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On the reliability of the Matuyama–Brunhes record in the Sulmona Basin—Comment to 'A reappraisal of the proposed rapid Matuyama–Brunhes geomagnetic reversal in the Sulmona Basin, Italy' by Evans and Muxworthy (2018)

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SUMMARY

The Matuyama–Brunhes Boundary (MBB) recorded in the lacustrine sequence in the Sulmona basin (central Apennines, Italy) raised considerable scientific interest and has been the focus of various papers (Giaccio *et al.* 2013; Sagnotti *et al.* 2014; 2016). The interest comes from evidence for a very sharp geomagnetic polarity transition, that is radioisotopically dated. A paper recently published by Evans and Muxworthy (2018) questions the reliability of the Sulmona palaeomagnetic record. With new measurements on companion samples from the same stratigraphic block studied by Evans and Muxworthy, we show that directional results obtained by different demagnetization treatments (AF, thermal and thermal + AF) are in close agreement. We here propose a different interpretation of the magnetostratigraphy, and confirm that the palaeomagnetic record of the MBB geomagnetic reversal in the Sulmona basin is properly documented

Key words: Reversals: process, time scale, magnetostratigraphy; Rock and mineral magnetism.

The lacustrine Quaternary infill of the Sulmona basin mainly consists of bioinduced carbonate silt divided into three main sedimentary units. The units are geochronologically constrained by ⁴⁰Ar/³⁹Ar dating and tephrochronological determinations between about 800 and 90 ka (Giaccio et al. 2012, 2013, 2015; Regattieri et al. 2015, 2016, 2017). The lowermost unit, SUL6, contains the MBB and a number of tephra layers acting as reliable stratigraphic markers (Giaccio et al. 2013; Sagnotti et al. 2014, 2016) and chronological control points (Fig. 1a). Specifically, there are four parallel sections bracketing the MBB that have been studied in high-resolution, each one containing the same stratigraphically ordered succession of tephra, two of which have been dated at 779.6 \pm 2.0 ka (SUL 2–16, about 1 m above MBB) and 789.3 \pm 1.9 ka (SUL 2-22, about 1.2 m below MBB) (Fig. 1a). Three sections are from the informally named Horseshoe (HS) outcrop where they are several metres to tens of metres apart along strike, and one section is from a core (SC-1), that is about half a kilometre away. This makes the Sulmona paleomagnetic record one of the best studied stratigraphic intervals spanning the MBB.

In three out of the four sections, two at the Horseshoe locality (HS-1 and HS-2) and in the SC-1 core, the MBB occurs about 26 cm above the top of tephra SUL2-19 (Sagnotti *et al.* 2014, 2016). In the fourth section that we name HS-3 and that coincides with the section analysed by Evans & Muxworthy (2018), the MBB is instead about 38 cm above the top of tephra SUL2-19. At each locality, the change from reverse (Matuyama) to normal (Brunhes) polarity is between two adjacent samples that span 4 cm, and there are no intermediate directions found between the two full states of polarity.

According to the oxygen isotope palaeoclimatic record of the SUL6 unit and the related Bayesian age model based on 40 Ar/ 39 Ar geochronology (Giaccio *et al.* 2015), the MBB occurs at the early stage of marine isotope stage 19c (MIS 19c; Fig. 1b) and was dated at about 787 ± 2 ka, relative to an age of 1.193 Ma for the Alder Creek sanidine (ACs) monitor standard. By considering the new age determinations for ACs, at 1.1891 Ma and 1.1848 Ma, recently proposed by Niespolo *et al.* (2017), the age of Sulmona MBB would become slightly younger, specifically about 783 ± 1 ka and 780 ± 1 ka, respectively (Mark *et al.* 2017). Although the



Figure 1. Synopsis of the stratigraphy, geochronology and palaeoclimatology of unit SUL6 from Sulmona basin and ChRM inclination records straddling the MBB from four parallel sections of the SUL6 unit, investigated in this and previous studies (a) Composite section and 40 Ar/ 39 Ar geochronology of the basal part (from 15 m- to 50 m-depth) of unit SUL6 spanning the marine isotope stage 20-17 (MIS 20-17; from Giaccio *et al.* 2013; Sagnotti *et al.* 2014; Giaccio *et al.* 2015); (b) Oxygen isotope profile of unit SUL6 showing glacial–interglacial and millennial-scale palaeoclimatic variability that replicates the general features of the palaeoclimatic change observed in reference global records of the MIS 20-MIS 17 interval (Giaccio *et al.* 2015); (c) Three metre-long records from HS section 1 (HS-1; Sagnotti *et al.* 2014) and SC1 core (Sagnotti *et al.* 2016); (d) Detail of the 40 cm-long records from the ultra-high-resolution record of HS-2 section (Sagnotti *et al.* 2016) compared with HS-1 and SC-1 records; (e) Records from HS-3 sections (Evans & Muxworthy 2018; this study) showing the displacement of about 12 cm of the MBB. Thin (a few centimetre) layers of lacustrine sediments on top of tephra layers deposited below the MBB shows spikes to positive ChRM inclinations due to a (slightly) later remagnetization. The consistency of the data in the HS-1, HS-2 and SC-1 records is at the centimetre scale. The 12 cm displacement of the MBB in section HS-3 is due to a combination of remagnetization effects linked to crytoptephra SUL2-18 and to lock-in depth variation in the lacustrine sediments.

age and climatostratigraphic position of the MBB is a critical and currently debated issue (e.g. see Mark *et al.* 2017), it is not the focus of this and previous palaeomagnetic investigations in the Sulmona basin. In fact, as noted in Sagnotti *et al.* (2014), we focused on the rate and dynamics of the magnetic reversal that are independent of any potential phenomenon of delayed remanence acquisition (e.g. lock-in depth) that might affect the estimation of the MBB absolute age.

We obtained new palaeomagnetic measurements using thermal stepwise demagnetization up to 580°C on companion samples from the same block analysed by Evans & Muxworthy (2018). The natural remanent magnetization (NRM) of contiguous specimens (cubes 2 cm side size) was measured after each demagnetization step on a small-access (45 mm diameter) automated pass-through '2 G Enterprises' DC 755 superconducting rock magnetometre (SRM) in the magnetically shielded room of the palaeomagnetism laboratory of the Istituto Nazionale di Geofisica e Vulcanotogia (Rome). Following former results (Sagnotti et al. 2014), these sediments are not expected to undergo significant alteration during thermal heating. We confirm that samples from 30 to 36 cm above tephra SUL2-19, that are from about 4 to 10 cm above the MBB as determined by Sagnotti et al. (2014, 2016), contain a reverse characteristic remanent magnetization (ChRM) isolated between about 200° and 400–450°C, after removal of a low-stability overprint at 200°C. The low-stability component is of normal polarity and accounts for more than 90 per cent of the NRM intensity (Fig. 2). Some

samples (Figs 2a and 3a) were completely demagnetized at about 400°C, and directional data obtained at higher temperatures are almost random. A sample 49 cm above tephra SUL2-19 shows a well-defined ChRM (isolated between 200°C and 390°C) of normal polarity (Fig. 3a), consistent with results obtained from the other three sections at the same stratigraphic horizon (Sagnotti et al. 2014, 2016). At that horizon (49 cm above the top of SUL2-19) Evans & Muxworthy (2018), report a sample containing a 'hint of reverse polarity', following alternating field (AF) demagnetization with 'a poorly constrained component with negative inclination', but demagnetization diagrams are not shown in their paper. The sample at 28 cm, corresponding to cryptotephra SUL2-18, also has a normal polarity ChRM, but the spectrum of blocking temperatures is quite different from all of the samples far from the tephra influence, and the ChRM is stable at higher temperatures and is fully demagnetized at 580°C (Fig. 3b). This is consistent with the inference of a different magnetic carrier for samples around SUL2-18 consisting mostly of magnetite grains linked to volcanic ashes, and with a relatively higher coercivity, as indicated by Sagnotti et al. (2016) and described in detail by Evans & Muxworthy (2018). The remanence held by this high-coercivity component is a secondary component acquired by remagnetization at a later time (i.e. during the Brunhes Normal Chron) that masked the original reverse magnetization of the sediments. In our analysis, the sample 30 cm above SUL2-19, after removal of a large normal overprint at 200°C that accounts for more than 90 per cent of the initial NRM intensity, shows a reverse



Figure 2. Demagnetization diagrams for specimens collected at 36 cm (a) and 32 cm (b) in the HS-3 section, which are 8 and 6 cm above cryptotephra SUL2-18. From upper left-hand side to lower right-hand side: orthogonal projection diagrams of remanence vectors measured at each demagnetization step with projection on the N–S and W–E vertical planes (diagram on the upper right-hand side is a magnification for demagnetization steps for $T > 240^{\circ}$ C); variations of the remanence intensity as a function of the demagnetization steps; stereographic (equal area) projection of unit vectors defined at each demagnetization step.



Figure 3. Demagnetization diagrams for specimens collected at 49 cm and 28 cm (b) in the HS-3 section. The sample at 28 cm includes cryptotephra SUL2-18. From upper left-hand side to lower right-hand side: orthogonal projection diagrams of remanence vectors measured at each demagnetization step with projection on the N–S and W–E vertical planes (diagram on the upper right hand side is a magnification for demagnetization steps for $T > 240^{\circ}$ C); variations of the remanence intensity as a function of the demagnetization steps; stereographic (equal area) projection of unit vectors defined at each demagnetization step.

polarity component indicated by the data in the 270–360°C step range (with demagnetization diagrams very similar to those shown in Fig. 2(a) for an adjacent sample at 32 cm). At 30 cm above SUL2-19, Evans and Muxworthy report a sample of normal polarity. We interpret this discrepancy as a variable effect of the normal remagnetization linked to cryptotephra SUL2-18 in two adjacent samples.

With this exception and with that referred to the specimen at 49 cm above SUL2-19, which is for us of clear normal polarity, we conclude that our new palaeomagnetic results are consistent with those of Evans & Muxworthy (2018). Specifically, regardless of the demagnetization technique used (i.e. both thermal, AF and thermal + alternating field treatments) the palaeomagnetic results are essentially identical and indicate that the MBB is very sharp and is recorded 10-12 cm above the previously determined position (Figs 1c–e).

Evans & Muxworthy (2018) clearly indicate that the Sulmona lacustrine sediment is characterized by a complex magnetic mineralogy composed of a magnetite population of different origin, and confirms that the fraction related to volcanic ashes caused a remagnetization of centimetre-thick intervals around tephra and cryptotephra layers, as also noted by Sagnotti et al. (2014, 2016). In the interpretation of the overall palaeomagnetic record, the normal polarity remagnetization introduced by unknown causes associated with volcanic ashes has been properly identified. The sedimentary ChRM is instead likely affected by the typical uncertainties linked to normal processes of field acquisition in sediments, which can result in a variable lock-in depth on the order of several tens of centimetre. This is a phenomenon known in Holocene marine sediments from the Tyrrhenian Sea (Sagnotti et al. 2005) that display a range of lock-in depth variability compatible with that observed in the HS subsections.

In conclusion, the only new evidence for the Sulmona MBB record presented by Evans & Muxworthy (2018), as well as in this study, is that the MBB is 10-12 cm higher in the section than reported by Sagnotti et al. (2014, 2016). We think this is an effect due to the variability of the sedimentary lock-in depth and/or the overprinting efficiency linked to the SUL2-18 cryptotephra. In any case, given the estimated average sedimentation rate in the lacustrine unit SUL6 (~0.35 mm yr⁻¹; Giaccio et al. 2015; Sagnotti et al. 2016), a 12-cm shift in the MBB position would correspond to about 340 yr, which is well within any optimistic statistical uncertainty associated to its age determination. More importantly, the observed shift of the MBB has no effect in terms of the assessment of the rate of the polarity flip, because, regardless of its precise stratigraphic position, after four high-resolution studies no intermediate palaeomagnetic directions have been found between the two adjacent samples recording entry into the Brunhes Normal Chron. The intermediate directions reported in Fig. 1(c) for core SC1 are an artefact due the smoothing effects of continuous measurements on u-channel samples (see fig. 14 in Sagnotti et al. 2016). An independent support to the sharpness of the MBB and its stratigraphic position comes from a recent study of the MBB in the marine sediments of Valle di Manche (VdM) in Calabria in southern Italy, at a distance of about 450 km from the Sulmona basin (Macrì et al. 2018). That study indicates that in the VdM section the MBB polarity flip is as brief as in the Sulmona basin (perhaps in the range of 100 yr) and that it occurred with no intermediate directions at approximately the same climatostratigraphic position, that is, early part of the MIS 19c. A very fast directional flip during (regional) polarity changes has also been reported for the Laschamp geomagnetic excursion at 41 ka from Black Sea sediments (Nowaczyk *et al.* 2012), with an estimated duration of 2–3 centuries.

In the HS-3 profile of the Sulmona Horseshoe outcrop, palaeomagnetic data yield results slightly deviating from those obtained in the formerly studied profiles (HS-1 and HS-2). Inconsistencies are on the order of cm and may be due the variable effects of the tephra layers, the interplay between different populations of magnetic grains (Evans & Muxworthy 2018), and the complexity of the phenomena that can concur in the acquisition of a remanent magnetization in sediments during diagenesis (e.g. Sagnotti 2018). In any case, all results point to a sharp B-M polarity flip at the end of a period of geomagnetic instability, which started with a geomagnetic polarity precursor that occurred a few kyr earlier (Sagnotti et al. 2014). This polarity flip can be dated in the Sulmona basin at the highest resolution, due to the presence of several volcanic tephra layers that allow an accurate estimate of the sedimentation rate. The tephra layers are also characterized by a distinct high coercivity phase of volcanic origin that carries a secondary remanence, and are therefore in many cases associated to a normal polarity remagnetization affecting thin (centimetre to decimetre) stratigraphic intervals. These remagnetized intervals can be identified (Sagnotti et al. 2014, 2016; Evans & Muxworthy 2018) and discarded from the analysis of the MBB polarity flip. For all these reasons, we believe that the Sulmona record of the MBB is at least as reliable as other MBB sedimentary records, and is documented at the highest resolution.

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