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Updated evidence and discussion of the Triassic palaeomagnetic age of the Kupferschiefer Cu-Ag ore deposits in Poland

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In the 1987 palaeomagnetic study of the Kupferschiefer ore deposits in Poland by Jowett, Pearce, and Rydzewski, the reversed palaeomagnetic pole obtained for the ore-stage Rote Fäule oxide zone of 49.0°N, 157.2°E corresponded to a mid-Triassic age on the apparent polar wander path (APWP) calculated from contemporary databases. A late diagenetic origin for the Rote Fäule oxide zone, and thus the economic sulphides, was supported by geological evidence and by subsequent dating methods of palaeomagnetism, sulphides, and clays. In response to these results being challenged in a 2011 critical analysis, updated evidence from palaeomagnetic laboratories in Kiev and Utrecht/Milano showed that the 1987 Rote Fäule palaeopole lies directly on the newest APWPs. However, its actual age depends on applying 'inclination shallowing corrections' to the palaeopole and to the APWP. Although accurate shallowing corrections cannot be calculated retroactively, the corrected Rote Fäule palaeopole matches a Triassic age on corrected APWPs, just as the uncorrected pole does on the uncorrected 1987 APWP. The Rote Fäule palaeopole also closely matches palaeopoles from the Triassic Buntsandstein rocks in subsequent studies in Germany and Poland, supporting an ore genesis timing of Triassic or later.

Key words: Kupferschiefer, APWP, ore deposits, oxidation-reduction front, palaeomagnetic dating, inclination shallowing, Triassic rifting.

INTRODUCTION

A critical analysis by Symons et al. (2011) (referred to as 'the 2011 paper' below) questioned the results and methodology of the palaeomagnetic paper on the Kupferschiefer copper sulphide deposits in Poland and on pyritic facies in W. Germany and England (Jowett et al., 1987b). Their criticisms centred on claims that there was no stable remanence found in the copper sulphide facies and that the hematitic Rote Fäule (RF) component was Permian in age, not Triassic, and was not associated with copper mineralization. Yet, a stable palaeopole of 78.6°N, 163.4°E was indeed reported for the Polish copper sulphide facies, similar to the palaeopole of 76.1°N, 164.2°E documented in the German copper sulphide facies (Symons et al., 2011). Importantly, the 1987 paper demonstrated that their Polish copper sulphide facies palaeopole was statistically similar to their barren, iron-sulphide facies palaeopoles from England and Germany. The 2011 paper argued that the ore-stage mineralizing event was reflected by their copper sulphide palaeopole and not by that of the Rote Fäule, though they did not sample barren iron sulphide or Rote Fäule facies for comparison.

Part of the 2011 group subsequently used their palaeomagnetic result to propose an epigenetic type origin during the Late Jurassic to mid-Cretaceous crustal re-arrangement of Pangea (Borg et al., 2012). However, since their palaeopole of the German copper sulphides was indistinguishable from the barren iron sulphide palaeopoles in the 1987 study, it is difficult to claim that both are ore-stage, and their reliance on a single mine site appears over-reaching.

This paper discusses the relationship between the Rote Fäule and ore bodies, possible mechanisms of ore formation and their relative timing, and updates the discussion of ore genesis and palaeomagnetic dating with more recent evidence.

SIGNIFICANCE OF KUPFERSCHIEFER SULPHIDE AND OXIDE ZONATION

Models of ore deposit genesis need to be comprehensive to help exploration geologists find new resources. For Kupferschiefer-type Cu-Ag deposits, the sedimentary basin requires a physical-chemical trap to concentrate sulphides, metalliferous source rocks, palaeotopography to channel fluids to the trap, and a tectonic or thermal event to provide a fluid-driving mechanism. The relative timing of the fluid movement is crucial to successful exploration; did the fluid enter the trap laterally during sedimentation or early diagenesis, or did it have a post-lithification, late-diagenetic origin, more akin to an oil and gas analog? The regional metal zoning in the Kupferschiefer shale and basal Zechstein carbonates (Rydzewski, 1969, 1978; Oszcze-

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palski and Rydzewski, 1997; Oszczepalski, 1999) and its relationship to organics of various types (Jowett, 1992) suggest the latter.

The idea of metals originating in adjacent mountains and precipitating in near-shore areas during sedimentation has an enduring history (e.g., Squire and Keays, 2024). However, the detailed metal zoning maps of the Polish Geological Institute – National Research Institute (Chmielewski and Oszczepalski, 2025a, b) make this genetic scenario untenable for the Kupferschiefer. The original barren pyrite facies, not the ore bodies, occur closest to the near-shore and the precursor mountains. Instead, the Cu-Ag ores lie concentrically around shallow domes of hematitic (Rote Fäule) zones farther out in the basin and cross-cut the host rocks in plan and section. These oxidized domes in the basal Zechstein, in turn, are closely associated with underlying basement highs within the Rotliegend continental basins (Pokorski, 1978, 1981) that could act to focus upwelling ore fluids around them to the basal Zechstein.

Overall metal concentrations in the Rote Fäule Kupferschiefer shale are similar to those in the original barren pyrite shale, so the Cu-Ag metals must have been sourced outside of the Kupferschiefer. The Rote Fäule domes and ore bodies are regionally associated with underlying basal Rotliegend volcanic rocks (Ryka, 1981; Maliszewska et al., 2016) that could act as a metal source, with a deep pseudo-batholith now suspected (Speczik et al., 2025). Much of the sulphur, however, would have been indigenous as pyrite, and simply relocated from the Rote Fäule oxide zone to the Cu-Ag sulphide zone by fluid migration and redox reactions (Jowett et al., 1991).

In the 1980s, Andrzej Rydzewski of the Polish Geological Institute, together with the Erindale geophysical group at the University of Toronto, expanded on his earlier work to present a late diagenetic model of ore-forming fluids from the Rotliegend basins upwelling around the underlying buried basement highs (Jowett et al., 1987a). These fluids oxidized the lower Zechstein and precipitated metal sulphides along a shallowly discordant oxidation-reduction front (Oszczepalski, 1999; Chmielewski and Oszczepalski, 2025a). They emphasized, as did earlier authors, that the Rote Fäule oxidation is an integral part of the Cu-Ag, Pb, and Zn sulphide zones advancing out away from the Rote Fäule oxidized areas. Wodzicki and Piestrzyński (1994) also associated their main 'Ore Stage II' directly with the Rote Fäule facies. This ore-stage redox zonation is imprinted onto the original barren pyritic shale, cutting across the host rocks in plan and section.

Given that such a large ore-forming system needs a substantial driving mechanism, and, along with evidence that ore-stage sulphide veinlets were Triassic-Jurassic in orientation (Salski, 1977), Jowett et al. (1987a) suggested that the required basinal fluid migration could be instigated by tectonic extensional rifting and high heat flow associated with the opening of the Tethys Ocean and lithospheric thinning during the Triassic.

These copper sulphide veinlets, very striking in appearance, were interpreted by Jowett (1987) as 'crack-seal' fillings of natural antitaxial hydrofractures formed by gas generated internally within the organic-rich Kupferschiefer shale during rapid burial in the Triassic. Petrographic study of copper sulphides occurring as disseminations, lenses/streaks and veinlets indicates a multifaceted paragenesis. Disseminations and lenses appear coeval; veinlets and lenses can appear coeval or veinlets can cross-cut the lenses; vertical veinlets cross-cut horizontal veinlets; copper-rich sulphides such as chalcocite replace and cut across more iron-rich copper sulphides such as bornite and chalcopyrite (Jowett, 1987). These relationships conform to those expected when copper-rich, oxidizing fluids produce an oxidation-reduction front advancing with time through the originally pyritous basal Zechstein under changing tectonic stresses.

Consequential inferences therein are that (a) the Kupferschiefer organics would have reached temperatures high enough to generate natural gases, and (b) the Kupferschiefer and Weissliegend pore fluids would have been under near-lithostatic pressure in order for the fractures to remain open and allow metal-bearing solutions to fill the fractures in the crack-seal manner observed. In a hydrostatic fluid environment, hydrofractures would have closed immediately after opening and would not have been filled. This hydraulic regime during ore formation could potentially bear on any corrections made for magnetic 'inclination shallowing' in the Rote Fäule, as discussed below.

The change from horizontal to cross-cutting vertical veinlets suggests a change to lateral tectonic extension during ore formation. Mikulski and Stein (2015) obtained a late Triassic Re-Os age of ~212 Myr using uncontaminated copper sulphides from these same antitaxial veinlets. Alderton et al. (2016) obtained Permo-Triassic to Jurassic Re-Os ages. Bechtel et al. (1999) obtained a late Triassic to early Jurassic K-Ar age for diagenetic illite believed to be ore stage. More thorough discussion of dating techniques of the Polish Kupferschiefer can be found in Mikulski and Stein (2017) and Chmielewski and Oszczepalski (2025a).

From the above discussion, the palaeomagnetic age of the Rote Fäule hematite also represents the age of the ore deposit, as the Rote Fäule is an integral part of the larger metal sulphide zoning system. A reasonable absolute age of formation should be obtained by revealing the hematite magnetic components and comparing them with available apparent polar wander paths (APWPs). Geological evidence is, however, always needed to support or refute any palaeomagnetic evidence.

PALAEOMAGNETIC ANALYSIS OF KUPFERSCHIEFER SHALE

In their critique of the palaeomagnetic work of Jowett et al. (1987b), the core argument of Symons et al. (2011) is that the 1987 authors were: (i) *"unable to isolate a reliable remanence in the mineralized Kupferschiefer shale, because palaeomagnetic technology had not yet been sufficiently refined"*; (ii) were *"unable to isolate a stable ChRM*[1] *component from samples of unoxidized Kupferschiefer mineralization samples from underground mines in Poland"*; and (iii) that the apparent polar wander path (APWP) developed in the 1987 work was surpassed by later APWPs *"with larger databases"*.

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[1] Characteristic remanent magnetization (ChRM) refers to the stable magnetic component after secondary or viscous components are removed by demagnetization. CRM or chemical remanence refers to magnetic minerals being formed by chemical reaction (e.g., oxidation of iron sulphides to magnetic hematite). This CRM preserves the direction of the contemporary Earth's magnetic field at the time of hematite formation, and this component direction can subsequently be revealed or isolated by de-magnetization methods to ultimately become the ChRM component.

Palaeomagnetic analysis isolates magnetic components that represent the orientation of Earth's magnetic field at the time of the component's acquisition in the rock. Magnetization components that are later superimposed onto the original component are removed in a palaeomagnetic laboratory by demagnetization to try to reveal the direction of the original component, which is then matched to an APWP. The APWP is built up from catalogues of accepted palaeopoles from rocks with known ages to obtain the numerical age of a magnetic component. In some cases, the original component cannot be isolated, which seems to be the case for barren and mineralized samples in the Kupferschiefer as no Permian-age components were detected in the 1987 and 2011 studies.

'Inclination shallowing' is a correction now applied to sedimentary palaeopoles to account for a decrease in magnetic inclination during deposition and compaction (e.g., Vaes et al., 2021). The 1987 components were not corrected for inclination shallowing, and, at that time, neither were the APWP databases. The 2011 paper used the APWP dataset from Torsvik et al. (2001) which was then updated by Torsvik et al. (2012) which included inclination shallowing corrections. When the Jowett et al. (1987b) Rote Fäule palaeopole is adjusted the same as the APWP of Torsvik et al. (2012), it matches a Triassic age (see below).

SULPHIDE STUDIES

The cryogenic magnetometer used at the University of Toronto was built with a very high sensitivity specifically for NASA's lunar rock research (Develco, 1972), and, in the 1987 study, was able to isolate a stable remanence in copper sulphide and pyritic facies from three countries using 70 rock samples (several hundred individual specimens; Table 1). Stepwise demagnetization measurements were sufficient and accurate enough to meet Kirschvink's (1980) objective 5° line fit criterion for acceptance of an isolated component. Table 1 compares the number of samples used in both studies, and shows that the resultant palaeopoles are similar in both copper ore and barren pyrite facies.

The 1987 Polish copper shale palaeopole 78.6°N, 163.4°E (Miocene 10–20 Ma; less likely Cretaceous 110 Ma or Jurassic 180 Ma) matched the 2011 German copper shale palaeopole of 76.1°N, 164.2°E (Table 1). The 1987 barren pyritic German and England palaeopoles were statistically similar to the 1987 copper sulphide palaeopole. The 2011 study claimed that their copper sulphide component (Table 1) represents the timing of ore deposition, being Late Jurassic (~149 Ma) or possibly Eocene (~53 Ma) (by contrast, the 1987 study maintained that only the Triassic age Rote Fäule palaeopole was ore-stage). Because no barren or ore-stage sulphide sample revealed an original depositional mid-Permian age, and the two components are statistically similar, it is difficult to claim that the barren pyritic component is also ore-stage.

Symons et al. (2011) collected palaeomagnetic samples at two locations in one mine in the historic Mansfeld-Sangerhausen district. For the Kupferschiefer copper shale horizon, they sampled 9 *"sites"* or 117 *"specimens averaged"*, assumed herein to mean 'used in their calculations' (their table 1). The palaeomagnetic age for these copper sulphides was given as 149 or 53 Myr and assumed by them to be 'ore-stage'. No Permian age components were mentioned in the 1987 and 2011 studies to suggest the survival of an original depositional magnetic component. The following two paragraphs (abridged) by Chmielewski and Oszczepalski (2025b) provide an independent summary of the palaeomagnetic situation with respect to updated APWPs, discussed later.

"Symons et al. (2011) came to the conclusion that, regardless of whether their 149 ±3 Ma age or their 53 ±3 Ma age is correct, the Kupferschiefer at Sangerhausen underwent a thorough chemical reorganization and remagnetization long after the Rote Fäule formation (cf. Jowett et al., 1987b). Thus, the Kupferschiefer ores and Rote Fäule in their view were not formed in coeval events".

"Jowett et al. (1987b) obtained a Triassic palaeomagnetic age of 250–220 Ma for hematitic Rote Fäule rocks of the Kupferschiefer series using samples from the Konrad, Lena and Nowy Kościół copper mines. Using a more recent apparent polar wander path, this age was recalculated by Nawrocki (2000) to 255–245 Ma (Upper Permian–Lower Triassic) and by

Table 1

Stable palaeomagnetic components in the 1987 and 2011 studies are similar for both copper ore and barren pyrite facies, suggesting that both cannot be of 'ore stage' timing

		Magnetic component			Palaeopole		
Study	Shale facies and location	Samples used	Declination [	Inclination [	Latitude N	Longitude E	A_{95} [
*Symons et al. (2011)	Germany copper	9	4.1	60.9	76.1	164.2	4.7
†Jowett KV2[2] Jowett et al. (1987b: table 1)	Poland copper	26	8.2	59.3	78.6	163.4	6.7
	Germany pyrite	23	2.5	65.1	86.2	166.0	5.4
	England pyrite	21	9.9	64.1	79.7	130.1	6.6

* – samples ('sites' in 2011 text) from two mine stopes in Germany (117 specimens); † – Kirschvink (1980); (KV) – components from Poland, Germany, and England sites (200–300 specimens)

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[2] See Appendix 1 for explanations of 1987 palaeomagnetic component terminology.

Symons et al. (2011) to 254 ±6 Ma. Palaeomagnetic data from the North Sudetic Synclinorium suggested a Rote Fäule age of 258–250 Ma (Nawrocki, 2017)".

Jowett et al. (1987b) collected 154 samples of copper ore and barren pyritic Kupferschiefer and lower carbonate facies in the historic and modern mines in Poland (three underground mines, two open-pit mines), and from outcrops in Germany and England. Symons et al. (2011) maintained that the 1987 study did not sample underground mine sulphides in Poland; *"These authors favoured this attribution because they were unable to isolate a stable ChRM component from samples of unoxidized Kupferschiefer mineralization samples from underground mines in Poland".* However, it was clearly stated that stable sulphide components were isolated from both historic and modern underground mines, and are similar to the sulphide component found in their own study (table 1).

The 1987 samples were cut[3] into 474 specimens, of which 200 specimens were subjected to an average of 6 demagnetization steps. The large 100 mm sample tube in the magnetometer (Develco, 1972) enabled the use of larger cut specimens or irregularly shaped specimens of up to 500 g. Even very delicate shale samples could be measured without gluing or coating, as the magnetometer measurements involved no physical spinning of the sample.

Of the 474 sulphide specimens from the three countries, the stable remanence VS2 was revealed in 85 samples or 247 specimens. Each specimen had 2–5 clustered measurements *aligned along the VS2 direction*, which constituted the measurements used to obtain the component vector direction, but these represented only a subset of the total number of demagnetization measurements. This 2–5 number may be why the 2011 paper claimed incorrectly that *"… Jowett et al. (1987b) utilized an average of only approximately four steps in their demagnetization protocols because of equipment limitations of that time…".*

Visually choosing which demagnetization steps to use for each component is always somewhat subjective, but the Kirschvink (1980) method provided an objective approach, being less dependent on personal bias with its built-in threshold for alignment of vectors. In the 1987 paper, the Kirschvink directions matched those of other methods used.

There were never any issues with the number of sample measurements or equipment limitations at Toronto, and this criticism in the 2011 Symons et al. (2011) paper is wholly unfounded.

IRON OXIDE STUDIES

In the 1987 study, the hematitic Rote Fäule facies revealed a reversed component of much earlier age than that documented in the pyritic or copper shale samples (Miocene, less likely Cretaceous or Jurassic, but which preserve no recoverable Permian or Triassic components). Magnetization at the base of the copper shale in Poland did trend towards a reversed direction as in the Rote Fäule, but an end component could not be isolated. Of the original 114 specimens of Rote Fäule, 70 specimens from 29 field samples were used to calculate the preferred MM3 component (Table 2). Symons et al. (2011) did not sample the Rote Fäule or barren sulphide shale in their study area, nor did they go to Poland to verify the 1987 results.

The 1987 reversed palaeopole (MM3 in Table 2) coincided with a mid-Triassic age on the APWP calculated using databases available at that time (Jowett et al., 1987b) (this novel APWP was accepted by *Journal of Geophysical Research* re-

Table 2

Comparison of hematite-bearing samples from the Kupferschiefer and Buntsandstein

		Magnetic component			**Palaeopole**		
	Site	Samples used	Declination [ ]	Inclination [ ]	Latitude N	Longitude E	A_{95} [ ]
Symons et al. (2011)	Germany Rote Fäule	0	n/a	n/a	n/a	n/a	n/a
Jowett et al. (1987) MM3	Poland Rote Fäule	29	205.4	–28.2	**49.0**	**157.2**	3.9
VS3		20	203.5	–29.9	50.6	159.1	5.5
MMVS3		30	207.3	–28.5	48.3	154.7	4.5
KV3		17	206.4	–25.6	47.7	156.6	6.4
Nawrocki et al. (2003)	Poland Buntsandstein	29*	210.0	–32.0	**49**	**155.0**	2.4
		4*	210.0	–31.0	**48**	**155.0**	4.5
Szurlies (2007)	Germany Buntsandstein	129†	23.3	26.1	**49.1**	**154.1**	6.5

German and Polish Buntsandstein palaeopoles are well constrained and similar to the Rote Fäule pole. Using recent APWPs, the Buntsandstein poles would be compatible with a Permian age unless corrected for inclination shallowing (see text), a quandary when considering strata of definitive Triassic age

* – 29 samples in 4 localities calculated separately;† – specimens used

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[3] A slow-speed bandsaw with a diamond-encrusted blade was used to cut the samples dry and so to keep them intact.

viewers and consequently included in the publication). A late diagenetic age of magnetization in the Rote Fäule is supported by the cross-cutting nature of the redox boundary, the orientation of sulphide veinlets, other dating methods, a thermal driving mechanism, and general geological evidence.

For the Upper Buntsandstein (Lower to Middle Triassic) continental sequence in Germany, Szurlies (2007) obtained a palaeopole of 49.1°N, 154.1°E, very similar to the 49°N, 155°E palaeopole obtained by Nawrocki et al. (2003) for the Lower to Middle Buntsandstein (Lower Triassic) in Poland (Table 2). Both results closely match the 1987 Polish Rote Fäule palaeopole of 49.0°N, 157.2°E, supporting a similar Triassic magnetization age for the Rote Fäule component. Normal and reversed poles were found in both studies, with reversed directions more common in the Middle Buntsandstein of the Nawrocki et al. (2003) study. Both studies were corrected for bedding tilt, as in the 1987 study, but there is no mention of adjustments for inclination shallowing in either paper, in which case these palaeopoles can be directly compared to the 1987 Rote Fäule MM3 palaeopole (Symons et al., 2011 did not refer to these Buntsandstein studies).

The detailed petrographic analysis of the Buntsandstein by Bertier et al. (2022) shows that reddening was caused by diagenetic clay rims stained by iron hydroxides, similar to the diagenetic Rote Fäule staining in the Kupferschiefer, so both lithologies should display similar CRM properties and behaviour with respect to inclination shallowing.

Using the newer APWPs corrected for inclination shallowing, these uncorrected Buntsandstein palaeopoles would indicate a Permian age, which of course is not defensible. It is therefore concluded that the magnetization events of Triassic Buntsandstein deposits in Poland and Germany, and the hematite magnetization of the Rote Fäule in Poland were synchronous, in the Triassic or later.

CONTEMPORARY PALAEOMAGNETIC ANALYSIS

In late 2024, two palaeomagnetic laboratories were approached to comment on the age of the Rote Fäule components; *"My question and favour to ask is, using the newer APWP calculations, what would be the age of a measured palaeopole MM3 of this value and for this location? Palaeopole: 49.0°N, 157.2°E, A_{95} = 3.9° and Location: 51.3°N, 16.2°E".*

One laboratory is that of Dr. Douwe J.J. van Hinsbergen of Utrecht University and Dr. Bram Vaes of the University of Milano-Bicocca. They developed a distinctive technique for calculating their APWP (Vaes et al., 2023) and the MM3 Rote Fäule component fits directly onto it (Fig. 1). Their APWP included corrections for inclination shallowing (flattening factors[4]), and when the MM3 palaeopole was corrected for shallowing, it coincided with a Triassic age. The following quote is a personal communication from these researchers in 2024.

"The declination fits with an age between 300 and 240 Ma or so. Interestingly, if you apply some correction for inclination shallowing, the inclination matches a younger age. For instance, when applying a flattening factor of 0.7 (moderate inclination shallowing), the inclination becomes 38.7°. As shown in the attached figure, this matches with an Early Triassic age (dark red datapoint). Varying degrees of inclination shallowing would allow for an age between the mid-Permian (no shallowing) to the Middle Triassic (significant shallowing, with a flattening factor of 0.5–0.6). I am certainly not an expert of the processes leading to inclination shallowing, but I have learned that samples carrying a CRM are typically less or not at all affected by shallowing."

The second laboratory consulted is that of Dr. Volodymyr Bakhmutov at the Institute of Geophysics, National Academy of Sciences of Ukraine. His detailed response (abridged) is as follows.

"To estimate the age of your palaeomagnetic pole, the reference APWP for Baltica/Stable Europe was taken (Torsvik et al., 2012), in which the corresponding poles for sedimentary rocks are corrected for inclination shallowing".

"As for inclination shallowing … the coefficient f can vary and depends on the type of detrital sediments, but f = 0.6 is considered 'standard' (see Torsvik et al., 2012). But it is necessary to take into account that this correction applies to sediments with detrital or post-detrital magnetization. But in your case, the magnetization should be chemical, and it is not clear if there was a significant inclination shallowing after its formation".

Recalculations of the 1987 Rote Fäule palaeopoles by the Kyiv group using the geographic location of S_{lat} = 51.3°N, S_{lon} = 16.2°E are tabulated in Table 3A (uncorrected for inclination shallowing) and in Table 3B after an f = 0.6 correction for inclination.

"Figure 2 shows the APWP of Torsvik et al. (2012) for Baltica/Stable Europe, where the poles MM3 and KV3 (without correction for inclination) and MM3-C and KV3-C (with correction) are plotted. As can be seen, the MM3 and KV3 poles fall on the ~270 Ma APWP section. The poles with the correction already fall on another part of the trajectory; MM3-C falls on the section of age 260–240 Ma, and the pole KV3-C, taking into account the larger A_{95}, falls on the section 270–240 Ma".

"So, without the shallowing correction, the age of magnetization can be estimated as the Early-Middle Permian boundary, whereas with the corrected poles, we obtain the age from the Middle–Late Permian to the Middle Triassic (or from the Early–Middle Permian to the Middle Triassic, if we used KV3 poles) (International Chronostratigraphic Chart of Cohen et al., 2025)".

DISCUSSION OF INCLINATION SHALLOWING

To summarize the above section, two geophysical laboratories (Kiev and Utrecht/Milano) used two different APWPs (Torsvik et al., 2012; Vaes et al., 2023), both of which incorporated inclination shallowing, to date the 1987 Rote Fäule palaeopoles with no inclination shallowing. Both laboratories found that the uncorrected Rote Fäule palaeopole has a Permian age [similar to the calculations of Nawrocki (2000) and Symons et al. (2011)], but has an Early to Middle Triassic age after a standard correction for inclination shallowing to match the APWPs. Both groups point out, however, that chemical remanence such as in the Rote Fäule hematite might not be subject to inclination shallowing.

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[4] A flattening factor of f = 1 is no flattening, and f = 0.5–0.7 is moderate flattening.

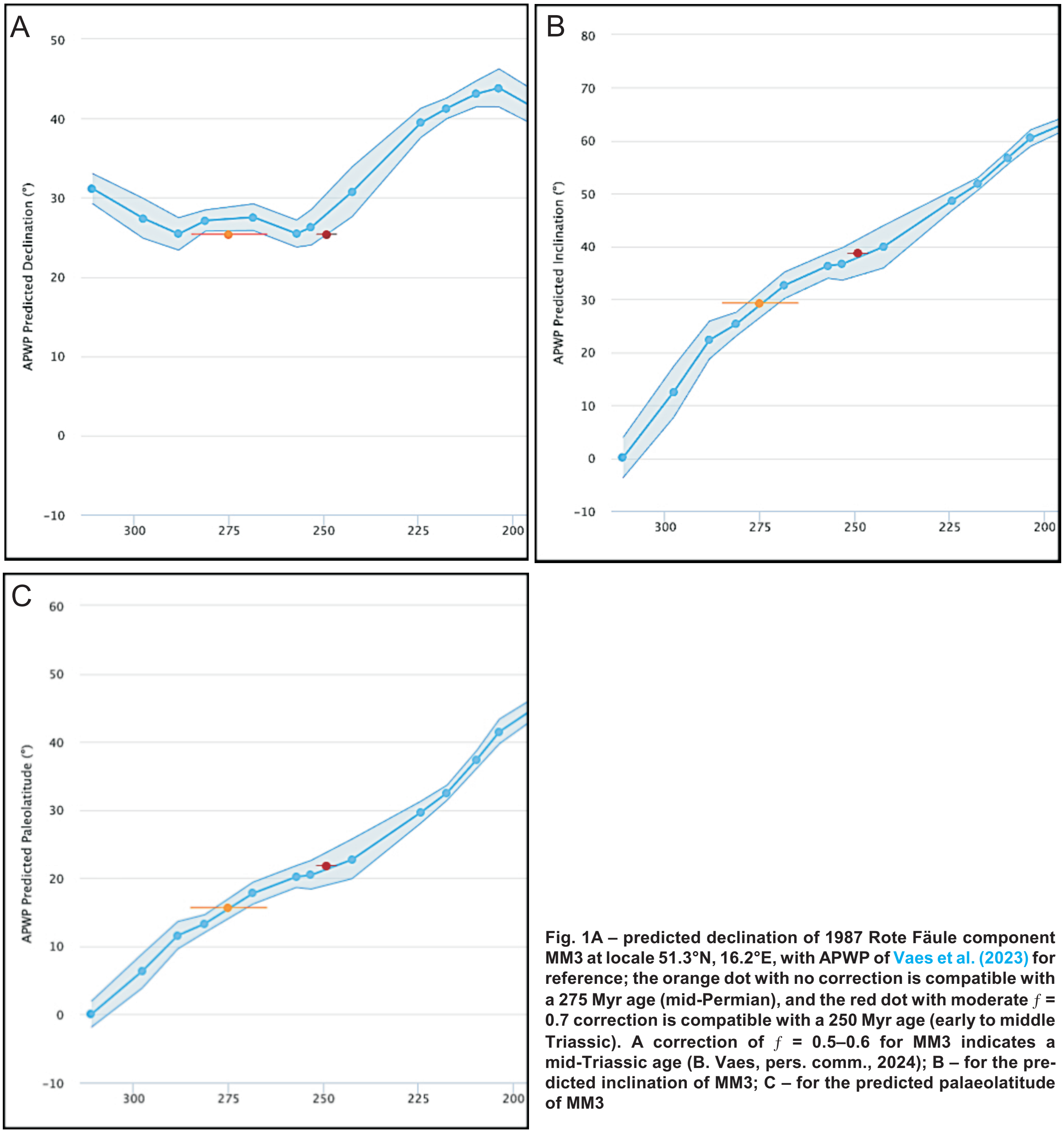

Fig. 1A – predicted declination of 1987 Rote Fäule component MM3 at locale 51.3°N, 16.2°E, with APWP of Vaes et al. (2023) for reference; the orange dot with no correction is compatible with a 275 Myr age (mid-Permian), and the red dot with moderate f = 0.7 correction is compatible with a 250 Myr age (early to middle Triassic). A correction of f = 0.5–0.6 for MM3 indicates a mid-Triassic age (B. Vaes, pers. comm., 2024); B – for the predicted inclination of MM3; C – for the predicted palaeolatitude of MM3

Vaes et al. (2021) and Pierce et al. (2022) describe specialized methods of discerning the rate of inclination shallowing within sedimentary rocks, with both emphasizing the uncertainties of applying flattening factors without very specific work during the original study. Hematite-bearing detrital grains could be subject to flattening, depending on size and shape, but pigmentary hematite would likely not. Without such detailed studies beforehand, a single correction applied to all sedimentary palaeopoles appears to be an imprecise response.

Another consideration is whether carbonate rocks should be corrected in the same fashion as clastic rocks. Carbonate rocks do not compact uniformly like clastic rocks but instead undergo ‘pressure solution’, leaving behind dark stylolite seams between the less-compacted rock. Because the stylolites contain the insoluble component of the carbonate, a palaeomagnetic study would need to remove the stylolites completely to obtain the original pre-compaction component. Applying a blanket flattening factor in this case would be problematic.

Furthermore, the Rote Fäule is an organic-rich black shale in which early diagenetic pyrite has been oxidized to hematite by upwelling oxidizing fluids. The pigmentary hematite formed would not likely reflect inclination shallowing when measured. The magnetized hematite in the Buntsandstein clastic rocks also occurs as pigmentary coatings and interstitial cements,

Table 3A

Uncorrected Rote Fäule (RF) palaeopoles recalculated by V. Bakhmutov (pers. comm., 2024)

	1987 RF component			2024 RF palaeopole		
	Declination [°]	Inclination [°]	$_{95}$ [°]	P_{lat} [°]	P_{lon} [°]	A_{95} [°]
MM3	205.4	–28.2	4.2	–48.4	337.6	3.4
KV3	206.4	–25.6	7.3	–46.6	337.2	5.8

Table 3B

As in Table 3A but Rote Fäule palaeopoles are corrected by *f* = 0.6 for inclination

	2024 RF component corrected			2024 RF palaeopole corrected		
	Declination [ ]	Inclination [ ]	$_{95}$ [°]	P_{lat} [°]	P_{lon} [°]	A_{95} [°]
MM3-C	205.4	–41.8	4.2	–56.5	331.0	4.0
KV3-C	206.4	–38.6	7.3	–54.0	331.5	6.7

and most likely some lithic detrital grains – the role of each type in any inclination shallowing would be difficult to unravel. Detailed petrography to accompany palaeomagnetic work is critical, such as that done for the Buntsandstein by Bertier et al. (2022), especially when substantive corrections are to be made.

The thick Zechstein evaporites that provided the overlying hydraulic aquiclude, together with the crack-seal nature of the ore-stage antitaxial veinlets, suggest an over-pressured, near-lithostatic regime for the pore waters during formation of the Rote Fäule-copper system (Salski, 1977; Jowett, 1987). With a lateral tensile force imposed during the opening of the Tethys Ocean, such dilatant veinlets could open and stay open under these hydraulic conditions even during the rapid subsidence of Triassic-Jurassic times (such small internal hydrofractures would not result in a breach of the overlying evaporite seal, but additional regional tectonic extension would ultimately do so). It is conceivable that compaction of the Kupferschiefer shale, thus possibly producing some inclination shallowing, could have occurred when the overpressure was relieved later, possibly during the Cretaceous uplifting (Jowett, 1987: figs. 6 and 7). Nawrocki (2017) has interpreted the 1987 Rote Fäule magnetic component as having compacted 10–15° after its formation.

The flattening factor issue remains unresolved for the moment. However, the 1987 Rote Fäule palaeopole of Jowett et al. (1987b), uncorrected for flattening, denotes a Triassic age

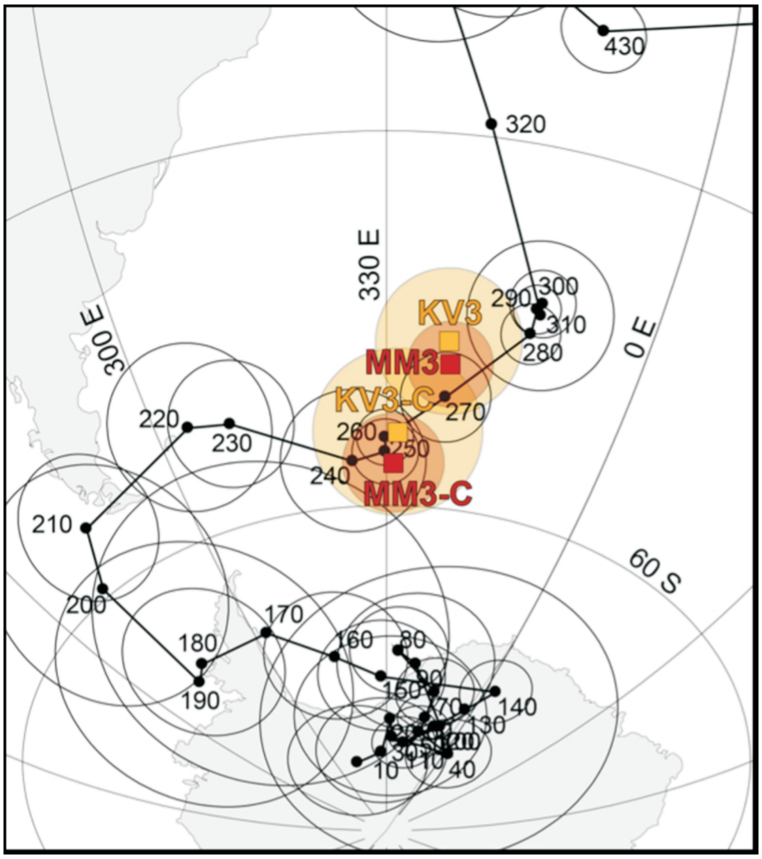

Fig. 2. Stable 1987 hematitic Rote Fäule components before (KV3, MM3) and after (KV3-C, MM3-C) being corrected by flattening factor f = 0.6, plotted on Baltica/Stable Europe APW path of Torsvik et al. (2012) which uses f = 0.6 (V. Bakhmutov, pers. comm., 2024)

when compared to an APWP also uncorrected for flattening. Similarly, when corrected for flattening, it denotes a Triassic age when compared to an APWP that is also corrected for flattening. Strong support comes from the independently calculated Early to early Middle Triassic Buntsandstein palaeopoles that coincide with the 1987 Rote Fäule palaeopole.

CONCLUSIONS

The sharp criticisms of Symons et al. (2011) have been answered accordingly by the evidence and reasoning presented in this paper. The original estimate of a Triassic age of the Polish Rote Fäule palaeomagnetic component is upheld within the uncertainty of inclination shallowing adjustments. A Triassic age for the formation of the Kupferschiefer Cu-Ag ore deposits remains a valid interpretation of the geological and geophysical evidence in the literature.

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APPENDIX 1

PALAEOMAGNETIC COMPONENT TERMINOLOGY OF THE 1987 PAPER

The numbering system of 1, 2, and 3 in the magnetic component names refers to the first, second, and third components revealed or isolated in the Kupferschiefer rock samples (Jowett et al., 1987b). The first component isolated is a 'viscous remanent magnetization' that is the easiest to remove by demagnetization, and reflects the Earth's magnetic field of the present day and recent past. The second component isolated after the first was removed is an earlier magnetic component with the magnetic characteristics of iron hydroxides, and was considered to be of Alpine orogeny age in the 1987 study. The third component revealed after the first two were removed is the original chemical remanence in the hematitic oxidized zone or Rote Fäule. It is carried by hematite, and is considered to be synchronous with the ore-forming event due to its being an integral part of the metal zoning. Only the first two components were found in the sulphide zones, whether copper or barren iron sulphides. No Permian age component was revealed in any of the sulphide-bearing facies.

The term 'MM' refers to the actual moment measured by the magnetometer and includes all magnetic component vectors left in the sample. It is less useful when it includes other components, but is best for defining the third component more precisely after other, later components have already been removed by demagnetization.

'VS' refers to the vector or component direction subtracted between each demagnetization measurement, and delineates the first and then the second components as they are being removed. It is a simple method, uses pairs of demagnetization steps objectively, and is a check on the standard Kirschvink method. 'KV' refers to the standard Kirschvink analytical method of 1980 which computes component directions using sequences of demagnetization steps. The term 'MMVS3' is a combination of two methods used specifically for comparison purposes for the Rote Fäule component.