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Interactive comment on "Tectonic Exhumation of the Central Alps Recorded by Detrital Zircon in the Molasse Basin, Switzerland" *by* Owen A. Anfinson et al.

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The article of Anfinson and co-authors reports a detailed study of three sedimentary sections in the Swiss Molasse basin: the main focus of their research is on a 'central' section in the canton Luzern, an eastern section from the vicinity of Bregenz, near Lake Constance on the Austrian-Swiss border, and a western section from the vicinity of the town of Thun, in the canton Berne. The objective of the paper is to investigate the exhumation of the hinterland of the three sections. It is hypothesized that, given that the sections encompass depositional ages from ∼30 Ma up to ∼13 Ma (central section), 27 - <20 Ma (western section) and 27 – 15 Ma (eastern section) unroofing

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of the central Alps, and in particular the Lepontine Dome, would be recorded. In the light of the story as it unfolds further into the paper, was this a realistic expectation? I'll come back to this question further into the review.

The paper first gives an overview of ranges of zircon provenances, signaling recycling of central European crust through time from the Proterozoic until the Variscan. As zircon often is quite robust small signals from all these periods have been recovered. Although the paper is quite extensive in its citing of previous work, at this stage I am missing an important paper: that of Gebauer et al. in the Swiss Petrographoische and Mineralogische Mitteilungen (1988„ v: 68, pg 485-490) which reports Archean zircons in a retrograde Caledonian eclogite from within the Gotthard Massif, as probably the first report of Precambrian provenance of recycled zircons from Switzerland.

The next necessary step is a short overview of the tectonic development of the Alps as a mountain range and as a collisional orogen. Both aspects are important, as the Lepontine dome which provenance is one of the targets of the study formed by orogenic processes in the final continent-continent collision stages of the orogenic development. The former aspect is important as the formation of mountain ranges and their paleogeographic distribution will allow or as the case may be prevent detritus to enter the sedimentary pile in the northern foreland basins.

Finally, the introduction ends with an up to date summary of the stratigraphy of the Swiss Molasse basin from the Oligocene up to the Middle Miocene, again a necessary piece of information if we want to understand the complex signals as expected form the zircon provenance studies.

When presenting their data set the authors go a long way to graphically present their data sets. For me the probability density diagrams (limited at 1000 Ma) probably worked best, while the pie charts were somewhat helpful to get a handle on age distribution.

What then is the main result of the paper, based on several thousands of individual analyses from three depo-centers deposited over a time period from ca 30 to ca 15 Ma is that during that period the detritus is exclusively Variscan in age. Apart from one single Eocene grain suggested to be of volcanic origin. The most important new finding of the paper is that two different provenance spectra are recorded clearly separated in time: in the younger sediments a young Variscan peak dominates: 250 – 320 Ma, and in the older sediments a more complex pattern is found with Variscan peaks at that show more complexity: 250-300 Ma in the lowest Flysch units, and complex even more complex Variscan signals in the following units: 300 – 320 Ma 320 – 350 Ma, and in addition a 350 – 400 Ma signal. All samples have reworked pre-Variscan zircons, but in the lowest Lower Freshwater Molasse and the underlying Lower Marine Molasse they are a dominant component. In these units an even older Panafrican component becomes increasingly important.

What does this tell us: there is a distinct switch in provenance between the lower units and the uppermost units, and this switch lies within the Lower Freshwater Molasse, where the upper unit of the LFM belongs to the upper provenance domain and the lower unit of the LFM and the units below it belong to the lower provenance domain. What the paper contributes is a wealth of information on the erosive removal of first the thrust sheets of the Austro-Alpine, and subsequently the thrust sheets containing the European Variscan middle crust as exposed probably as the material coming from the Aare-Gotthard massifs. There is a clear divide where significant amounts of Austro-Alpine cover was exposed in the hinterlands and where it ceased to contribute sometime around 21 Ma ago.

This aspect is discussed in the paper, but to my mind the discussion could be pushed further. The connection between the Variscan signal in the younger units had already been recognized by Von Eynatten and Wijbrans (2003) of course, and it is good to see this confirmed. A positive link between this age signal and the eroding Variscan basement could have been made by presenting a a compilation of U/Pb zircon ages from in situ rocks from the external massifs and their enveloping metamorphics. The other

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point that perhaps should be developed somewhat further is the zircon provenance of the signal in the lower units, attributed to eroding Austro-Alpine cover. This easily made first point of course is that the provenance f zircons in these units is dramatically different than that of the upper units, and reflect formation in a domain geographically removed from the European Variscan crystalline basement. The question is where was the Adria plate where it could incorporate Panafrican-Cadomian aged zircons and Caledonian aged zircons in addition to a fundamentally different spectrum of Variscan ages when compared with the spectrum of the younger rocks that reflect European crystalline middle crust? Some addiitonal information is a little obscure yet in the public domain: the PhD thesis of Claudia Panwitz from the University of Halle (2006) that reports Panafrican muscovite ages from the Nördlichen Grauwackenzone of the Tauern Window in Austria.

Another fundamental observation that isn't expanded sufficiently in the discussion is the fact that not a single grain was found that can reasonably be attributed to the Lepontine dome. This was one of the main research questions formulated in the introduction of the paper. Its absence needs to be discussed more fully. Is this absence of a Lepontine signal in the data a disappointment? Not really, although the authors embarked on a study to find where and when the detritus coming from the Lepontine dome enters the Swiss Molasse basin, the answer must be it doesn't. Or at least it doesn't in the sections and time slices that they selected for study. Is this surprising? May be not, in that for the Luzern section of the present study, Von Eynatten and Wijbrans (2003) in their section 3, which is very close to the Luzern section of the present study found exactly the same thing: no Lepontine signal... And von Eynatten and Wijbrans found for their section 1+2, which is very near the Bregenz section in the present study that it is dominated by detritus coming from the Austro-Alpine. The consistency between the result of the present study and that of Von Eynatten and Wijbrans could have been made a in a little more strongly. Probably the most intriguing result is that for the Thun section, which is the section 4 of the Von Eynatten and Wijbrans study, Von Eynatten and Wijbrans do report muscovites with ages consistent with a Lepontine provenance.

It now becomes intriguing to speculate as to why the muscovite does show a Lepontine provenance and the zircons do not. Unlucky sampling seems to be excluded, as the zircon study used sample sets large enough to say with some confidence that the signal found is representative for the total population to within 2-sigma. Another explanation that comes to mind is that the metamorphic grade of the exposed Lepontine at the time of the Middle LFM upwards was high enough to crystallize muscovites, but not high enough to crystallize zircons or thin films of Lepontine overgrowths on pre-existing zircons. The thin films of zircon overgrowth could well have been missed when applying a laser ablation technique. Other studies have attempted depth profiling of zircons using a SHRIMP, which allows a better handle on excavating into a zircon, when compared with a laser ablation technique (e.g. Keay et al. 2001). So either the signal wasn't there or it was too subtle to be recorded with the analytical technique used. Coming than to the ultimate research question of the paper: did the Lepontine dome come up first and the external massifs of the Aar-Gotthard second, or was it the reverse. For the rivers streaming to the north and the north-east, there was in fact a barrier preventing the Lepontine detritus from reaching the Molasse basin in the vicinity of Luzern, and Bregenz during much of the Miocene. Detritus carried by rivers flowing to the northwest and west did carry some detritus from the Lepontine dome into the Molasse basing but this was not recorded by U/Pb zircon, but was in fact recorded by muscovite Ar/Ar. Therefore it would seem that during the early Miocene the drainage and the orographic barriers were not too different from todays: the present day Reuss river draining the Aare Gotthard massifs toward the north do not contain a Lepontine signal to the present day, as the Reuss comes from the Ursenental and the Furka, and doesn't connect in any significant way with the Lepontine domain which only really starts in earnest south of the Gotthard massif. The Rhine near Bregenz, most likely doesn't contain a lLepontine signal today either. Although there is a small chance that it does contain a small Lepontine fraction now, as one of the tributaries of the Rhine joining the main triunk near Disentis comes from the Lukmanier pass where at the drainage divide today the Lepontine metamorphism reaches garnet-staurolite grade in the meta-pelites in my recollection.

In summary the paper contains so much new information that a little more in depth discussion would be welcome. And in this review, I have tried to start this discussion. More discussion of the significance of the data set in terms of zircon provenance itself, but also what the differences are between the present data set and that of the muscovite studies of Von Eynatten and Wijbrans (2003), and also more recently, on the Austrian river provenance signals reported by Gemignani et al in Tectonics 2017. How do the similarities and the differences between these data sets contribute to our understanding of the tectonics of the central Swiss Alps and provenance of various rock units.

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