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Interactive comment on "Neoproterozoic and post-Caledonian exhumation and shallow faulting in NW Finnmark from K/Ar dating and p/T analysis of fault-rocks" *by* Jean-Baptiste P. Koehl et al.

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Dear Sir, Madam, thank you very much for your input on the manuscript. Here is our response to your comments. We hope that the changes we implemented improve the shortcomings of the manuscript highlighted by your comments and suggestions. Please do not hesitate to contact us shall this not be the case for some of your comments.

1. Comments from Anonymous referee

Comment 1: the text is excessively long and could reasonably be expected to be

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shorted to make the salient points more accessible to the readership. Comment 2: The ages are distinct from other high temperature and Ar/Ar texturally constrained results from Finnmark which illustrate the importance of Caledonian processes. Much better evaluation of the results in the context of these other geochronometers is needed. Specifically, why are the ages so different, is it simply due to different fabrics being dated, a different closure temperature of the system and mineral, or are secondary alteration processes at play? It is trivial to address this question but is needed to place the work in the current regional context. The reported ages may very well be correct but then more detail is required to put them in the context of post Caledonian process (in the main). Comment 3: More evidence is required to demonstrate that the clay minerals all formed at the same time and that they have not been subsequently modified with later fluid movement on the "dated" structures. For example, more SEM and EBSD textural work would be a distinct advantage in addressing how many different fabrics are associated with each of the sampled structures. Comment 4: What is the potential of fine fraction feldspar modifying the K/Ar results? Is there evidence of significant fluid alteration on these structures? Comment 5: I am somewhat concerned with the number of references to unpublished works that are cited as "submitted" (e.g. Koehl et al., Davids et al.,). I do not think it acceptable to heavily rely on such currently unpublished work so I would suggest that a summary of the salient points in those unpublished works is presented in this paper so all the evidence for statements in this work is available to readers. Comment 6: Line 16: sentence structure I think you mean "during the opening of": : :. Line 34: replace "which" with "whose". Comment 7: Line 50; you probably should mention the timing of collisional phases as constrained this region prior to discussing post-Caledonian extension. See Kirkland et al., 2006, The structure and timing of lateral escape during the Scandian Orogeny: A combined strain and geochronological investigation in Finnmark, Arctic Norwegian Caledonides, which discusses the constraint on the timing of the collisional phase (431-428 Ma). Comment 8: Line 65: you need to present the evidence or at least discuss (if it is already published) the evidence for Timanian deformation in northern Finnmark. Comment 9: More

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discussion on the rational for a 30'c/km geotherm is needed. There are some regional thermobarometry studies that point to the peak P-T conditions which may be relevant assist in placing constraints on the retrograde thermal pathway. Comment 10: There are some sections of the text that need rewritten, for example evaluating the results against an unpublished (e.g. submitted) model (e.g. TKFZ development) by the same authors and coming to the conclusion that the previous unpublished model is wrong seems odd to me. You already know it doesn't work with your data. Comment 11: Line 105-115; I would have thought it relevant to discuss the results on basement metamorphism as provided by pseudosection thermobarometry, as it is likely to be some of the most accurate P-t constraints in the region and at least provides some constraints for subsequent processes. âËŸA ′c Gasser et al., 2015; D. Gasser, P. JeËĞrábek, C. Faber, H. Stünitz, L. Menegon, F. Corfu, M. Erambert, M.J. Whitehouse Behaviour of geochronometers and timing of metamorphic reactions during deformation at lower crustal conditions: phase equilibrium modelling and U–Pb dating of zircon, monazite, rutile and titanite from the Kalak Nappe Complex, northern Norway. âËŸA ′c Kirkland et al., 2016: C.L. Kirkland, T.M. Erickson, T.E. Johnson, M. Danišík, N.J. Evans, J. Bourdet, B.J. McDonald, Discriminating prolonged, episodic or disturbed monazite age spectra: An example from the Kalak Nappe Complex, Arctic Norway, Chemical Geology, Volume 424, 2016, Pages 96-110.

2. Author's response

Comment 1: Agreed. Comment 2: The correlation with other high-temperature chronometers is clear, as they are dealing with higher closure temperatures (U–Pb in zircon, or K–Ar and Ar–Ar in muscovite), the data we present simply have to be younger. K–Ar and Ar–Ar cooling ages on biotite are of special interest, because they are interpreted to reflect the cooling below 300°C (McDougall & Harrison, 1999). This temperature marks the transition from ductile to brittle deformation (Tullis & Yund, 1977; Scholz, 1988; Hirth & Tullis, 1989). Therefore, oldest fault gouge ages could be in the range of biotite cooling ages, but should never be older. For example, we obtained

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one Silurian age (427.3 ± 8.4 Ma) representing either mixing with host-rock (inherited muscovite/illite) or Silurian brittle faulting. Based on the dominant transport direction and kinematics along the Talvik fault (dip-slip top-south), we propose that the Silurian age reflects continued thrusting rather than lateral escape (as proposed in Kirkland et al., 2006 for orogeny-oblique thrusts). This age is consistent with U–Pb ages on titanite and pseudosection thermobarometry of Gasser et al. (2015) constraining Caledonian retrograde shearing at temperature < 550°C to Silurian times (440-420 Ma). To carry out investigations on other low-temperature chronometers like U–Th/He dating or fission track is beyond the scope of this manuscript, which rather focuses on the structural framework. As fault gouges are the weakest point in the crust, they are often reactivated by ongoing deformation. This can lead to repeated growth of clay mineral, yielding significant ages in different grain fractions or to meaningless mixing ages. Secondary alteration processes are unlikely as clay minerals are very stable in the shallow crust, but can never be excluded. The context of post-Caledonian processes as been widely discussed by several authors, onshore and offshore (e.g., Davids et al., 2013; Gudlaugsson et al., 1998; Indrevær et al., 2013; Torgersen et al., 2014; Ksienzyk et al., 2016).

Davids, C., Wemmer, K., Zwingmann, H., Kohlmann, F., Jacobs, J. and Bergh, S. G.: K-Ar illite and apatite fission track constraints on brittle faulting and the evolution of the northern Norwegian passive margin, Tectonophysics, 608, 196-211, 2013. Gasser, D., Jerábek, P., Faber, C., Stünitz, H., Menegon, L., Corfu, F., Erambert, M. and Whitehouse, M. J.: Behaviour of geochronometers and timing of metamorphic reactions during deformation at lower crustal conditions: phase equilibrium modelling and U–Pb dating of zircon, monazite, rutile and titanite from the Kalak Nappe Complex, northern Norway, Journal of Metamorphic Geology, 33, 513-534, 2015. Gudlaugsson, S. T., Faleide, J. I., Johansen, S. E. and Breivik, A. J.: Late Palaeozoic structural development of the South-western Barents Sea, Marine and Petroleum Geology, 15, 73-102, 1998. Hirth, G. and Tullis, J.: The Effects of Pressure and Porosity on the Micromechanics of the Brittle-Ductile Transition in Quartzite, Journal of geophysical Research, 94, 17825-17838, 1989. Indrevær, K., Bergh, S. G., Koehl, J-B., Hansen,

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J-A., Schermer, E. R. and Ingebrigtsen, A.: Post-Caledonian brittle fault zones on the hyperextended SW Barents Sea margin: New insights into onshore and offshore margin architecture, Norwegian Journal of Geology, 93, 167-188, 2013. Ksienzyk, A.K., Wemmer, K., Jacobs, J., Fossen, H., Schomberg, A.C., Süssenberger, A., Lünsdorf, N.K. & Bastesen, E. 2016. Post-Caledonian brittle deformation in the Bergen area, West Norway: results from K–Ar illite fault gouge dating, Norwegian Journal of Geology, 96, 1-29. McDougall, I. & Harrison, T. M. 1999. Geochronology and Thermochronology by the 40Ar/39Ar Method, 2nd Oxford University Press, New York. Scholz, C. H.: The brittle-plastic transition and the depth of seismic faulting, Geologische Rundschau, 77/1, 319-328, 1988. Torgersen E., G. Viola, H. Zwingmann and C. Harris. 2014. Structural and temporal evolution of a reactivated brittle-ductile fault – Part II: Timing of fault initiation and reactivation by K-Ar dating of synkinematic illite/muscovite. Earth Planet. Sci. Lett., vol. 407, pp. 221-233. Tullis, J. and Yund, R. A.: Experimental deformation of dry Westerly Granite, Journal of geophysical Research, 82, 36, 5705-5718, 1977. Comment 3: It would be nice to have all kinds of accompanying investigations, but this is not the focus of our studies. The overwhelming majority of fault gouge papers in literature is accepted without SEM and EBSD work. Comment 4: The influence of older feldspar leading to younger ages by the low closure temperature has been explained in the text. A significant fluid alteration of feldspar in the fault gouge structure would lead to the formation of sericite, which in many cases can be recognized easily by a well-crystallized 001-white mica peak. We did not find any indication for this in our x-ray patterns. Comment 5: The work by Davids et al. submitted is only briefly integrated to the study for comparison purposes and the conclusions of the present manuscript do not rely at all on the conclusions of Davids et al. submitted. Regarding the Koehl et al. (submitted) work, it is already available on Researchgate and on the data repository of the University of Tromsø as part of the PhD thesis of the main author (Koehl, 2018; paper 1). Thus, we find it acceptable to refer to this earlier work. Koehl, J-B. P.: Mid/Late Devonian-Carboniferous extensional faulting in Finnmark and the SW Barents Sea, Unpublished PhD Thesis, University of Tromsø, Norway, 2018.

Comment 6: Agreed. Comment 7: Agreed. Comment 8: Agreed. Comment 9: Agreed. See answer to comment 11. Comment 10: We do not know whether the model presented in Koehl et al. (submitted; Norwegian Journal of Geology) is wrong or right. However, we hereby present an alternative to this model and try to be critical with our own work. We believe that mentioning the model presented in Koehl et al. (submitted) is important to the follow up of the that study, and does not impede the clarity of the present contribution. Comment 11: Agreed for the Gasser et al. (2015) study. However, we do not think the proposed work of Kirkland et al. (2016) is suitable to discuss the exhumation of Paleoproterozoic basement rocks in Finnmark because the samples dated in this study are from younger rocks of the Kalak Nappe Complex. This work is not appropriate either to discuss the exhumation history of Caledonian rocks during post-Caledonian extension because the ages obtained are pre-Caledonian and do not yield any information about peak Caledonian metamorphism.

3. Changes implemented

Comment 1: Removed "cf." trough manuscript (23 occurrences); changed "top-to-the-" expressions to "top- " consistently through the whole manuscript ; deleted "Caledonian" line 717; deleted "/age" line 722; changed "top-to-the-south, brittle (-ductile?), Caledonian" to "top-south Caledonian brittle" line 722; deleted fault orientation, e.g., "NNE-SSW striking", lines 332, 340, 353, 365-366, 1424, 1425-1426, 1427, 1429, 1430, 1435, 1437. Comment 2: see answer to comment 11. Added Tullis & Yund (1977), Gasser et al. (2015) and Ksienzyk et al. (2016) to reference list. Comment 3: none. Comment 4: none. Comment 5: none. Comment 6: changed "which" by "whose" line 34. Comment 7: added "Near the end of Caledonian contraction, lateral escape initiated in a NE-SW direction, and this episode of deformation was constrained to ca. 431–428 Ma by U–Pb and Ar–Ar dating (Kirkland et al., 2005, 2006; Corfu et al., 2006)" lines 51-53, and Kirkland et al. 2006 to the reference list. Comment 8: added "Siedlecka & Siedlecki, 1967; Roberts, 1972; Siedlecka, 1975" as supporting literature for Timanian deformation in northern Finnmark. Comment 9: see answer to comment 11. Also, we added the following references to support the choice of a 30°C/km geothermal gradient: Bugge et al., 2002; Chand et al., 2008; Vadakkepuliyambatta et al., 2015. Comment 10: none. Comment 11: added "U–Pb ages on titanite from northern Troms provide a minimum estimate of ca. 440–420 Ma for retrograde (< 550°C) Caledonian shearing (Gasser et al., 2015)" line 108-110, and Gasser et al. 2015 to reference list. Also added ", which is consistent with pseudosection thermobarometry and U–Pb ages on titanite constraining retrograde Caledonian shearing < 550°C (i.e., < 18 km depth) in the Kalak Nappe Complex in northern Troms to 440–420 Ma (Gasser et al., 2015)" in discussion chapter, line 655-657 and "This is consistent with thermobarometry and U–Pb ages constraining Caledonian retrograde shearing at temperature < 550°C to the Silurian at ca. 440 –420 Ma (Gasser et al., 2015)." lines 728-730.

Best regards, Jean-Baptiste

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