First Full-Vector Archeomagnetic Data From Central Asia (3 BCE to 15 CE Centuries): Evidence for a Large Non-Dipole Field Contribution Around the First Century BCE


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Abstract
Unraveling the short-term behavior of the Earth's past geomagnetic field at regional scales is crucial for understanding its global behavior and, thus, the dynamics of the deep Earth. In this context, obtaining accurate full-vector geomagnetic field records from regions where archeomagnetic data are absent becomes essential. Here, we present the first full-vector archeomagnetic data from Central Asia, derived from the analysis of nine archeological kilns sampled in South Uzbekistan, dating back to the period between 200 BCE and 1429 CE. To obtain these new data, we conducted thermal and alternating field demagnetization procedures, along with Thellier-Thellier paleointensity experiments, including partial thermoremanent magnetization checks, thermoremanent magnetization anisotropy and cooling rate corrections. The comparison between the new data, previous selected data from Central Asia, and available global models reveals important differences between approximately 400 BCE and 400 CE, especially concerning the geomagnetic field intensity element. In order to investigate this in detail, we have developed a regional update of the SHAQW global models family by incorporating, for the first time, high-quality data from Central Asia. The results suggest that this deviation is linked to non-dipolar sources of the geomagnetic field in Central Asia reaching a maximum contribution around the first century BCE. According to the updated global paleoreconstruction, this non-dipole feature, manifested at the Earth’s surface as low intensities, is associated with the presence of a reversed flux patch at the core-mantle boundary beneath this region.

Plain Language Summary
The geomagnetic field is a global feature that changes over time and space. These changes are known over the last few centuries through direct observations collected by satellites and geomagnetic observatories. However, indirect measurements, based on the paleomagnetic study of archeological and geological materials, are needed to disentangle geomagnetic field behavior over longer time scales. In this context, archeomagnetism is the discipline that studies the direction and strength of the past geomagnetic field by investigating the magnetic properties of well dated archeological baked clay material. In order to properly describe the behavior of the Earth's magnetic field it is crucial to have a good temporal and spatial coverage of archeomagnetic data. In this work, we present the first full-vector archeomagnetic data for Central Asia, a large region that remained unexplored from an archeomagnetic point of view. The new data were obtained from 9 kilns excavated in South Uzbekistan, with ages ranging from 200 BCE to 1429 CE. We then developed a regional update of the SHAQW global models family by incorporating, for the first time, high-quality archeomagnetic data from Central Asia. The results indicate a relevant non-dipole feature presented over this region around the first century BCE.

1. Introduction
The existence of a magnetic field enveloping our planet (the so-called geomagnetic field) is crucial for life on Earth. This field serves as a shield that safeguards the Earth from charged particles coming from the solar wind and space. The geomagnetic field is mainly (about 95% of the total field) generated in the Earth's outer core by the complex convection of melted metals. The outer-core field, often referred to as the main field, is not fixed and changes at different spatial and temporal scales. Since the Earth's magnetic field is constantly changing in both
strength and direction, obtaining evenly distributed measurements is essential to obtain a satisfactory understanding of its behavior. Changes in the geomagnetic field on time scales of decades or centuries, known as secular variation (SV), are well-constrained in the recent past thanks to instrumental measurements from geomagnetic observatories and satellite missions. However, to decipher geomagnetic field changes at centennial to millennial scales, indirect measurements relying on the paleomagnetic study of baked archeological materials or rocks are needed. In particular, archeomagnetic data obtained from well-dated baked clays from kilns, hearths, burned sediments, or potteries are invaluable to constrain the behavior of the geomagnetic field during the Holocene period. In fact, the identification of past changes in the geomagnetic field is achieved through the analysis of the thermoremanent magnetization (TRM) recorded by archeological remains when they are heated and cooled in the presence of the Earth's magnetic field. This is because the TRM is parallel to, and under certain conditions, also proportional to the ambient magnetic field (Thellier & Thellier, 1959). For areas with a radius less than 1,000 km, archeomagnetic data can be compiled to generate a local paleosecular variation curve (e.g., Rivero-Montero et al., 2021). For more extensive areas, regional or global models are typically developed based on spherical harmonic analysis (e.g., Campuzano et al., 2019; Schanner et al., 2022) to decipher past geomagnetic field changes. In both cases, the availability of a well-distributed database, spanning both time and space, is of great importance for obtaining accurate paleomagnetic reconstructions.

In this context, the main objective of this study is to provide the first full-vector archeomagnetic data from Central Asia for the last few millennia and to evaluate the predictions of global paleoreconstructions in this vast area characterized by an important lack of archeomagnetic information. In terms of directional archeomagnetic data, no declination values have ever been provided for this region, and limited inclination information is available (Brown et al., 2015 updated in 2021; and references therein). While intensity is the most extensively documented geomagnetic field element, with more than 250 entries, it is important to note that the majority of archeointensities fail to meet the minimum quality criteria commonly applied in modern studies (please, see Bonilla-Alba et al., 2021 for a deeper discussion). Therefore, the new full-vector data presented here will enhance the existing database that defines the geomagnetic field changes in Central Asia and, consequently, will help improve future global paleoreconstructions.

2. Archeological Context and Chronology

Here, we present the rock-magnetic and archeomagnetic study of nine pottery kilns sampled in three archeological sites from southern Uzbekistan: Kampyr Tepe (KAF) (37.41°N, 67.03°E), Dalverzin (38.1°N, 67.85°E), and Termez (37.27°N, 67.2°E) (Figure 1). These sites are now included in the Surkhan Darya province and were occupied simultaneously during different periods. The studied kilns are dated between the third century BCE and the fifteenth century CE based on archeological evidence and radiocarbon analyses conducted on charcoal samples found within the internal stratigraphy of the kilns (see Table S1 in Supporting Information S1).

The archeological site of KAF is located around 20 km northwest of Termez (Figure 1). The archeological sequence of the site begins in the Hellenistic period, and it is considered one of the phrourion (fortresses) founded by Alexander the Great in northern Bactria during the late fourth century BCE, located on the right bank of the Amu Darya. In addition to its military functions, it served as a trading post along the route connecting Bactria and its capital Bactra (in northern Afghanistan), with Maracanda (Samarkand, Uzbekistan) in Sogdia (for more details, see Martínez Ferreras et al., 2016). During the Greco-Bactrian period (around 250–150 BCE), the settlement covered approximately 13 ha and included a walled Citadel or Acropolis, as well as a dwelling area or low city surrounded by a wall that extended to the north and east, including a moat. In the mid-second century BCE, the city endured the territory's occupation by nomadic tribes, known as Tocharians in Greek sources, which marked the end to the Greco-Bactrian kingdom. Nevertheless, KAF continued to be inhabited and experienced a major expansion during the early Kushan period, from the latter half of the first century BCE. Most of the currently visible structures date from this period. The city was finally abandoned toward the end of Kanishka's kingdom in the mid-second century CE (Riveladze, 2009). Archeological evidence points to the existence of an important and long-lasting pottery production during the Seleucid and Greco-Bactrian periods. The archeomagnetic samples were taken from a circular kiln of about 2 m in diameter (kiln 1: KAF2) in the pottery workshop located in the eastern sector outside the walls. This kiln has been dated to the second century BCE based on archeological constraints and the ceramic repertoire associated with it (see Martínez Ferreras et al., 2016 for details).
The second studied site, Dalverzin Tepe (DAF), is located 115 km north from Termez (Figure 1). The site was excavated by the Art Institute of Tashkent between 1967 and 1978. The primary findings were initially published by Pugachenkova and Rtveladze (1978) and have been since updated by other researchers (Turgunov et al., 2008). According to these studies, the initial settlement dates back to the Greco-Bactrian period and consisted of a rectangular fortress known as the Citadel. However, significant urban development began in the second half of the second century BCE when the Yuezhi nomadic tribes settled in both the Citadel and the low city. The peak of urban expansion occurred during the period of the Great Kushans (first to second centuries CE), with the low city densely occupied. Evidence of fire and destruction point to a gradual decline and eventual abandonment of the city starting from the third century CE, although the Citadel remained intermittently occupied until the sixth to seventh centuries CE (Bernard, 1980). At the site, a pottery workshop with 11 kilns was discovered in the artisanal quarter located in the southwestern corner of the low city. Archeomagnetic samples were collected from two of
these firing structures: kilns 3 (DAF3) and 4 (DAF4). The two studied kilns correspond to the Kushan period (first century CE to third century CE), according to their characteristics and the associated pottery, with kiln DAF3 being younger than kiln DAF4 (see Table S1 in Supporting Information S1). Moreover, these kilns are very similar to a ceramic kiln found and studied at Tchingiz Tepe (Termez) by the Uzbek-Spanish IPAEB team. The Tchingiz Tepe kiln was dated through radiocarbon analysis of a substantial amount of charcoal found in the fire chamber. The results indicate that it was in use between the mid-second and mid-third centuries CE (for more details, see Martínez Ferreras et al., 2014). Therefore, this absolute dating, along with the structural similarities between the kilns, archeological evidence, and the study of the ceramic typologies associated with DAF3 and DAF4, supports the chronology framework proposed by the archeologists (see Table S1 in Supporting Information S1).

The third site, ancient Termez, is made up of several fortified enclosures that prove a long-lasting occupation from the Hellenistic to the Islamic period. Following the Islamic occupation in the late seventh century, Termez gained significant political, economic and commercial importance (Leriche, 2001; Leriche & Pidaev, 2007, 2008). The Citadel and the shahristan (low city) were densely occupied, and an active artisanal area was established in the rabad (suburbs), extending to the north and southwest. According to archeological research, multiple pottery production centers (workshops n. 1, 2, 4, 8, 9, 10, 11) were active during the early Islamic period (approximately seventh to ninth centuries CE) both inside and outside the northern wall of the rabad. However, the pottery workshop located in the shahristan (workshop 5) dates to a latter period and reflects changes introduced in the urban plan following the Mongol conquest led by Genghis Khan in 1220 (Fusaro et al., 2019, 2022; Lesguer, 2015; Martínez Ferreras et al., 2020; Portero et al., 2021). This date marks the end of Termez as a major urban center, although residual occupations persisted in some areas until at least the seventeenth century CE.

In the shahristan area (SHF), three kilns (kilo 5-1: SHF1; kiln 5-2: SHF2; and kiln 5-3: SHF3) from workshop 5 were selected for archeomagnetism. Based on archeological data, these kilns are associated to the same archeological context and can be considered contemporaneous. Radiocarbon data suggest a date range of 1306–1429 CE (see Table S1 in Supporting Information S1).

Sampling for archeomagnetism also included three pottery kilns from two different workshop workshops located in the northern area of the rabad. Two kilns (2-1 and 2-2), discovered by the Uzbek-French MAFOuz mission in workshop 2 and coded as F1A2 and F2A2 for archeomagnetism, were sampled. The MAFOuz team conducted a superficial cleaning of kiln 2-1 (F1A2) and a primary excavation of kiln 2-2 (F2A2) (Leriche, 2001; Lesguer, 2015). The latter kiln has been recently re-excavated by the Uzbek-Spanish mission IPAEB, and the radiocarbon analysis provided a date ranging from the second half of the eighth century to the end of the tenth century (see Table S1 in Supporting Information S1). An absolute date for kiln 2-1 (F1A2) is unavailable, but the spatial relationship with kiln 2-2 (F2A2) indicates that it corresponds to the same chronological framework. The IPAEB team also excavated two kilns in workshop 11, although archeomagnetic samples were taken only from kiln 11-1 (F1A8). Radiocarbon dating places kiln 11 (F1A8) between the second half of the eighth century and the end of the tenth century (Fusaro et al., 2019, 2022; Martínez Ferreras et al., 2020; Portero et al., 2021).

3. Methodology

3.1. Sampling

Sampling procedures have a considerable effect on the uncertainty of the archeomagnetic directions. Hence, particular attention was given to the archeomagnetic sampling process of the archeological kilns. Samples were collected from different walls or sections of the kilns to guarantee a good spatial coverage (Figure 1). We prioritized sampling the sectors of the kilns that appeared to be more consolidated, and thus most probably fired at elevated temperatures. We collected between 13 and 18 oriented hand samples, each of several centimeters in size, from each kiln. We used plaster of Paris to obtain flat surfaces that were oriented and marked in situ using solar and magnetic compasses prior to the detachment of the samples. These hand samples were then consolidated using water-glass at the paleomagnetic laboratory of the Complutense University of Madrid, where cubic specimens measuring 2 cm on each side were prepared. We specifically selected specimens that exhibited evidence of higher-temperature exposure for further archeomagnetic and rock-magnetic studies.
3.2. Rock-Magnetism

Rock-magnetic experiments were conducted on 27 independent hand-samples, typically three specimens per kiln. To perform these experiments, we used a Variable Field Translation Balance (VFTB, Mag-Instruments, Petersen & Petersen, 2008) to measure magnetization versus temperature (Ms-T) curves, Isothermal Remanent Magnetization (IRM) curves, back-field Saturation IRM curves, and hysteresis loops. Ms-T curves were measured in an air atmosphere, involving heating the samples up to 700°C and subsequently cooling them back to room temperature. These experiments were used to determine the Curie/Neél temperature of the magnetic minerals, using the second derivative method according to Tauxe et al. (2018). Ms-T curves are also useful for identifying potential thermally-induced mineralogical alteration during laboratory heating. In addition, IRM acquisition curves were measured using a maximum applied field of 1 T. Back-field IRM curves were used to calculate the remanent coercive field (Hc). The maximum field applied for hysteresis loops was also 1 T, allowing to calculate the saturation magnetization (Ms), the saturation remanent magnetization (Mrm) and the coercive field (Hc). We used the RockMagAnalyzer 1.1 software, developed by Leonhardt (2006), for these calculations. The hysteresis parameters were represented in a Day diagram (Day et al., 1977), a classical approach used to make inferences about the magnetic domain state of magnetic mineral assemblages. However, it should be noted that this diagram should be interpreted with caution because of the complexities that limit Day diagram interpretation for domain state diagnosis, as highlighted by Roberts et al. (2018). All measurements were performed in the paleomagnetic laboratory of the Complutense University of Madrid.

3.3. Full-Vector Archeomagnetic Measurements

One hundred and sixty-eight oriented specimens, from more than 100 oriented hand-samples, were used for archeomagnetic analysis. We applied the classical Thellier-Thellier method (Thellier & Thellier, 1959), including partial TRM (pTRM) checks, as well as TRM anisotropy and cooling rate corrections. These measurements were conducted in the paleomagnetic laboratories of the Complutense University of Madrid, and CCiTUB—GEO3BCN CSIC in Barcelona. The workflow of this study is similar to our previous work conducted on pottery samples from Uzbekistan (Bonilla-Alba et al., 2021). In these studies, specimens were progressively heated in a MMTD-24 (Magnetic Measurements) thermal demagnetizer from 100°C to 530–600°C. Between 14 and 17 temperature steps were applied. At each temperature, two heating-cooling cycles were performed. First, the specimens were heated and cooled with an applied laboratory field of 50 μT, applied along the Z axis of the specimens. Subsequently, they were heated and cooled once more at the same temperature, but with the field applied in the opposite sense (Z axis). In addition, and in order to verify the thermal stability of the samples during the experiments, partial thermoremanent magnetization (pTRM) checks were performed every two steps of temperature. Magnetization measurements were conducted using a 2G cryogenic Superconducting Quantum Interference Device (SQUID) magnetometer, and a slow-speed spinner magnetometer Molspin Minispin. Additionally, after each temperature step, susceptibility measurements were performed using a MS3 susceptibility meter (AGICO) to check for possible magnetic alteration.

To meet contemporary quality standards for paleointensity determination, the TRM anisotropy effect was investigated at the specimen level. While this effect is generally low in fired clays from archeological kilns (Genevey et al., 2008; Gómez-Paccard et al., 2006; Kovacheva et al., 2009), recent studies have indicated that in certain cases the magnetic record of specific in situ structures may be significantly affected by TRM anisotropy. This influence not only impacts intensity estimations but also affects the directional record, as highlighted by Palencia-Ortas et al. (2021). To estimate the TRM anisotropy tensor, six additional heating and cooling cycles were performed when approximately 70% of the natural remanent magnetization (NRM) was lost. During these cycles, the laboratory magnetic field was applied in six different directions: X, X, Y, Y, Z, Z. Subsequently, all the measurements were corrected based on the TRM anisotropy tensor calculated for each specimen. After completing the TRM anisotropy measurements, or in some cases at the end of the Thellier experiments due to laboratory needs, we measured the cooling rate effect following the protocol detailed by Gómez-Paccard et al. (2006). For this purpose, four additional measurements were carried out at the same temperature. The first measurement involved heating the samples for 45 min with the magnetic field applied in Z and then cooling them for 45 min, following a process similar to the cycles performed previously. The same methodology was applied for the second measurement, although the magnetic field was fixed along Z. For the third measurement, the samples were heated for 45 min with the magnetic field applied in Z, but the cooling time was extended to 24 hr. Lastly, the fourth step was similar to the second one. By comparing the magnetization of the first and the
third measurements, we obtained the cooling rate factors used to correct the archeointensity estimates. Meanwhile, the second and fourth steps helped us to estimate the potential changes in TRM acquisition capacity due to thermally induced mineralogical alterations. Cooling rate correction factors were applied only when they exceeded the mineralogical evolution. In cases where it was not feasible to determine the cooling rate factor, we used the value provided by sister specimens. When this was not an option, we decided to apply a mean value of 5% as suggested in older studies (Genevey et al., 2008) and consistent with other results obtained from archeological fired clays (Gómez-Paccard et al., 2012; Hervé et al., 2019).

The direction of the Characteristic Remanent Magnetization (ChRM) was calculated from Thellier and Thellier experiments performed on oriented samples, following standard paleomagnetic procedures. In addition, we conducted alternating field (AF) demagnetization experiments on 31 specimens using a 2G cryogenic SQUID magnetometer with an AF demagnetization system. These AF demagnetization experiments were conducted using a field range from 5 mT to a maximum of 120 mT. Archeointensity and directional analysis was carried out with the StarmacAW3.0 and Stereo_V3.0 software developed by Dr. Pierrick Roperch at Géosciences-Rennes. The archeointensity mean values were determined by calculating arithmetic averages, and the associated intensity errors were reported as standard deviations. The mean directions were calculated according to Fisher statistics (Fisher, 1953), and are provided along with the precision parameter (k) and the 95% cone of confidence (α95). It is worth emphasizing that we maintained the hierarchical order (specimen-sample-structure). Both the directional and intensity means were indeed derived from the means obtained at the sample level, which were based on the retained values at the specimen level.

4. Results

4.1. Magnetic Mineralogy

The combination of magnetic hysteresis, IRM acquisition curves and thermomagnetic tracks reveals the presence of a mixture of magnetite, maghemite, and hematite in varying proportions and grain sizes. Hysteresis loops display saturated curves with varying coercivities. In some samples, small traces of high coercivity are visible, with the upper branches of the hysteresis loops not fully closed (Figure 2a). IRM acquisition curves typically saturate at around 200 mT (Figures 2b and 2e). These curves also exhibit a gentle start of magnetization at low applied fields (Figure 2b), and correspond to Curie temperature of approximately 560–580°C (Figure 2c). These samples are mainly composed by SD-like magnetite/titanomagnetite with low Ti content, although with some traces of hematite observed at the thermomagnetic curves in some specific cases (Figure 2c). Alternatively, other samples are characterized by a lower coercivity at the hysteresis that is saturated (Figure 2d). In these samples, IRM acquisition curves still saturate at approximately 200 mT, but the magnetization at the lowest field exhibits a higher slope, indicating a larger domain size (Figure 2e). The thermomagnetic curves also reveal the presence of a magnetic phase that demagnetizes at around 580°C, along with traces of a second magnetic mineral with a higher transition temperature (Figure 2f). This suggests the prevalence of a Pseudo-Single-Domain (PSD)-Multidomain (MD) magnetite and small amounts of hematite in these samples. Indeed, a third group of samples exhibits medium coercivities in their magnetic hysteresis loops (Figure 2g), but their IRM acquisition curves reach saturation in a higher field range, typically between 700 and 1,000 mT, indicating the presence of a harder magnetic mineral in their composition (Figure 2h). Additionally, the thermomagnetic curves for these samples show the presence of a mineral that loses magnetization at temperatures around 600–610°C, suggesting the presence of maghemite (Figure 2i).

Day plot, which summarizes the results obtained from hysteresis and back field-curves (Figure 2j), was originally designed for magnetite/titanomagnetite particles (Day et al., 1977). However, over the past two decades, it has been widely applied to infer information about grain size distribution (Peters & Dekkers, 2003). Based on the results described above, we conclude that magnetite/titanomagnetite is the primary magnetic mineral in our samples (Figures 2a–2j). The domain state of these minerals varies from one sample to another, with some falling within the MD zone and others approaching the SD region in the Day plot (Figure 2j). This variation in domain state has been previously reported in archeological data, as documented in an early work by Dunlop (2002) and further research by other scholars (e.g., Bonilla-Alba et al., 2021; Rivero-Montero et al., 2021).
4.2. First Full-Vector Archeomagnetic Data From Central Asia

In our study, NRM-TRM plots were analyzed using a set of quality criteria similar to those used in our earlier research on pottery fragments from Uzbekistan. For a detailed description of the selection criteria applied, please refer to Bonilla-Alba et al. (2021). Figure 3 displays representative Arai plots together with the corresponding Zijderveld diagrams. Approximately 60% of the studied specimens yielded reliable results. These specimens...
exhibited a single component of magnetization pointing to the origin in the Zijderveld plots, and displayed linear
trends in the NRM‐TRM plots, as shown in Figures 3a–3d. Samples displaying concave‐up plots on NRM‐TRM
graphs, which typically indicate multidomain behavior, or showed evidence of magnetic alteration during the
experimental process, were discarded for paleointensity determination (Figures 3e and 3f).

In certain cases, we observed a weak viscous component up to temperatures of 100–200°C in the Zijderveld plots. However, the characteristics components (ChRM) considered as a TRM acquired during the last heating/cooling, were well isolated after removing the viscous component. The ChRM was generally eliminated at maximum temperatures of 540–580°C, in agreement with the rock‐magnetic experiments showed before. Only samples with differences lower than 10% between pTRM checks and the corresponding TRMs were considered for further evaluation. Moreover, all the accepted paleointensities were calculated using more than 50% of the fraction of the NRM component used for slope calculation ($f$, Coe et al., 1978) and corresponded to quality factors ($q$, Coe et al., 1978) higher than 8. To ensure the reliability of our results, we also established maximum allowable values for two key parameters. The angular deviation, MAD (Kirschvink, 1980) and the deviation angle, DANG (Tauxe & Staudigel, 2004), were limited to 10° and 5°, respectively. These restrictions align with the methodology of Shaar et al. (2016). The archeointensity results at the specimen level have been compiled in Table S2 in Supporting Information S1. Figure S1 in Supporting Information S1 shows the quality parameters associated to our accepted results. The accepted values were derived from experiments that involved at least 7 temperature steps, and the results correspond to $f$ values falling within the range 50%–98%. The quality factors, denoted as $q$, range from 8.9 to 156.6. The MAD values display variability between 1.2° and 7.4°, but it is worth noting that
only 12 specimens exceed the 5° threshold for MAD. The highest DANG value obtained in our analysis is 4.7° (Figure S1 in Supporting Information S1). The curvature parameter \(k\) and the \(\beta\) ratio fell within the ranges of 0.0004 and 0.8360, and 0.0056 and 0.0728, respectively. It is important to clarify that while these values were not employed as criteria for either accepting or rejecting specimen-level determinations, they were taken into consideration for qualitative interpretation purposes.

Recent studies have shown the critical importance of evaluating the TRM anisotropy effect to ensure accurate full-vector archeomagnetic determination, as highlighted by Palencia-Ortiz et al. (2021). In this study, this effect was calculated at the specimen level. The impact of TRM anisotropy on archeointensity determination was found to vary between 0.1% and 16.4% (see Figure S2 in Supporting Information S1). On average, this effect was determined to be 3.2%. As expected, the TRM anisotropy observed is relatively low when compared to highly anisotropic archeological materials like tiles or pottery. In such cases, substantial differences are often observed between the TRM anisotropy-corrected and the uncorrected intensity values (e.g., Gómez-Paccard et al., 2012, 2019; Osete et al., 2016). Additionally, we calculated cooling rate correction factors, which ranged between 0.5% and 17% (see Figure S2 in Supporting Information S1), with a mean value of 5.7%. This result is similar to those obtained from other archeomagnetic materials (Genevey et al., 2008; Hervé et al., 2019).

Characteristic directions were determined from the accepted specimens thermally demagnetized in the course of Thellier-Thellier experiments, using the same temperature intervals employed for archeointensity determinations. These characteristic directions were calculated using best-fit lines that were not anchored to the origin (see Figure 3 for some examples). However, since only specimens pointing to the origin in the Zijderveld plots were retained, the direction not anchored to the origin are indistinguishable from the anchored ones. In Table S3 in Supporting Information S1 declination and inclination values obtained at the specimen level, with and without the TRM anisotropy correction, are shown. Although the difference between the corrected and uncorrected directions is relatively minor, it is worth noting that the mean of the MAD values is lower when the correction is applied. Specifically, without the TRM anisotropy correction, the MAD stands at 2.0°, whereas it decreases to 1.8° when this correction is applied (Table S3 in Supporting Information S1). Additional characteristic directions were also calculated from AF demagnetization experiments conducted on sister specimens (see Figure S3 in Supporting Information S1). The results indicate that the majority of the studied specimens were almost completely demagnetized at 120 mT. To determine the ChRM from the AF experiments, between 8 and 16 steps were necessary. For kilns F1A2 and F2A2, the initial magnetic field selected to obtain the characteristic direction varied between 10 and 25 mT. However, kilns SHF2 and SHF3 exhibited a secondary component that, in certain cases, persisted up to 50 mT. Table S3 in Supporting Information S1 shows the results obtained at the specimen level. As expected, thermal and AF demagnetization results are very similar.

From the directions and intensities obtained at the specimen level, we derived nine new full-vector archeomagnetic data (see Table 1). Mean paleointensities have been calculated using at least 4 specimens per kiln and mean directions with at least 10 specimens per site. The hierarchical order specimen-sample-structure has been employed to calculate final means. The \(\alpha_95\) values, ranging from 1.8° to 3.6°, and the \(k\) values, ranging from 130 to 484, provide important insights into the quality and reliability of our directional data. Additionally, the uncertainties obtained for the mean intensity values, falling within the range of 2.3 and 6.4 μT, further affirm the high quality of our new data.

The directional results reveal a significant variation in declination, ranging from 24.5°W and 6.3°E, within the time interval investigated spanning from the third century BCE and the fifteenth century CE. Inclination values also exhibit variability, ranging from 50.4° to 65.0°. As expected, archeomagnetic directions from kilns of the same age are well grouped (Figure 4).

Our new data from KAF indicate that a geomagnetic field direction of approximately \(D = 24.5°\) W and \(I = 50.4°\) (\(\alpha_{95} = 2.2°\)) was achieved during the second century BCE in South Uzbekistan. After that, the magnetic field exhibited a rapid eastwards drift, reaching eastern declinations of approximately 5°E and inclination values around 55°, during the first three centuries of the CE. Moving toward recent times, the new data obtained from kilns sampled in the northwest rabad of Ancient Termez reveal a consistent pattern of western declinations, of about 10°W. These western declinations are associated with higher inclinations, reaching approximately 62°, during the period spanning from the eighth and the tenth centuries CE. Finally, the most recent data, corresponding to the fourteenth to the fifteenth centuries and obtained for the kilns studied in Ancient Termez, specifically in the shahristan area, indicate northern declinations of about 1°W and inclinations around 55°.
Table 1

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<td>2.1</td>
<td>481</td>
<td>11</td>
<td>18</td>
<td>63.5</td>
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<td>3. Ancient Termez</td>
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<td>a) Shahristan—workshop 5</td>
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<tr>
<td>SHF1 (kiln 5-1)</td>
<td>1306–1429 CE</td>
<td>37.27</td>
<td>67.19</td>
<td>11</td>
<td>12</td>
<td>1.4</td>
<td>56.8</td>
<td>2.6</td>
<td>347</td>
<td>10</td>
<td>11</td>
<td>54.2</td>
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<td>SHF2 (kiln 5-2)</td>
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<td>b) North-West rabad—workshops 2 &amp; 11</td>
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<td>F1A2 (kiln 2-1)</td>
<td>776–981 CE</td>
<td>37.27</td>
<td>67.2</td>
<td>9</td>
<td>12</td>
<td>9.8</td>
<td>62.5</td>
<td>1.8</td>
<td>785</td>
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<td>14</td>
<td>60.8</td>
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<tr>
<td>F1A8 (kiln 11-1)</td>
<td>776–971 CE</td>
<td>37.27</td>
<td>67.2</td>
<td>11</td>
<td>11</td>
<td>9.2</td>
<td>61.3</td>
<td>2.1</td>
<td>475</td>
<td>11</td>
<td>11</td>
<td>60.8</td>
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<tr>
<td>F2A2 (kiln 2-2)</td>
<td>776–981 CE</td>
<td>37.27</td>
<td>67.2</td>
<td>10</td>
<td>10</td>
<td>12.4</td>
<td>65.0</td>
<td>2.9</td>
<td>272</td>
<td>4</td>
<td>4</td>
<td>59.4</td>
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</table>

Note. Kiln, name of the kiln studied; Date, age proposed; Lat, longitude; Long, latitude; Nd (nd), number of samples (specimens) used to obtain the mean direction; Dec, declination; Inc, inclination; α95, semiangle of 95% confidence limit; k, precision parameter; nH, number of samples (specimens) used to obtain the mean paleointensity; Bmean, mean intensity and standard deviation obtained considering both the thermoremanent magnetization anisotropy and cooling rate corrections.

Concerning the geomagnetic field strength (as shown in Figure 5c), our new data do not reveal significant fluctuations in intensity. The values remain relatively stable, ranging from approximately 55 and to 65 μT throughout the entire analyzed time period.

In summary, our new results indicate a significant change in the geomagnetic field in Central Asia between the second century BCE and the second century CE. This variation is characterized by a rapid transition from western to eastern declinations, minor variations in inclination, and relatively high values of intensity (Figure 5). After this, a significant decrease in declination, accompanied by an increase in inclination and consistent intensity values of about 62 μT, is observed between the second century CE and the eighth to ninth centuries CE. Finally, an increase in declination and a decrease in the inclination of the geomagnetic field, with a slight decrease in intensity is observed up to the fourteenth to fifteenth centuries CE. Despite the significance of our new data, which represent the first set of full-vector archeomagnetic data from Central Asia for the studied period, it is challenging to obtain a more precise description of geomagnetic field changes during this period solely relying on our limited data set. In order to further decipher geomagnetic field changes in Central Asia, in the following section, we compared our new data set with previously available results and with predictions of some of the most recent global geomagnetic field models, taking into account their error bands.

5. Discussion

5.1. First Full-Vector Archeomagnetic Data From Central Asia: Comparison With Previous Data and Geomagnetic Field Models

To conduct a more comprehensive investigation into the SV of the geomagnetic field in Central Asia, we carried out a comparative analysis. We first compared our new results with other archeomagnetic data obtained from archeological sites located within a radius of 1,000 km around Termez (37.3° N, 67.2°E) and corresponding to the time period from 400 BCE to 1900 CE.

![Figure 4](image-url) Stereoplot projection of mean directions obtained per kiln together with their confidence limit α95 (95% of probability according to a Fisher distribution).
Data were downloaded from the GEOMAGIA50.v3 database (Brown et al., 2015, 2021), which was updated in 2021, and were relocated to Termez coordinates assuming a tilted dipole field. Additionally, we calculated predictions using the most recent global geomagnetic field models at Termez coordinates. These models include the SHAWQ family (Campuzano et al., 2019; Osete et al., 2020) and ArchKalMag14k.r model (Schanner et al., 2022, see also https://ionocovar.agnld.uni-potsdam.de/Kalmag/Archeo/). The data and the models’ results are plotted in Figure 5. Furthermore, we included the paleosecular intensity curve published for Central Asia in our previous study (Bonilla-Alba et al., 2021), which was established for the time frame spanning from 600 BCE to 600 CE.

As can be seen, no declination data were available before our study for the studied period and region (Figure 5a). The new declination values obtained for Dalverzin Tepe (first and second centuries CE) and Ancient Termez (eighth to fifteenth centuries CE) agree well with global reconstructions. In contrast, the datum obtained for Kampir Tepe (second century BCE) differs by more than 10° from the models’ predictions, indicating a strong western direction. It seems, therefore, that present global reconstructions are not able to properly reproduce geomagnetic field values in Central Asia during this period. However, it is worth noting than since only a single value is available, additional data are needed to confirm the behavior observed.

In contrast, a significant number of inclination values is available in the literature. To be precise, there are 186 entries documented in the GEOMAGIA50.v3 database, all of which correspond to the time interval 900–1900 CE. Unfortunately, no data are available for earlier time periods (Figure 5b). These inclination data (gray dots in Figure 5b) come from some older studies conducted on displaced bricks or baked clays, for which declinations were not obtained (Burakov & Nachasova, 1978; Burlatskaya et al., 1969, 1977, 1986). It is important to note the high dispersion associated with the available inclination data, with differences of more than 30–40° in contemporaneous data (see for example the most modern results in Figure 5b). The absence of declination information in these data suggests that the materials were not sampled in situ, and that certain assumptions about their position during heating were made to infer the inclination values. However, detailed information about the sampling procedure and the laboratory protocol followed in these earlier studies cannot be easily found in the original publications. This, coupled with the significant dispersion evident in the data and their inconsistency with global model predictions (see for example data from the last centuries), points out the need for caution when interpreting these inclination values. On the contrary, the new inclination values from Uzbekistan obtained in this study (Figure 5b) fit well to global geomagnetic field models, with the exception of the Dalverzin Tepe data (first
and second centuries CE) for which some discrepancies are observed. For this period, inclinations of about 52–55°, not recovered by the SHAWQ or the ArchKalMag14k.r models, were achieved in South Uzbekistan. The available quantity of robust data is presently insufficient to draw in-depth conclusions about the directional behavior of the geomagnetic field in Uzbekistan during this specific time period. Further research would greatly benefit from an increased data set of directional information, which would facilitate more comprehensive analyses in subsequent studies.

Finally, and despite being the paleointensity the best covered geomagnetic parameter with 249 available results more or less well timely distributed (as shown in Figure 5c), it should be noted that the majority of the available archeointensities (Burakov & Nachasova, 1978; Burlatskaya et al., 1969, 1977, 1995; Nachasova & Burakov, 1994, 1996, 1997; Tang et al., 1991) fail to meet modern quality standards (see Bonilla-Alba et al., 2021 for a detailed discussion). These data were acquired from bricks, potteries or baked materials, which have the potential to exhibit a significant TRM anisotropy. Importantly, these data were obtained without conducting experimental determinations of the TRM anisotropy tensor at the specimen level. Only in few studies this effect was considered by applying the laboratory field parallel to the NRM in some selected specimens. However, this method was not applied for the whole collection. Therefore, these intensity data must also be interpreted with caution. For the region and period studied only the archeointensities recently obtained from Bonilla-Alba et al. (2021) and Troyano et al. (2021) meet the current quality standards. In this study, these data have been deemed as the sole reliable source for inferring geomagnetic field changes in Central Asia. For a detailed discussion of the different modern quality standards used for paleointensity determination, please refer to Bonilla-Alba et al. (2021) and Campuzano et al. (2019). Figure 5c illustrates how, in general, the new data presented in this study agree well with global model predictions. However, an exception is observed in the data obtained from Dalverzin Tepe, which indicate higher intensities than the models during the first and second centuries CE. It is worth noting that, during this period, some discrepancies with the models in terms of inclination are also observed.

Taking a closer look, the new intensity data obtained from Kampil Tepe, dating back to the second century BCE, indicate slightly higher intensity values when compared to contemporaneous data and the PSVC from Bonilla-Alba et al. (2021). The data from Dalverzin Tepe, dating back to the first and second centuries CE, suggest a significantly larger increase in intensity during this period compared to the trends depicted by previous data from Bonilla-Alba et al. (2021), the PSV intensity curve or by the prediction of global models. Subsequently, from 850 CE to 1900 CE, there is a closer agreement between the archeomagnetic data and paleomagnetic reconstructions. Nevertheless, it is worth noting that for the most recent four centuries, geomagnetic field reconstructions tend to predict higher intensities than what is observed in the high-quality intensity data available for this region. For a more detailed discussion, please refer to Troyano et al. (2021).

Based on the preceding description, our primary focus now centers on geomagnetic field changes within the time frame spanning from 400 BCE to 400 CE, where the most important differences between robust data and models are observed. For the following discussion we considered the new data obtained here along with the data obtained in our previous study (Bonilla-Alba et al., 2021). Any previous data that do not meet modern standards of quality (represented by gray dots in Figure 5) have been excluded from our interpretation.

As already noted previously, this period is characterized by a significant discrepancy between archeointensity data and the predictions of global models (see Figure 5). From 400 BCE to 1 CE, the data reveal a rapid decrease in intensity, characterized by a SV rate of approximately 6 μT per century. Remarkably, this SV rate aligns closely with the decay rate of about 5 μT per century, as estimated from the more recent data by Troyano et al. (2021), which cover the later centuries (yellow data points in Figure 5c). Following this initial decrease, observed between 400 BCE to 1 CE, there is a notable increase in the field strength. Note than our new data obtained from Dalverzin Tepe, dating back to the first to the second centuries CE, significantly contribute to a better understanding of this rapid intensity increase, revealing high intensity values for this period. This increase is characterized by an average rate of approximately 4 μT per century between 1 CE and 400 CE.

This observed increase, following the preceding decline, results in a distinctive V-shaped pattern in the field strength across Central Asia during the period from 400 BCE to 400 CE. This V-shaped pattern in the field strength is associated with SV rates ranging from 4 to 6 μT per century (in absolute values). It is worth highlighting that these values significantly differ from other prominent local intensity anomalies, such as the Levantine Iron Age Anomaly (LIAA, Shaar et al., 2022 and references therein), which exhibits higher
characteristic intensity rates of change of approximately 35–55 μT per century (almost 10 times higher than the SV rates found in our study). In the next section, we will examine this interesting V-shaped feature in greater detail.

5.2. Evidences of a Non-Dipole Field Contribution in Central Asia Around the First Century BCE

In our previous study (Bonilla-Alba et al., 2021), we already suggested that the V-shaped intensity feature may have originated from a non-dipole contribution of the geomagnetic field. The new intensity data acquired here further corroborate this V-shaped pattern and contribute to a refined definition of the increasing branch by revealing high intensities at the end of the second century CE. Our study also suggests that current geomagnetic field models are not able to reproduce with an appropriate amplitude this V-shaped feature. Therefore, it is interesting to conduct a thorough investigation into the nature of this feature. We decided to carry out a study over the time interval from 400 BCE to 400 CE, a period for which robust data are available (see Figure 5c). For this time window, our new high-quality data set presents larger discrepancies with the most recent paleomagnetic reconstructions SHAWQ family and ArchKalMag14k.r. These differences were expected since no high-quality intensity data were available in this region at the time of construction of these models. Therefore, these models may not be the most suitable option for investigating the dipole and non-dipole contribution to the studied feature.

To address this issue, we have developed a regional update of the SHAWQ family paleoreconstructions using the same database as the SHAWQ family but now incorporating the high-quality data of Bonilla-Alba et al. (2021) and the new data from this study. This update, called SHAWQ-U (with U indicating Uzbekistan), specifically covers the time period from 400 BCE and 400 CE and was constructed following the same approach than the SHAWQ family model (for more details, see Campuzano et al., 2019; Osete et al., 2020). In these models, different weights have been assigned to the data, with less robust data associated to a weight of one, and high-quality data assigned to weights of 10. Consequently, model results are predominantly influenced by high-quality data, even if the entire database is used for model computation. We would like to note that the primary goal of this updated model is not to create a new paleoreconstruction within the designated time frame, since the acquisition of additional directional data is vital for a more thorough analysis. Instead, it is designed to shed light on the underlying cause of the V-shaped field strength pattern depicted by high-intensity quality data.

Figure 6 displays the SHAWQ-U model predictions at the coordinates of Termez, together with the results of the SHAWQ family models. For directions, the new model tends to fit better the few available declination and inclination data. It is remarkable that the model substantially differs from the SHAWQ family for directions, even if only three directional data were incorporated (Figures 6a and 6b). As expected, the SHAWQ-U model fits better the V-shaped trend, due to the inclusion of the high-quality intensity data set (Figure 6c). The new data help to identify two intensity maxima around 300 BCE and 125 CE, with a prominent intensity minimum around 25 BCE which is smoothed out in previous models. The new model and the previous intensity PSV curve of Bonilla-Alba et al. (2021) agree from 300 BCE up to the change of Era. However, the model exhibits a maximum around 125 CE that was not reflected in the PSV curve. This discrepancy is attributed to the inclusion of the two new intensity data from Dalverzin Tepe (first and second centuries CE). Overall, we consider that the SHAWQ-U model fits quite well the observations in Uzbekistan. However, we acknowledge that additional high-quality data, particularly directional results, would be greatly welcomed to provide a more accurate description of geomagnetic field changes in Central Asia.

To analyze the non-dipole characteristics of the geomagnetic field in the region during the time span between 400 BCE and 400 CE, we conducted a comparative study using the dipole terms of the SHAWQ-U model. Specifically, we examined the geomagnetic north pole’s positions and the dipole moment (DM). In Figure 6d, the positions of the geomagnetic poles according to SHAWQ-U model are compared with the virtual geomagnetic poles (VGP) inferred from the three directional data (depicted in Figures 6a and 6b). Notably, around 150 BCE (considering the age uncertainty within the range of 200 BCE to 0 CE), the directional VGP exhibits the most significant angular deviation from the polar path, signaling a non-dipole behavior during this time period. It is important to note that our conclusion about this non-dipole feature primarily relies on a single data point, emphasizing the need for additional directional data to corroborate our hypothesis. Nevertheless, the non-dipole nature during the first century BCE becomes markedly evident when we analyze the virtual axial dipole moment (VADM) in Figure 6e. To assess this, we calculated the average VADM using a sliding time window of 100 years, moving every 50 years, based on the intensity data shown in Figure 6c. We then compared the obtained VADM...
with the DM from the SHAWQ-U model. In the case of the first century BCE, the VADM exhibits clear discrepancies when compared to the DM curve, thereby accentuating the non-dipole characteristics prevalent during this specific time interval.

The observed variations in geomagnetic field, as detected on the Earth's surface, are intricately linked to changes in the radial geomagnetic field (Br) at the core-mantle boundary (CMB) (e.g., Terra Nova et al., 2015). In order to unravel the underlying cause of the V-shaped feature, we have plotted a Br snapshot map at the CMB (Figure 7a, with an animation in Movie S1) computed from the SHAWQ-U model. This map, shown at the epoch corresponding to the minimum intensity, dated at 25 BCE, reveals the presence of a reversed flux patch (RFP) exhibiting positive polarity directly beneath Uzbekistan (Termez is indicated by the black star in Figure 7a). This RFP is responsible for the pronounced intensity minimum observed at the Earth's surface. Furthermore, we have calculated the spatial average Br within a circular region of 10° (violet circle in Figure 7a) to track the temporal evolution of this particular geomagnetic field contribution in Central Asia. The mean Br, accompanied by a standard deviation error band, is represented in Figure 7b. At the beginning of the time window (400 BCE), the mean Br registers negative values, characteristic of normal polarity typically found in regions located in the northern hemisphere (as evident in Figure 7a). However, a significant transition occurs around 200 BCE when the RFP makes its appearance and expands in Central Asia. The intensity of this RFP continues to increase until it reaches its maximum positive mean Br value at 25 BCE. Subsequently, around 100 CE, the RFP diminishes, transitioning back to negative values once again. Here, it is important to note that this analysis was also conducted using the models ArchKalMag14k and the SHAWQ family. These models also record the minimum intensity and the RFP at the CMB, although not as distinctly as in the SHAWQ-U model.

To establish a connection between the behavior of the identified RFP at the CMB and the observed intensity variations at the Earth's surface, we have plotted a map that illustrates the non-dipole intensity. This non-dipole
intensity is determined as the difference between the total intensity and the dipole intensity given by the SHAWQ-U model (see Figure 7c). Consistent with the presence of the RFP at the CMB, the intensity map at the Earth's surface for 25 BCE clearly exhibits non-dipole characteristics in the Central Asia region, featuring negative anomaly values in contrast to the dipole term. Similar to our approach with the Br element, we have also computed a spatial average to track the temporal evolution of this non-dipole intensity (Figure 7d). As expected, this
temporal analysis reveals the distinctive V-shaped behavior, with the non-dipole intensity reaching its minimum value around 25 BCE.

6. Conclusions

Here, we present the first full-vector archeomagnetic data from Central Asia for the last few millennia. These data were obtained from the study of nine archeological kilns sampled in South Uzbekistan, with ages ranging between 200 BCE and 1429 CE. The new data allow for a better description of geomagnetic field variations in Central Asia over the last few millennia. The comparison between the new data, previous selected data from Central Asia, and available global models reveals important differences between 400 BCE and 400 CE, especially concerning the geomagnetic field intensity element. This suggests that current global models are not able to accurately reproduce geomagnetic field changes during this period. For this reason and in order to investigate these discrepancies in detail, we have developed the SHAWQ-U model, a regional update of the SHAQW family models, that incorporates, for the first time, high-quality data from Central Asia. The results suggest that the observed discrepancies are linked to an increased contribution of non-dipole sources to the geomagnetic field in Central Asia that takes high relevance around the first century BCE. According to the SHAQW-U paleoreconstruction, this non-dipole feature, expressed as local low intensities at the Earth’s surface, is associated with the presence of a reversed magnetic flux patch at the core-mantle boundary beneath this region.

Data Availability Statement

The data that support the findings of this study are openly available in MagIC (10.7288/V4/MAGIC/20006) and GEOMAGIA (https://geomagia.gfz-potsdam.de/). Data set were downloaded from the GEOMAGIA05.v3 database (Brown et al., 2015, 2021), which was updated in 2021 and the new data from Bonilla-Alba et al. (2021) and Troyano et al. (2021). We used Matlab software licensed by the Complutense University of Madrid, RockMagAnalyzer 1.1 software, developed by Leonhardt (2006), and Starmac developed in Rennes University by Dr. Pierrick Roperch. All these referenced were cited in the main text.

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References


