Reply

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Reply to discussion on 'Middle Jurassic shear zones at Cap de Creus (eastern Pyrenees, Spain): a record of pre-drift extension of the Piemonte–Ligurian Ocean?' *Journal of the Geological Society, London*, 174, 289–300

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We welcome the discussion by Elena Druguet, Jordi Carreras and Jochen Mezger (Druguet *et al.* 2017) of our paper (Vissers *et al.* 2017*b*) in which we report Jurassic ^{40}Ar/^{39}Ar ages from shear zones at Cap de Creus, NW Spain. The authors argue that our interpretation of these results and the inferred development of the Cap de Creus shear zones during Jurassic stretching and opening of the Piemonte Ligurian ocean contradicts structural and tectonic evidence, and that it is not sufficiently supported by geochronological data. Below we first consider their structural and tectonic arguments from the tectonic–palaeogeographical scale down to the smaller field scale, and then proceed to discuss our Ar/Ar results.

Druguet *et al.* (2017) note that prior to the Oligo-Miocene rifting event the Corso-Sardinian block was fixed east of NE Iberia, hence that the rocks at Cap de Creus were not located at the Jurassic pre-drift continental margin and that the northern Cap de Creus shear zones could not have formed as normal faults related to continental rifting.

This palaeogeographical argument builds on a previous hypothesis by Stampfli & Borel (2002), Stampfli *et al.* (2002) and Stampfli & Hochard (2009) in which Iberia, the Corso-Sardinian block and the Briançonnais domain formed one single microcontinent. This hypothesis, however, must be discarded on the basis of recent palaeomagnetic work on Sardinia by Advokaat *et al.* (2014) showing that between Late Jurassic and Eocene time Sardinia underwent no vertical-axis rotations relative to Eurasia and was fixed to Europe in a rotated position that results from post-Eocene deformation, whereas all available evidence indicates that Iberia was located much further west and underwent some 35° counterclockwise rotation during the Cretaceous (van Hinsbergen *et al.* 2017; Vissers *et al.* 2017*a*). Sardinia, and by inference Corsica and the Briançonnais terrane, were hence not part of Iberia. We emphasize that the palaeogeography pertinent to the present discussion concerns the Jurassic. Some confusion may have arisen from figure 9 of Vissers *et al.* (2017*b*), whereby we displayed opening of the Piemonte Ligurian ocean with respect to Iberia in present-day coordinates (see also Vissers *et al.* 2013, fig. 5). To clarify the palaeogeographical setting, we show in Figure 1 a plate-kinematic reconstruction for the period of Jurassic break-up and oceanization with respect to a fixed Europe, and taking the recent palaeomagnetic data of Sardinia into account. It should be noted that an initially more easterly position of Adria, as required by the scenario advocated by Druguet *et al.* (2017), would imply a much larger Iberian continental microplate that cannot be accounted for in the geological record. We conclude that the Variscan rocks of the Cap de Creus massif were indeed close to the Jurassic continental margin, and that there is no argument whatsoever against such a position.

Druguet *et al.* (2017) note that we have not placed the northern Cap de Creus shear zones in the context of the occurrence of other steep shear zones in the central Pyrenees such as the Mérens fault, indicated in our figure 8a at the southern side of our section across the Soulcem thermal high. This shear zone has been interpreted in the context of Variscan compression or transpression (Denèle *et al.* 2008; Mezger *et al.* 2012) but also as a major Alpine fault zone (Williams & Fischer 1984; Casas *et al.* 1989). In general, shear zones in the Variscan basement of the Pyrenees have been associated (1) with late Variscan dextral strike-slip or transpression, (2) with Mesozoic sinistral shearing or extension, and (3) with Alpine compression (see references given by Druguet *et al.* 2017), and several researchers have considered reworking of initially Variscan shear zones. The implicit assumption of Druguet *et al.* (2017) that Variscan structures in basement units incorporated in Pyrenean thrusting were not tilted, even if there is widespread evidence of large-scale duplexing in the Pyrenees (e.g. Muñoz 1992), and thus maintained their original Variscan orientation is an *a priori* assumption that is hard to defend, but that is essential for the interpretation that these structures represent strike-slip faults. It was precisely because of this ambiguity arising from different studies that we wished to refrain from interpretation of the northern Cap de Creus shear zones on the basis of correlation with shear zone structures in the central Pyrenees, and instead decided to try and date some of these shear zones. Our results demonstrated that the structures at Cap de Creus are most probably not Variscan, and were in all likelihood strongly tilted in the Pyrenean orogeny.

Druguet *et al.* (2017) criticize our attempt to explain the present-day orientation of the Variscan structure at northern Cap de Creus by an Alpine rotation about a WNW–ESE axis, first because the Variscan metamorphism in the Pyrenean Axial Zone is associated with gneiss domes where isograds and dominant foliations are dome-shaped, flat-lying in the central part and steeply inclined at the flanks, and second because in this rotation we exclude the southern Cap de Creus shear belt associated with the Roses granodiorite. We agree, of course, on the existence of dome-shaped Variscan structures as also evident from figure 8a in our paper, but emphasize that the structure at Soulcem implies a broadly vertically oriented

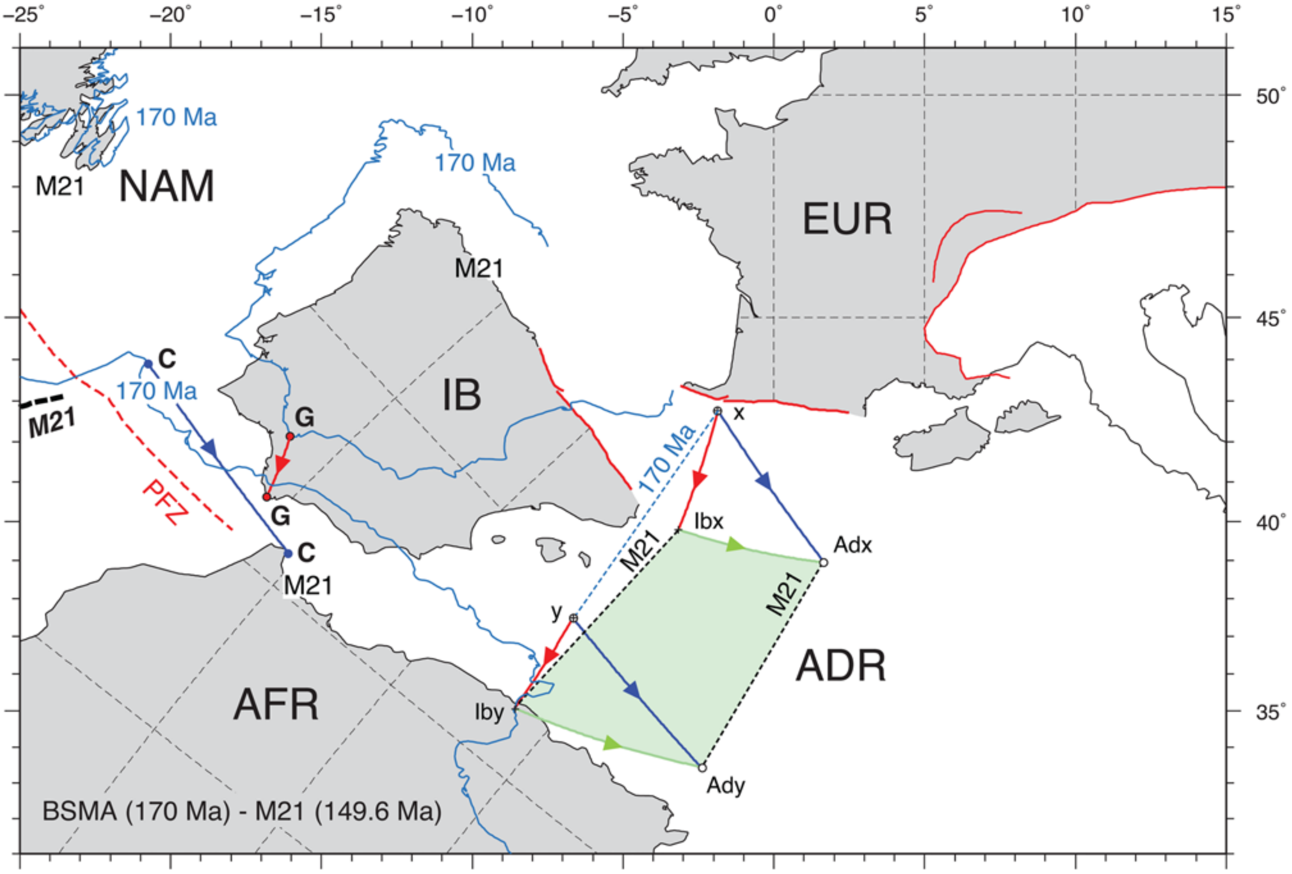

Fig. 1. Plate motions in the central Atlantic and western Mediterranean region, from the Black Spur Magnetic Anomaly (BSMA, 170 Ma) to anomaly M21 time (149.6 Ma). Continental outlines for 170 Ma in blue, those for M21 times in black with shading in grey. EUR, Europe; NAM, North America; IB, Iberia; AFR, Africa; ADR, Adria; G, Gibraltar; C, Ceuta. Euler poles for NAM, IB and AFR according to Vissers *et al.* (2013), using poles for NAM with respect to EUR adopted from Torsvik *et al.* (2012), and updated for the Gradstein *et al.* (2012) timescale. Red arrows indicate motion of Iberia relative to Europe; blue arrows indicate motion of Africa relative to Europe. Points x and y denote two marker points SE of Iberia at 170 Ma that are displaced with Iberia towards Ibx and Iby at M21 times, whereas motion of Adria together with Africa displaces these markers towards Adx and Ady. The differential motion between AFR and IB is indicated by the green arrows, illustrating the consequent opening of the Piemonte Ligurian basin. It should be noted that the choice of marker points x and y is arbitrary, but that a much more easterly position of these markers would imply a much larger Iberian continent, for which there is no evidence.

increase of metamorphic peak temperatures and a structure that is best illustrated in vertically oriented cross-sections, whereas in the northern Cap de Creus area a similar geometry is present in map view and the metamorphism clearly increases northward. Further north, the structure and associated metamorphism can unfortunately not be ascertained, because the continuation of the Variscan structure to the north is entirely concealed by the recent continental margin structure and associated submarine sediments. We suggest that the present-day structure of the Cap de Creus peninsula may at least in part result from alpine crustal-scale deformation, but also note that there are not many constraints on the details of that deformation. Our suggestion to ascribe the present-day structural geometry of northern Cap de Creus to an Alpine phase of rotation, however, seems a viable hypothesis because backrotation would bring the Variscan structure into concordance with structures in the central Pyrenees such as the Soulcem dome, and although the proposed rotation axis is at best approximate, backrotation brings the shear zone structures into orientations compatible with pre-alpine crustal extension on the eastern Iberian margin. We disagree with the criticism of Druguet *et al.* (2017) that excluding the southern Cap de Creus shear belt with its present-day, predominantly sinistral movement from the same rotation as the northern shear belt would lead to inconsistencies in our model interpretation. The Alpine structure of the well-documented ECORS profile in the central Pyrenees clearly shows, in one and the same section, domains with large tilts and almost non-tilted domains, and there is no reason to *a priori* preclude similar variations in alpine structure at the Cap de Creus peninsula.

Druguet *et al.* (2017) criticize our interpretation of the presented muscovite ^{40}Ar/^{39}Ar dates and suggest that they could represent partial (or complete?) resetting of the K/Ar clock during post-Variscan thermal events (Costa & Maluski 1988; Monié *et al.* 1994; Maurel *et al.* 2004; Boutin *et al.* 2016), rather than representing a Middle Jurassic mylonitic foliation. Interpreting those Jurassic muscovite results is not necessarily straightforward and we present one plateau date (CDC 13-3) and two disturbed datasets. The few grains from sample CDC 13-3 that we analysed were even-sized, optically inclusion-free grains devoid of any discoloration. The additional samples were unfortunately of a lower quality and, although care was taken to separate visibly inclusion-free grains, we present them here only as supporting evidence for the date obtained from sample CDC 13-3.

Druguet *et al.* (2017) raise a critical point in suggesting that we are not aware of the closure temperature (T_c) of the muscovites we analysed, and suggest a range of 250–400°C, which needs to be considered, although higher T_c (*c.* 420°C) has been estimated for grains $\geq$100 µm based on diffusion kinetics derived from laboratory experiments at hydrothermal conditions (Harrison *et al.* 2009). Theoretically, the closure temperature (Dodson 1973) for a particular mineral phase is highly dependent on the diffusive length scale (approximated by the grain size) and cooling rate. Using muscovite diffusion parameters of Harrison *et al.* (2009), Duvall *et al.* (2011) estimated closure temperatures as low as 250°C for 0.05 mm illite/muscovite grains. The white mica population in our analysis were in the range 180 – 250 µm, so theoretically T_c would be at the higher end of that range. However, there is increasing evidence that a fixed closure temperature cannot easily be applied to a particular mineral phase (Mulch & Cosca 2004), but, more importantly, scaled laboratory experiments seem to overestimate the natural diffusion rate in white micas (e.g. Villa *et al.* 2014; Villa & Hanchar 2017). Villa *et al.* (2014) observed that inherited ^{40}Ar in white micas was retentive to metamorphic temperatures ≥500°C, giving support for a higher T_c in white micas.

We cannot exclude the possibility that the grains we analysed exhibit an an open-system behaviour that closed in the Middle Jurassic, but even in the more retentive higher temperature part of the release spectra there is no evidence in the data, such as a staircase pattern (Kirschner *et al.* 1996), that would hint at a Variscan affinity. Our muscovite dates are also distinct from the younger 'major Jurassic fluid event' described by Cathelineau *et al.* (2012). On the other hand, bulk degassing experiments can mask intra-grain age variations (Kellett *et al.* 2016) caused by recrystallization and neocrystallization (e.g. Kirschner *et al.* 1996; Mulch & Cosca 2004). We therefore welcome studies to challenge our results and interpretation, possibly by the use of the *in situ* UV laser ablation technique (e.g. Mulch & Cosca 2004; Kellett *et al.* 2016). At this stage, however, the simplest interpretation of our results is that the Ar/Ar ages demonstrate Jurassic formation of the shear zones.

Druguet *et al.* (2017) claim that progressive Variscan polyphase tectonics associated with dextral transpression is well evidenced in Cap de Creus (Druguet 2001; Druguet *et al.* 2014) and that it can be recognized elsewhere in the Pyrenean basement. This model hinges on the assumption that the shear zones indeed reflect deformation during a late Variscan retrograde stage. We do not *a priori* reject transpressive deformation in the Variscan domain, but emphasize that our Ar/Ar results do not yield unequivocal evidence for late Variscan shearing. On the contrary, our results provide ages that happen to coincide with a well-documented stage of rifting and oceanization in the Alpine Tethys that reconstructs immediately adjacent to Cap de Creus in mid-Jurassic time. We therefore find it unwarranted to reject our Ar/Ar data in favour of the alleged late Variscan dextral transpression, which after all is a hypothesis hinging on the assumption that modern orientations reflect Variscan orientations unaffected by tilting during the Pyrenean orogeny, rather than data. Finally, the Variscan age of the shear zones documented by Carosi *et al.* (2012) from northern Sardinia, although possibly comparable with those in the Pyrenean Axial Zone, can hardly be taken as a valid argument for the age of the shear zones in the Pyrenees, in view of the large palaeogeographical distances between Sardinia and Iberia and the different orientations of these continental fragments during the Variscan orogeny as outlined above.

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References

Advokaat, E.L., van Hinsbergen, D.J.J. *et al.* 2014. Eocene rotation of Sardinia, and the paleogeography of the western Mediterranean region. *Earth and Planetary Science Letters*, **401**, 183–195.

Boutin, A., Saint Blanquat, M., Poujol, M., Boulvais, P., de Parseval, P., Rouleau, C. & Robert, J.-F. 2016. Succession of Permian and Mesozoic metasomatic events in the eastern Pyrenees with emphasis on the Trimouns talc–chlorite deposit. *International Journal of Earth Sciences*, **105**, 747–770.

Carosi, R., Montomoli, C., Tiepolo, M. & Frassi, C. 2012. Geochronological constraints on post-collisional shear zones in the Variscides of Sardinia (Italy). *Terra Nova*, **24**, 42–51.

Casas, J.M., Domingo, F., Poblet, J. & Soler, A. 1989. On the role of the Hercynian and Alpine thrusts in the Upper Paleozoic rocks of the Central and Eastern Pyrenees. *Geodinamica Acta*, **3**, 135–147.

Cathelineau, M., Boiron, M.-C. *et al.* 2012. A major Late Jurassic fluid event at the basin/basement unconformity in western France: ^{40}Ar/^{39}Ar and K–Ar dating, fluid chemistry, and related geodynamic context. *Chemical Geology*, **322–323**, 99–120, https://doi.org/10.1016/j.chemgeo.2012.06.008

Costa, S. & Maluski, H. 1988. Use of the ^{40}Ar–^{39}Ar stepwise heating method for dating mylonite zones: an example from the St. Barthélémy massif (Northern Pyrenees, France). *Chemical Geology*, **72**, 127–144.

Denèle, Y., Olivier, Ph. & Gleizes, G. 2008. Progressive deformation of a zone of magma transfer in a transpressional regime: the Variscan Mérens shear zone (Pyrenees, France). *Journal of Structural Geology*, **30**, 1138–1149.

Dodson, M.H. 1973. Closure temperature in cooling geochronological and petrological systems. *Contributions to Mineralogy and Petrology*, **40**, 259–274.

Druguet, E. 2001. Development of high thermal gradients by coeval transpression and magmatism during the Variscan orogeny: insights from the Cap de Creus (Eastern Pyrenees). *Tectonophysics*, **332**, 275–293.

Druguet, E., Castro, A., Chichorro, M., Francisco Pereira, M. & Fernández, C. 2014. Zircon geochronology of intrusive rocks from Cap de Creus, Eastern Pyrenees. *Geological Magazine*, **151**, 1095–1114.

Druguet, E., Carreras, J. & Mezger, J.E. 2017. Discussion on 'Middle Jurassic shear zones at Cap de Creus (eastern Pyrenees, Spain): a record of pre-drift extension of the Piemonte–Ligurian Ocean?' *Journal of the Geological Society, London*, first published online July 31, 2017, https://doi.org/10.1144/jgs2017-042

Duvall, A.R., Clark, M.K., van der Pluijm, B.A. & Li, C. 2011. Direct dating of Eocene reverse faulting in northeastern Tibet using Ar-dating of fault clays and low-temperature thermochronometry. *Earth and Planetary Science Letters*, **304**, 520–526.

Gradstein, F.M., Ogg, J.G., Schmitz, M.D. & Ogg, G.M. 2012. *The Geologic Time Scale 2012*. Elsevier, Amsterdam.

Harrison, T.M., Célérier, J., Aikman, A.B., Hermann, J. & Heizler, M.T. 2009. Diffusion of ^{40}Ar in muscovite. *Geochimica et Cosmochimica Acta*, **73**, 1039–1051.

Kellett, D.A., Warren, C., Larson, K.P., Zwingmann, H., van Staal, C.R. & Rogers, N. 2016. Influence of deformation and fluids on Ar retention in white mica: Dating the Dover Fault, Newfoundland Appalachians. *Lithos*, **254–255**, 1–7, doi.org/10.1016/j.lithos.2016.03.003

Kirschner, D.L., Cosca, M.A., Masson, H. & Hunziker, J.C. 1996. Staircase ^{40}Ar/^{39}Ar spectra of fine-grained white mica: Timing and duration of deformation and empirical constraints on argon diffusion. *Geology*, **24**, 747–450, https://doi.org/10.1130/0091-7613(1996)024≤0747:SAASOF≥2.3.CO;2

Maurel, O., Monié, P. & Brunel, M. 2004. ^{40}Ar/^{39}Ar Alpine ages of mylonitic shear zones in the Eastern Pyrenees: thermal resetting against deformation ages. *Geophysical Research Abstracts*, **6**, 02671.

Mezger, J.E., Schnapperelle, S. & Rölke, C. 2012. Evolution of the Central Pyrenean Mérens fault controlled by near collision of two gneiss domes. *Hallesches Jahrbuch für Geowissenschaften*, **34**, 11–29.

Monié, P., Soliva, J., Brunel, M. & Maluski, H. 1994. Les cisaillements mylonitiques du granite de Millas (Pyrénées, France). Age Crétacé ^{40}Ar/^{39}Ar et interprétation tectonique. *Bulletin de la Société Géologique de France*, **165**, 559–571.

Mulch, A. & Cosca, M.A. 2004. Recrystallization of cooling ages: *in situ* UV-laser ^{40}Ar/^{39}Ar geochronology of muscovite in mylonitic rocks. *Journal of the Geological Society, London*, **161**, 573–582, https://doi.org/10.1144/0016-764903-110

Muñoz, J.A. 1992. Evolution of a continental collision belt: ECORS-Pyrenees crustal balanced cross-section. *In*: McClay, K.R. (ed.) *Thrust Tectonics*. Chapman & Hall, London, 235–246.

Stampfli, G.M. & Borel, G. D. 2002. A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrons. *Earth and Planetary Science Letters*, **196**, 17–33.

Stampfli, G.M. & Hochard, C. 2009. Plate tectonics of the Alpine realm. *In*: Murphy, J.B., Keppie, J.D. & Hynes, A.J. (eds) *Ancient Orogens and Modern Analogues*. Geological Society, London, Special Publications, **327**, 89–111, https://doi.org/10.1144/SP327.6

Stampfli, G.M., Borel, G.D., Marchant, R. & Mosar, J. 2002. Western Alps geological constraints on western Tethyan reconstructions. *Journal of the Virtual Explorer*, **7**, 75–104.

Torsvik, T.H., Van der Voo, R. *et al.* 2012. Phanerozoic polar wander, palaeogeography and dynamics. *Earth-Science Reviews*, **114**, 325–368.

van Hinsbergen, D.J.J., Spakman, W., Vissers, R.L.M. & van der Meer, D.G. 2017. Comment on "Assessing discrepancies between previous plate kinematic models of Mesozoic Iberia and their constraints" by Barnett-Moore *et al. Tectonics*, corrected proof online November 4, 2017, https://doi.org/10.1002/2016TC004418

Villa, I.M. & Hanchar, J.M. 2017. Age discordance and mineralogy. *American Mineralogist*, corrected proof online, https://doi.org/10.2138/am-2017-6084

Villa, I.M., Bucher, S., Bousquet, R., Kleinhanns, I.C. & Schmid, S.M. 2014. Dating polygenetic metamorphic assemblages along a transect across the Western Alps. *Journal of Petrology*, **55**, 803–830, https://doi.org/10.1093/petrology/egu007

Vissers, R.L.M., van Hinsbergen, D.J.J., Meijer, P.Th. & Piccardo, G.B. 2013. Kinematics of Jurassic ultra-slow spreading in the Piemonte Ligurian ocean. *Earth and Planetary Science Letters*, **380**, 138–150.

Vissers, R.L.M., van Hinsbergen, D.J.J., van der Meer, D.G. & Spakman, W. 2017*a*. Cretaceous slab break-off in the Pyrenees: Iberian plate kinematics in paleomagnetic and mantle reference frames. *Gondwana Research*, **34**, 49–59.

Vissers, R.L.M., van Hinsbergen, D.J.J., Wilkinson, C.M. & Ganerød, M. 2017*b*. Middle Jurassic shear zones at Cap de Creus (eastern Pyrenees, Spain): a record of pre-drift extension of the Piemonte–Ligurian Ocean? *Journal of the Geological Society, London*, **174**, 289–300, https://doi.org/10.1144/jgs2016-014

Williams, G.D. & Fischer, M.W. 1984. A balanced section across the Pyrenean orogenic belt. *Tectonics*, **3**, 773–780.