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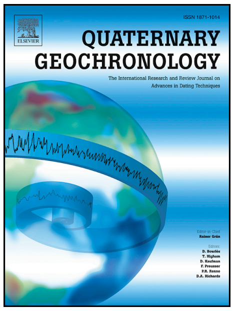

‘Radical interpretations’ preclude the use of climatic wiggle matching for resolution of event timings at the highest levels of attainable precision

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'Radical interpretations' preclude the use of climatic wiggle matching for resolution of event timings at the highest levels of attainable precision. Response: Comment on Mark et al. (2017): High-precision $^{40}Ar/^{39}Ar$ dating of Pleistocene tuffs and temporal anchoring of the Matuyama-Brunhes boundary. Quaternary Geochronology, 39, 1-23. Channell & Hodell (2017).

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Abstract: An age model (Mark et al., 2017) for ODP 758 and the Matuyama-Brunhes boundary transition and Termination IX in the equatorial Indian Ocean is robust and accurate. No significant magnetic lock-in delay is evident at the depth of the Matuyama-Brunhes boundary and the study highlights that $^{40}Ar/^{39}Ar$ *geochronology is critical for dissection of the Pleistocene at the highest levels of temporal precision and minimal model-dependence. Testing of leads and lags in global-scale climate*

response requires independently dated timescales to reveal the fine-detail recorded by the various climate archives.

We thank Channell & Hodell (2017) for their interest in our recent study. Although low sedimentation rate cores are not the ideal target for constraining complexities in the geomagnetic timescale or $\partial^{18}O$ isotope stratigraphies (as highlighted by Mark et al., 2017; Valet et al., 2016), the data we present are exceptionally robust and our conclusions are supported by other datasets (Bronk Ramsey et al., 2012; Lisiecki and Raymo, 2009, 2005, Mark et al., 2014, 2013, Sagnotti et al., 2016, 2014; Skinner and Shackleton, 2005; Valet et al., 2014). Much of these data have been ignored by Channell & Hodell (2017) in their critique of our work, but are essential for accurate interpretation of our results. Clearly the age of the last full reversal of the Earth's magnetic field (the Matuyama-Brunhes geomagnetic reversal, MBB) is important and as such, data suggesting inaccuracies in previous ages (and indeed other approaches that have attempted to constrain the event in time) (e.g., Mark et al., 2017) require scrutiny and when required, clarification. We provide such clarification here.

The MBB age that we calculate using Bayesian modelling combined with a tephrochronology and radio-isotopic dating approach is within uncertainty of the MBB age defined by the high-resolution Sulmona basin palaeo-lake record from Italy (Sagnotti et al., 2016, 2014), as well as the MBB age defined by numerous terrestrial North American sections and a re-interpretation of the transitionally magnetised $^{40}Ar/^{39}Ar$ dated lava flows that are associated with the geomagnetic reversal (Mark et al., 2017). Channell & Hodell (2017) do not discuss these records. The MBB age determined from ODP 758 is thus not a single datum or anomaly, but a robust and critical component of a growing data set that is re-defining the age and structure of this geomagnetic polarity reversal. We submit that dismissing high-quality data which appear to conflict with complex models imperils our ability to improve the accuracy of these models.

The geomagnetic and $\partial^{18}O$ isotope data presented by Valet et al. (2014) show more complexity to the MBB transition than the equivalent data from ODP 758 owing to the higher sedimentation rate in core MD90-0961, as expected. The age model for this core is an order of magnitude lower precision than our age model (± 5 ka versus ± 0.6 ka, respectively) and shows that the relative palaeo-intensity (RPI) drop associated with the MBB occurred at 784 ± 5 ka, which is indistinguishable from the global average age for the MBB that we calculate, 783.4 ± 0.6 ka. The key issue to highlight here is that in a slow sedimentation record the MBB transition displays as essentially instantaneous in time, represented by a spike in the RPI or a rapid transition in palaeo-magnetic direction (Figure 2, Mark et al., 2017). When comparing such records to a high sedimentation record (Valet et al., 2014), which show a more complex and protracted history (Figure 2, Valet et al., 2014), the instantaneous event is equivalent to the onset of the MBB transition in the high sedimentation core and not the mid-point of the transition. As such, there is no discrepancy between the timing of the MBB in both the ODP 758 and MD90-0961 records. Therefore, providing there is no magnetic lock-in delay, and such phenomena are not common at the relatively shallow depths of the MBB (Tauxe et al., 1996; Bleil and von Dobeneck, 1999; Horng et al., 2002), low sedimentation cores that define short lived excursions in palaeo-magnetic and proxy data are adequate to establish the age of geomagnetic events, whereas fast sedimentation rates facilitate interrogation of the complexities of geomagnetic reversals, including reversal durations.

Our data are further supported by the fact that Valet et al. (2014) place the Australasian Tektites at 790 ± 5 ka, which is indistinguishable from the age we propose for the same tektite horizon in ODP 758 (786 ± 2 ka, Mark et al., 2017), and the age of Termination IX at 788-789 (± 5 ka) (Valet et al., 2014) is also indistinguishable from our reported Termination IX age (785.6 ± 0.8 ka, Mark et al., 2017). The temporal alignment of three data points between two local records with different sedimentation rates, albeit one record at considerably higher precision, as well as data from Italy (Sagnotti et al., 2016, 2014) and North America (Mark et al., 2017), is compelling and should not be disregarded.

The temporal correlation indicates that downward bias (magnetic lock-in delay) of the MBB transition is not significant within ODP 758 (and certainly not significant at the level of precision we obtain using $^{40}Ar/^{39}Ar$ dating) and that the $\partial^{18}O$ isotope stratigraphy placement is accurate. However, the timeline of MBB-related events in the Indian Ocean (Mark et al., 2017) is not compatible with the age of the MBB at ca. 773 ka in the Atlantic Ocean (Channell et al., 2010). Again, we highlight that the age uncertainty reported with the ca. 773 ka age for the MBB by Channell et al. (2010) is not accurate (Mark et al., 2017) and this uncertainty is at least ± 5 ka (Lisieki & Raymo, 2005).

In attempting to align the records from the Atlantic Ocean with ODP 758 and MD90-0961, it is necessary to consider that previous studies detail leads and lags in the response of the Earth system between different climate archives (e.g., cryosphere, terrestrial and marine realms, (Bronk Ramsey et al., 2012; Mark et al., 2014, 2013) and within the same climate archives (e.g., marine-marine, Lisiecki and Raymo, 2009; Skinner and Shackleton, 2005). We (Mark et al., 2017) asked the question as to whether the level of dispersion in the location of the MBB within the

$\partial^{18}O$ record, and the age of Termination IX between the Atlantic and the equatorial Indian Ocean could be due to such processes. Such an interpretation should not be unexpected given the lag in response between the Atlantic and Pacific Oceans (Lisiecki and Raymo, 2009). Our contribution is thus not the first study to suggest (and demonstrate) such *'radical interpretations'* (Channell & Hodell, 2017) that preclude the use of climatic wiggle matching for resolving event timings at the highest levels of precision. Lisiecki and Raymo (2009) in fact identified that such problems are manifested in the LR04 stack (Lisiecki and Raymo, 2005) and highlighted that such recorda are only accurate to within ca. ± 5 ka as a consequence.

Finally, we highlight that although there exist various calibrations of the $^{40}Ar/^{39}Ar$ system, which for the Alder Creek sanidine standard have actually converged in recent years (Niespolo et al., 2017), a rapidly cooled mineral (e.g., sanidine) only has a single $^{40}Ar/^{39}Ar$ eruption age, or more specifically a single $^{40}Ar^{*}/^{40}K$ ratio. It is the conversion of this ratio to an age (using a decay constant and mineral standard of 'known' age) that leads to confusion in the appropriate use of the different $^{40}Ar/^{39}Ar$ calibrations. This is exemplified by Channell & Hodell (2017), who suggest that different calibrations account for the 10 ka discrepancy between the MBB age of (Mark et al., 2017) and (Channell et al., 2010). This is not so.

It is useful that Channell & Hodell (2017) highlight, as we begin to sequence the Quaternary at unprecedented levels of precision, that the previous chronological tools of choice can become incapable of resolving the fine detail needed for accurate dissection of the geological record (e.g., K-Ar dating). With respect to the level of temporal resolution and accuracy attainable by the $^{40}Ar/^{39}Ar$ technique throughout the Quaternary (Mark et al., 2017), we need to be increasingly aware of the assumptions (e.g., synchronicity in the global system) that underpin our dating techniques and the limitations associated with such techniques. For example, Simon et al. (2017) recognize that numerous potentially inaccurate assumptions underpin the hybrid tuning-^{40}Ar/^{39}Ar dating approach that they adopt, and construction of a chronology for the MBB from the Montalbano Jonico marine succession includes the extrapolation of age data and linear sedimentation rates, which are 'probably an oversimplified solution and that sedimentation rates might have varied correspondingly with the large MIS 19a oscillations' (Simon et al., 2017).

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