kinematic data and synorogenic sediments, *in* Mascle, A., et al., eds., Cenozoic Foreland Basins of Western Europe: Geological Society of London Special Publication 134, p. 189–211, doi:10.1144/GSL.SP.1998.134.01.09.

Lippitsch, R., Kissling, E., and Ansorge, J., 2003, Upper mantle structure beneath the Alpine orogen from high-resolution teleseismic tomography: Journal of Geophysical Research, v. 108, 2376, doi:10.1029/2002JB002016.

Mouthereau, F., Watts, A.B., and Burov, E., 2013, Structure of orogenic belts controlled by lithosphere age: Nature Geoscience, v. 6, p. 785–789, doi:10.1038/ngeo1902.

Piromallo, C., and Faccenna, C., 2004, How deep can we find the traces of Alpine subduction?: Geophysical Research Letters, v. 31, L06605, doi:10.1029/2003GL019288.

Rangin, C., Le Pichon, X., Hamon, Y., Loget, N., and Cresy, A., 2010, Gravity tectonics in the SE Basin (Provence, France) imaged from seismic reflection data: Bulletin de la Société Géologique de France, v. 181, p. 503–530, doi:10.2113/gssgfbull.181.6.503.

Schwartz, S., Guillot, S., Tricart, P., Bernet, M., Jourdan, S., Dumont, T., and Montagnac, G., 2012, Source tracing of detrital serpentinite in the Oligocene molasse deposits from western Alps (Barrême basin): Implications for relief formation in the internal zone : Geological Magazine, v. 149, p. 841–856, doi:10.1017/S0016756811001105.

van der Beek, P.A., Valla, P.G., Herman, F., Braun, J., Persano, C., Dodson, K.J., and Labrin, E., 2010, Inversion of thermochronological age–elevation profiles to extract independent estimates of denudation and relief history, II: Application to the French Western Alps: Earth and Planetary Science Letters, v. 296, p. 9–22, doi:10.1016/j.epsl.2010.04.032.

Whipple, K.X, 2009, The influence of climate on the tectonic evolution of mountain belts: Nature Geoscience, v. 2, p. 97–104, doi:10.1038/ngeo413.

Willett, S.D., Schlunegger, F., and Picotti, V., 2006, Messinian climate change and erosional destruction of the European Alps: Geology, v. 34, p. 613–616, doi:10.1130/G22280.1.

Zhao, L., et al., 2015, First seismic evidence for continental subduction beneath the Western Alps: Geology, v. 43, p. 815–818, doi:10.1130/G36833.1.

Zhao, L., et al., 2016, Upper mantle structure of the Alpine and Adriatic regions unraveled by high-resolution P-wave tomography: Geophysical Research Abstracts, v. 18, Abstract EGU2016-5791.

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