Pre-print

Reply to Comment on Resentini et al., 2020: "Ongoing exhumation of the Taiwan orogenic wedge revealed by detrital apatite thermochronology: The impact of effective mineral fertility and zero-track grains".

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Abstract

In their Comment to Resentini et al. (2020), Mesalles et *alii* pointed out supposed fundamental inaccuracies concerning analytical aspects and the tectonic interpretation of fission-track data. This would invalidate the main conclusions of our study. Here we demonstrate that their criticism is ill-founded.

Keywords: detrital thermochronology, Taiwan orogen, apatite fission tracks.

1. Introduction

The comments made by Mesalles *et alii* allow us to further elucidate crucial points of our article, taking into account that our main goal is that of illustrate methodological issues rather than the tectonic evolution of Taiwan, an orogenic region chosen as a most suitable test case. Therefore, we will first address the comments concerning analytical aspects, and then those concerning tectonic interpretation.

2. Analytical aspects

2.1 Issues concerning mineral fertility

Based on the occurrence of both rutile and apatite in the grain mount shown in our Fig. 1D, Mesalles *et alii* claim that the Raman identification of apatite grains performed in our study was a "desperate effort" to manage a supposed rutile contamination problem, thus shedding doubts on the total fertility map of Fig. 2C. This suspect is unjustified, because we systematically identify all minerals in the mount other than apatite, following the procedure explicitly referred to in section 4 and fully illustrated in Malusà and Garzanti (2019 p. 139): *"Point-counting under the microscope allows one to determine the percentage of apatite and zircon grains in these concentrates (step 8), which also typically include other diamagnetic dense minerals"*. Moreover, beside point-counting, we used in thus study also Raman spectroscopy to ensure that all spurious mineral grains were duly accounted for.

Our Fig. 1D, expressly conceived to illustrate the potential of Raman spectroscopy for a proper identification of all apatite and non-apatite grains, shows on purpose the most contaminated part of the mount, an unfavorable situation which is not representative of the entire mount, not to say of the other Taiwan samples. In theory, minerals as dense as rutile or zircon should be eliminated by gravimetric separation in liquid diiodomethane, but this may not happen in practice probably because a few denser grains adhere to the glassware during stirring. This inconvenient, however, does not affect fission-track counting. Rather, spurious zircon grains are sometimes exploited to more easily match an apatite mount with the corresponding print in the external detector.

Precisely because the occurrence of spurious grains may lead to an overestimation of inferred apatite fertility values, a proper detection of such grains is a qualifying point of the approach described by Malusà et al. (2016) and Malusà and Garzanti (2019), which was followed step by step in our study. This ensures the accuracy of the total fertility map presented in our Fig. 2C.

2.2 Issues concerning zero-track grains

Mesalles *et alii* also claim that we did not clearly define U-rich and U-poor apatite grains. This is indeed a crucial point, and although we did provide our explicit definition in Sect. 2, we shall repeat it here for the sake of clarity: "*U-poor zero-track grains are those that fail to induce tracks in the external detector because of their very low [U], whereas U-rich zero-track grains do induce tracks in the external detector*". Mesalles *et alii* also remark that we fail to explain how the [U] of U-poor zero-track grains was determined in our Fig. 8. Figure 8, however, does not include any U-poor zero-track grain, but only U-rich zero-track grains and grains with fission tracks. U-poor zero-track grains do not induce tracks in the external detector, which precludes any calculation of [U] based on induced-track densities.

We fully agree with Mesalles *et alii* that it is wrong to simply equate zero-track grains automatically with very young cooling ages. In our Sect. 2, we explicitly state that *"apatite grains in a sediment sample may not show spontaneous fission tracks, either because the residence time below the temperature of total annealing was too short, or because the [U] is too low"*. Only after the detailed analysis presented in our Sect. 6.3 we concluded that the absence of spontaneous tracks in many apatite grains from Taiwan is mainly due to a short residence time below the temperature of total AFT annealing, and not to low [U]. U-rich zero-track grains ideally encompass an age range between 0 Ma and a maximum age corresponding to Ns =1 (where Ns is the number of spontaneous tracks). This age range becomes narrower with increasing [U], as illustrated in Fig. 1A. U-poor zero-track grains do not provide any fission-track age constraint and are useless for detrital thermochronology. The crucial point here is that, instead, U-poor zero-track grains do contribute to the total apatite fertility (see Fig. 1B) and must thus be removed to measure the effective apatite fertility, a concept first introduced in our article.

The counting of U-rich zero-track grains is indeed a standard procedure in detrital and bedrock AFT studies, and we are aware that previously published AFT studies in Taiwan (e.g., Willett et al. 2003; Mesalles et al. 2014) did include zero-track grains in their AFT age calculations. What we emphasize in our article is a pitfall particularly insidious because easy to incur to, which Nobel Prize Kahneman (2011) labelled WSYATI (*What you see is all there is*) to emphasize our very human tendency to systematically overlook what is not obviously present under our eyes. This explains why essential information provided by zero-track grains may remain underexploited, as illustrated well by the Himalayan example discussed in our Sect. 8. The tendency to underestimate zero-track grains is even more serious in bedrock studies.

Mesalles *et alii* also state that our dataset "*is generally consistent with existing bedrock AFT ages in the drained catchments albeit with an underrepresentation of older unreset AFT age peaks known to be present in the source terrains*". They relate this suspect to the supposedly insufficient number of grains analysed per drainage basin to fully characterise basin-wide exhumation. While it is true that the number of dated grains in some samples is inadequate to faithfully reflect a polymodal grain-age distribution, the unimodal distribution observed for many other samples and the observed consistency of single grain-age data does provide adequate information. On the other hand, we reject the claim that the overwhelming abundance of U-rich zero-track grains found in our samples could result from a sampling bias that would be removed by increasing the number of dated grains. This unusual feature reflects the fact that Taiwan exhumation is very young, as demonstrated by a range of independent geologic constraints. Increasing the number of dated grains could improve precision but would not alter the preponderance of zero-track grains yielding very young AFT ages over grains yielding older unreset AFT ages. What Mesalles *et alii* describe as "*an underrepresentation of older unreset AFT age peaks in our detrital samples*" it is quite likely to represent instead an overrepresentation of older unreset AFT age peaks in bedrock samples because of non-random selection of apatite grains for fission-track counting.

3. Tectonic interpretation

3.1 Consistency with bedrock data

According to Mesalles *et alii*, there would be a certain number of omissions and misunderstandings underlying our tectonic interpretation. First, existing bedrock data would have been ignored. This is not. Bedrock data were fully considered. In our figures, they are synthesized by the reset zones proposed by Fuller et al. (2006). We are aware that Simoes et al. (2012) proposed a different AFT reset zone for southern Taiwan (as shown by Mesalles *et alii* in their Fig. 1), despite the close similarity between datasets in Fuller et al. (2006) and Simoes et al. (2012). This partly reflects the difficulties in the interpretation of fission-track data when the time elapsed between subduction and accretion and subsequent arc-continent collision is very short. The young detrital AFT ages that we obtained after full consideration of the overwhelming U-rich zero-track grains in Taiwanese river sands can be safely used to constrain arc-continent collision. As a result, our thermochronologic picture is similar, for the southernmost part of the island, to that proposed by Simoes et al. (2012), which also implies that the Fig. 1 in Mesalles *et alii* confirms our results. It is noteworthy that the main advantage of the detrital thermochronology approach is to provide a first-order picture of the average long-term erosion rate over large areas by using a relatively low number of samples.

By no means the detrital approach is expected to highlight the exhumation history of a target area with the same local details as the bedrock approach. In this perspective, the Taiwan study proves to be successful even in the Alishan area, where both reset and unreset ages were reported from bedrock: old ages are indeed found in our detrital sample 4, where U-rich zero-track grains yielding very young AFT ages are nevertheless dominant.

3.2 Impact of catchment geology

According to Mesalles *et alii*, our proposed extension of the AFT reset zone would ignore the local geology of individual drainage basins. The Western Foothills do include Plio-Pleistocene synorogenic successions such as the Toukoushan Fm. derived from the Central Range. We agree that including those conglomerates in the AFT reset zone would be incorrect. However, unlike what claimed by Mesalles *et alii*, we did not include these synorogenic successions in our AFT reset zone. Mesalles *et alii*'s criticism is based on the improper comparison between two maps (our Fig. 6 and their Fig. 1) drawn at substantially different scales. Our detrital samples 1, 3 and 10 may include apatite grains recycled from the Toukoshan Fm., but the exposure area of this formation, large in catchment 3, is minor in catchment 1, which makes it an unlikely dominant source for sample 1. Those conglomerates, when dated by Mesalles et al. (2014), yielded a youngest AFT age component at 4.7±0.5 Ma and single-grain ages mostly ranging from 4 to 20 Ma. In our samples 3 and 10, we observe instead a dominant youngest peak at ~1 Ma, which indicates that the reset grains in our samples did not originate from the Toukoshan Fm.

3.3 Evidence for southward progressing exhumation

We fully agree with Mesalles *et alii* that our AFT dataset, taken alone, does not provide conclusive evidence for an earlier collision in the north of the island. This is clarified in the abstract already, where we write: *"the revised AFT reset zone includes the* *southernmost part of the island and, when combined with published ZFT data, supports a scenario of southward progressing exhumation during arc-continent collision"*. The ZFT data discussed in our Sect. 7, and in greater detail in Malusà and Fitzgerald (2020) are now illustrated in the new Figure 1 for the sake of clarity. These data show that the removal of the rock pile with a thermochronologic fingerprint acquired before the onset of arc-continent collision was likely completed by 2 Ma in the northern part of the island, but after 1 Ma to the south. Our detrital AFT data suggest that rapid exhumation is now affecting the southernmost part of Taiwan, although the rock pile with a ZFT fingerprint acquired before the onset of arc-continent collision is not yet completely removed there. The main thermochronologic argument provided by Mesalles *et alii* to support a model of simultaneous collision is the occurrence of ZFT reset ages of 5-7 Ma in lower-greenschist metamorphic rocks of both the northern Hsuehshan Range and the southern Central Range. However, that information just indicates the time when those rocks crossed the ZFT partial annealing zone, not the onset of arc-continent collision. In that respect, the detrital approach provides a more reliable indication.

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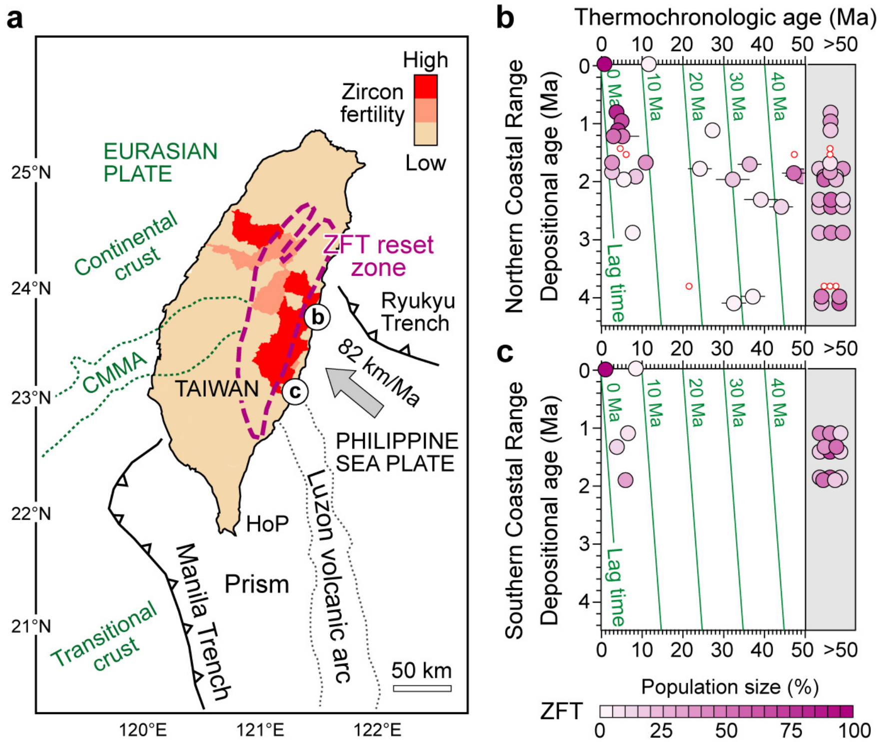

Figure 1. Synthesis of detrital ZFT data from Taiwan (after Malusà and Fitzgerald, 2020). (a) Plate-tectonic setting portraying regions with higher zircon fertility. CMMA = continental margin magnetic anomaly; HoP = Hengchun Peninsula; "b" and "c" = location of datasets from the northern and southern Coastal Range, illustrated to the right. (b, c) Detrital ZFT data from the Taiwan-derived Plio-Pleistocene successions of the northern (Kirstein et al., 2010) and southern (Kirstein et al., 2014) Coastal Range, and corresponding modern sediments (see Malusà and Fitzgerald, 2020 for full references). Different color intensities in the lag-time diagrams indicate the different size of each grain-age population (see color bar). Small red dots indicate grain-age populations in sediments from the orogen pro-side (Mesalles et al., 2014).