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# New paleomagnetic and paleointensity data from Georgia (Caucasus): a review

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**Abstract.-** Reliable paleomagnetic data from the Caucasus area, which forms part of the Alpine-Himalayan orogenic belt, are still sparse if compared to other regions of this fold belt, since the methodology employed in many of the studies carried out before the nineteen-nineties often does not fulfil the minimum reliability and quality criteria required for present-day paleomagnetic results. Nevertheless, since the 1990's a number of new paleomagnetic studies, which are based on a more up-to-date paleomagnetic methodology have been published, thus supplying more trustworthy paleomagnetic results from the Caucasus. In the Republic of Georgia, these paleomagnetic studies were directed towards different topics, including general paleomagnetic studies, paleomagnetism applied to tectonics, the study of the direction and intensity of the ancient geomagnetic field or archeomagnetic studies.

The present review tries to provide an outline and an integrated view of the new paleomagnetic and paleointensity results obtained during the last two decades in one of the countries belonging to the Caucasus region, the Republic of Georgia.

**Keywords:** Paleomagnetism, paleointensity, volcanic rocks, archeomagnetism, Caucasus, Georgia

**Resumen.-** Los datos paleomagnéticos fiables pertenecientes a la región del Cáucaso, parte del cinturón plegado Alpino-Himalayo, son aun escasos en comparación con los de otras áreas de dicho cinturón orogénico, debido a que la metodología empleada en muchos de los estudios llevados a cabo antes de la década de los 90 del siglo pasado, con frecuencia no cumplía los mínimos criterios de fiabilidad y calidad requeridos en los estudios paleomagnéticos actuales. Sin embargo, desde los años 90 del pasado siglo, se han publicado varios estudios paleomagnéticos basados en una metodología más moderna, proporcionando resultados nuevos y en principio más fiables del Cáucaso. En la República de Georgia estos estudios paleomagnéticos han cubierto diversos temas, incluyendo estudios paleomagnéticos de carácter general, de paleomagnetismo aplicado a la tectónica, estudios sobre la dirección e intensidad del campo magnético del pasado y también estudios arqueomagnéticos.

La presente revisión intenta proporcionar una visión general e integrada de los nuevos resultados paleomagnéticos y de paleointensidad obtenidos durante las últimas dos décadas en uno de los paises pertenecienes a la región del Caúcaso, la República de Georgia.

**Palabras clave:** Paleomagnetismo, paleointensidad, rocas volcanicas, arqueomagnetismo, Cáucaso, Georgia

## 1. Introduction

The mountain ranges of the Caucasus (Fig. 1) constitute a segment of the Alpine fold belt. Due to its geological and geophysical interest, the Caucasus region has already been the subject of several paleomagnetic studies. However, reliable paleomagnetic data from that area are still sparse if compared to other regions belonging to the Alpine fold belt (Bazhenov and Burtman, 2002), as many of those studies date back several decades and the methodology employed often does not fulfil the minimum reliability and quality criteria required for present-day paleomagnetic results. For instance, they are often based on results obtained from non or only partially demagnetised samples. In addition, most of those results have only been published in databases (*e.g.* Khramov, 1984) and in Russian, thus not being easily accessible to the international scientific community. Nevertheless, since the 1990's a number of new paleomagnetic studies, which are based on a more up-to-date paleomagnetic methodology have been published, thus supplying new and in principle more trustworthy paleomagnetic results from the Caucasus. These paleomagnetic studies were directed towards different topics, including general paleomagnetic studies (Goguitchaichvili et al., 2000; Goguitchaichvili et al., 2001), paleomagnetism applied to tectonics (Bazhenov *et al*., 1996; Bazhenov and Burtman, 2002), the study of the direction and intensity of the ancient geomagnetic field (Camps *et al*., 1996; Goguitchaichvili *et al*., 1997; Goguitchaichvili *et al*., 2009, Shcherbakova *et al*., 2009, Calvo-Rathert *et al*., 2011, Calvo-Rathert *et al*., 2013; Caccavari *et al*., 2014) or archeomagnetic studies (Goguitchaichvili and Parès, 2000; Calvo-Rathert *et al*., 2008; Shaar *et al*., 2013). The present review intends to provide an outline and an integrated view of the new paleomagnetic and paleointensity results obtained during the last two decades in one of the countries belonging to the Caucasus region, the Republic of Georgia.


**Figure 1.** Map of the Caucasus and adjacent areas. Adapted from Google Earth.

## 2. Geological background

The Caucasus system forms part of the Alpine-Himalayan orogenic belt, which is the largest continental collision zone in the world, resulting from the movement of the still-converging Eurasian and Arabian plates (Adamia *et al*., 2008). The Caucasus region belonged during the Late Proterozoic-Early Cenozocic, to the now-vanished Tethys Ocean and its margins (Adamia *et al*., 2011). After the closure of the Tethys (20 Ma), the continental collision was characterised by the northward drift of the Arabian plate, the lateral ejection of the Anatolian Plate to the West, and the Iranian Plate to the East (Philip *et al*. 1989). Fold-thrust belts were formed at the Greater and Lesser Caucasus during syn-collisional (Oligocene – middle Miocene) and post-collisional (late Miocene – Quaternary) stages (*e.g.* Adamia *et .al*, 2008).

The recent geodynamics of the Caucasus region is determined by its position between the converging Eurasian and Arabian plates and characterised by the complexity of its active tectonics. Three main directions of active faults compatible with the nearly N-S compression produced by the convergence of the Arabian and Eurasian plates can be distinguished in Georgia (Adamia *et al*., 2008). The first group of structures is characterised by a WNW-ESE or W-E strike and represented by compressional structures like reverse faults, thrusts and nappes. Two other groups of structures are characterised by either a NE-SW or a NW-SE strike. They are mainly extensional structures but have a considerable strike-slip component (Adamia *et al*., 2011).

The Caucasus region is also characterized by an important and continuous volcanic activity, at least from the Jurassic and lasting until present (*e.g.*, Rebaï *et al*., 1993). The Neogene-Quaternary magmatism in the Caucasus, which is associated to the collision between the Eurasian and Arabian plates (Koronovskii and Demina, 1999) started in middle Miocene and lasted until Holocene; the last volcanic eruptions taking place in historic time (*e.g.*, Aydar *et al*., 2003). The persistence of volcanism evidences a lithospheric thinning which remained in spite of the recent Arabian-Eurasian collision, because of the E-W extension linked to the lateral expulsion of the Anatolian and Iranian blocks (Rebaï *et al*., 1993). Milanowskii and Koronovskii (1973) distinguish three stages in the evolution of late magmatism in the Caucasus area: (1) late Miocene to early Pliocene, (2) middle Pliocene to Pleistocene and (3) Quaternary. Late-orogenic subaerial volcanism in Georgia occurred mainly in the Djavakheti Highland, the Khrami basin and the Kazbegi region (Fig. 2). In Georgia, many predominantly monogenetic and polygenetic central type volcanoes can be found forming eruption centres. The eruption products are represented by lavas and their pyroclastic equivalents, resulting in the formation of calc-alkaline and subalkaline series (Tutberidze, 2012).

## 3. A preliminary paleomagnetic and paleointensity reconnaissance study

Due to the reasons previously outlined, at the beginning of the present millenium available paleomagnetic data from Georgia were still rather scarce. Specifically, the available information about the Pliocene and Quaternary tectonic development in the Caucasus region was fairly limited. It is known that block rotations about vertical axes may play an important role in accomodating lithospheric plate deformations (*e.g.*, Kissel and Laj, 1989) and paleomagnetic declinations can be a good indicator of this kind of rotations. Thus, paleomagnetic results from the Caucasus region may provide important information about the tectonic development of this area during Pliocene and Quaternary.


**Figure 2.** Map of the Caucasus and adjacent areas with the Pliocene-Quaternary volcanic provinces of Georgia (1: Djavakheti region; 2: Khrami basin; 3: Kazbegi), and the Adjaro-Trialet tectonic zone (4). Adapted from Google Earth.

On the other hand, the need for a better knowledge of the variations of the Earth's magnetic field (EMF) not only demands the directional information provided by declination and inclination of the remanence vector, but also the determination of the strength of the paleofield vector. Unfortunately, the number of reliable paleointensity data available is still limited. The paleointensity databases PINT06 (Tauxe and Yamazaki, 2007) and PINT2010 (Biggin *et al*., 2010), show that available data are still scarce and unevenly distributed. At the beginning of the nineties, only few reliable data existed from the former Soviet Union area. As continental volcanic rocks carrying thermoremanent magnetisation (TRM) can be a suitable material for absolute paleointensity determinations, ascertaining the suitability of volcanic rocks from the Caucasus volcanic provinces for such studies is of major interest.

With both aims in mind, Goguitchaichvili *et al*. (2000; 2001) performed a reconnaisance study in three volcanic provinces in Georgia, Kazbegi, Kharmi and Djavakheti (Fig. 2). This reconaissance study also included the new evaluation of previous paleomagnetic results obtained by Sologashvili (1986) in an extensive paleomagnetic and magnetostratigraphic study carried out on more than a hundred lava flows from these three main Pliocene and Quaternary volcanic regions in Georgia. In addition, new paleomagnetic, rock-magnetic and paleointensity studies were carried out on lava flows belonging to those areas.

Samples belonged to 248 subaerial lava flows at 43 sites from the Djavakheti, Khrami and Kazbegi regions. In most cases, several consecutive flows were present at each site. In three cases, lacustrine sedimentary layers appeared interbedded between the flows and were also sampled. Generally, 1 to 3 oriented blocks of different size were taken from each site and several 2 cm cubes cut from each block for remanence measurements. All sampled lava flows as well as interbedded lacustrine sedimentary layers were horizontal. According to now available K-Ar dates, the studied flows cover a Pliocene to Quaternary (0.06 to 3.75 Ma) age interval (Rubinshtein *et al*., 1972; Maissuradze *et al*., 1980; Aslanian *et al*., 1982; Sologashvili, 1986; Lebedev *et al*., 2008a,b; Caccavari *et al*., 2014).

Paleomagnetic, rock-magnetic and paleointensity experiments were performed at the paleomagnetic laboratories of the Tbilissi State University (Georgia) and Université Montpellier II (France). Rock-magnetic experiments performed to identify the carriers of remanent magnetisation and check their thermal stability and domain state included the measurement of continuous susceptiblity versus temperature curves (κ-T curves) and hysteresis curves. Two different types of thermomagnetic curves could be distinguished. In most cases, they showed a simple and reversible thermomagnetic behaviour, with a single magnetic phase with Curie temperatures indicative of the presence of low-Ti titanomagnetite (Fig. 3a). In other cases, two phases could be recognised during heating, with the Curie temperature of the lower one not exceeding 400° C and that of the higher one reaching 570° C. The cooling curve, however, showed only a single phase with a Curie temperature close to that of magnetite (Fig. 3b). Hysteresis parameters indicte that all studied samples fall in the pseudo-single domain (PSD) range, which might also suggest a mixture of multidomain (MD) and single-domain (SD) grains. Similar rock-magnetic results were to be observed in different paleomagnetic studies carried out in later years in Georgia and which are reported below.

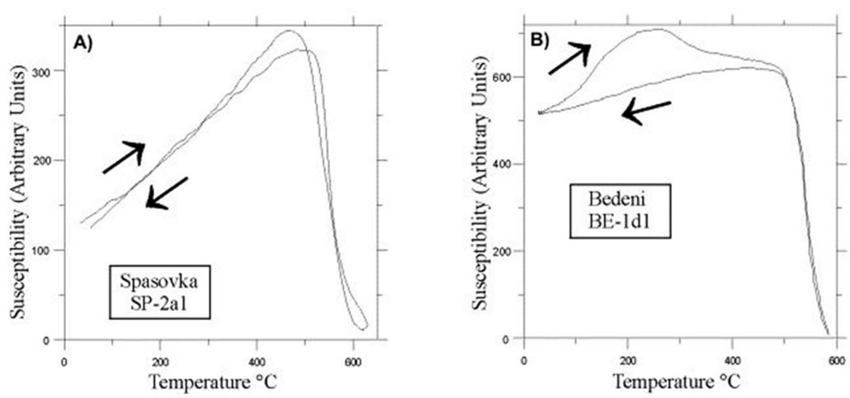


**Figure 3.** Thermomagnetic curves (susceptibility versus temperature) of representative samples from the Plio-Quaternary basaltic volcanism of Georgia (modified from Goguitchaichvili *et al*., 2000).

For paleomagnetic analyses, samples were subjected in most cases to stepwise alternating field demagnetisation and in some cases also to stepwise thermal demagnetisation. Almost 70% of the analysed samples are characterised by a single palomagnetic component, observed both upon thermal and alternating field treatment (Fig. 4). Mean site directions could be calculated for all flows and the three interbedded sedimentary layers. 115 flows and 1 sedimentary layer yielded a normal polarity direction, 129 and 1 sedimentary layer a reversed polarity direction and 6 flows and 1 sedimentary layer an apparently transitional direction.

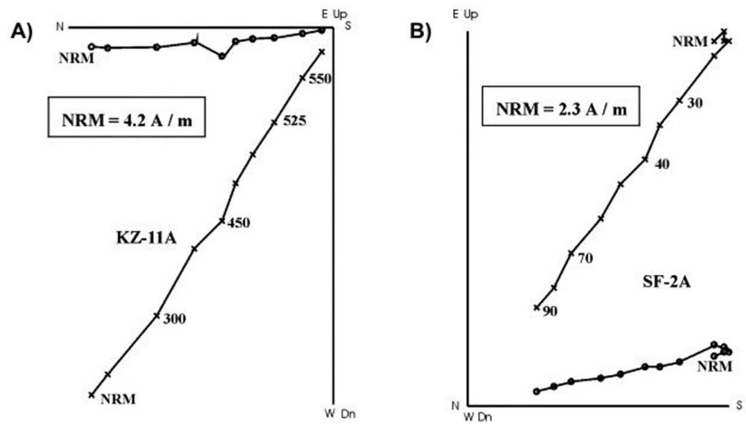


**Figure 4.** Orthogonal vector plots of stepwise thermal and alternating field demagnetization of representative samples from the Plio-Quaternary basaltic volcanism of Georgia (modified from Goguitchaichvili *et al*., 2000).

Besides sites consisting of only a single lava flow, several sites were formed of consecutive lava flows. Mean site directions were calculated from the latter, but if different polarities were recognised in such localities, mean directions were calculated for each polarity group. On the other hand, mean directions of interbedded sedimentary layers were determined separately from those obtined from lava flows. 26 of the directional units obtained in the aforementioned way showed normal polarity, 29 showed reverse polarity and 6 displayed intermediate polarity. Unfortunately paleomagnetic directions of 8 of these 61 directional units are based on only one or two samples. After rejecting for calculation those units with a single sample and those showing intermediate polarity, a mean Plio-Quaternary direction D = 6.0°, I = 57.8°, with k = 30 and $\alpha_{95}$ = 3.8° was obtained. Comparison with the expected directions for Georgia obtained from the 0 Ma window (D = 3.0°, I = 58.2°) and 5 Ma window (D = 3.7°, I = 58.3°) of the European synthetic APWP (Besse and Courtillot, 2002) showed no significant differences. Also if the three sampled volcanic provinces were considered separately, no significant deviations of the paleodeclination from the expected one were observed for the Kazbegi and Khrami provinces (Fig. 5). However, the paleodirection obtained in the volcanic province of Djavakheti showed a slightly eastwardly deviated paleodeclination (D = 13.7°, I = 58.1°, k = 24 and $\alpha_{95}$ = 7.0°; Fig. 5). In this region several units displayed paleodirections deviating from the expected one, and though these directions may arise due to the effect of secular variation, some of the studied units should include enough lava flows to average out this effect (*e.g.*, the normal polarity Korxi unit, with 14 flows). These deviations might have a tectonic origin.

Preliminary paleointensity experiments were performed with the classic Thellier method (Thellier and Thellier, 1959) in air on 28 specimens characterised by a single stable magnetisation component and reasonalbly reversable thermomagnetic curves and 17 samples yielded an acceptable paleointensity estimation. The absolute geomagnetic pleointensities obtained from Georgian volcanic units vary between 16.3 and 54.7 μT. It is worth mentioning that two intermediate-polarity samples yield significantly reduced paleointensities. Without the latter, a mean value of 41.5 ± 11.3 μT, corresponding to a mean virtual dipole moment (VDM) of $7.8 \pm 3.7 \cdot 10^{22}$ $Am^2$ is obtained. Rock-magnetic characteristics of the studied samples and results of these preliminary absolute paleointensity experiments carried out on them suggest that Pliocene and Quaternary lava flows from these three volcanic provinces of Georgia can be very suitable units for absolute paleointensity determinations, being able to provide valuable information about the variation of the EMF intensity during that period.

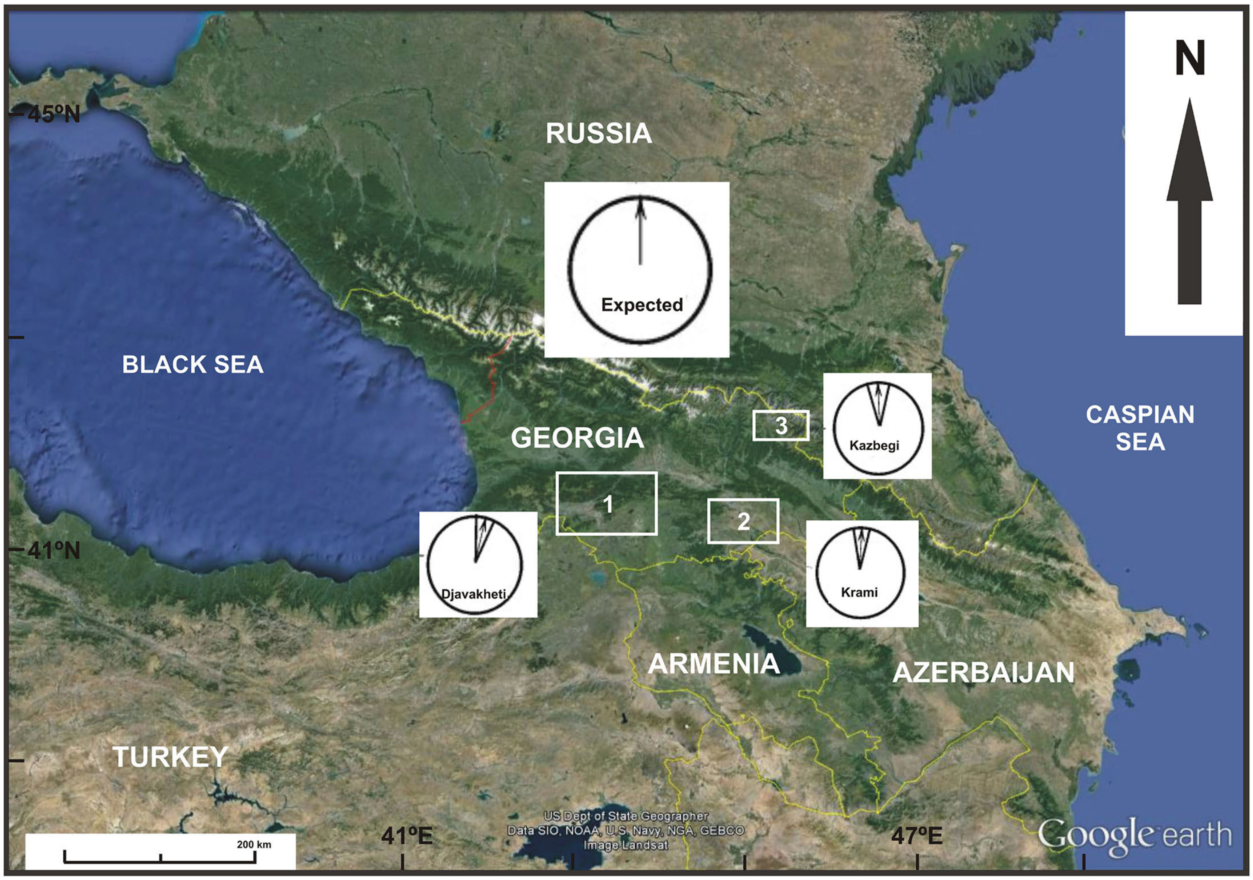


**Figure 5.** Paleomagnetic results from a paleomagnetic reconnaissance study performed by Goguitchaichvili *et al*. (2000) and Goguitchaichvili *et al*. (2001) in the Pliocene-Quaternary volcanic provinces of Georgia (1: Djavakheti region; 2: Khrami basin; 3: Kazbegi). Adapted from Google Earth.

## 4. Variation of the Earth's magnetic field recorded in lava flow sequences

Direction and strength of the EMF vary with time and knowledge of the characteristics of the ancient geomagnetic field can provide important information in order to better understand and constrain the processes related to the evolution of the Earth's deep interior. In addition to the knowledge about the behaviour of the EMF during its stable polarity states, the study of its characteristics during polarity transitions is of particular interest. Nevertheless, the magnetisation record provided by volcanic rocks is tied to volcanic eruptions and therefore discontinuous, but because volcanic rocks are in principle able to provide a real image of the EMF, the study of lava flows emitted in a relatively short period of time can be of major interest.

In many paleomagnetic studies, only the directional information provided by declination and inclination of the remanence vector is needed. The need for a better knowledge of the variations of the EMF, however, also demands the determination of the strength of the paleofield vector. Volcanic rocks allow a reliable and instantaneous record of the EMF by means of the acquisition of thermoremanent magnetisation (TRM) and are able to supply absolute paleointensity data. Unfortunately, the number of reliable paleointensity data available is still limited. As mentioned before, paleointensity databases PINT06 (Tauxe and Yamazaki, 2007) and PINT2010 (Biggin *et al*., 2010), show that available data are still scarce and unevenly distributed.

This is related to the fact that paleointensity determinations are experimentally much more difficult than estimations of the direction of the paleofield vector, and the failure rate of these experiments is often large. In addition, the scatter observed in paleointensity results is much higher than in directional results, often due to the fact that incorrect determinations are considered to reflect a correct paleointensity value (*e.g.*, Calvo *et al*., 2002). The paucity of reliable paleointensity data is directly related to the difficulty of obtaining reliable absolute paleointensity determinations. This is so because of different reasons: i) The primary remanence of a rock must be a thermoremanent magnetisation (TRM) in order to be suitable for paleointensity studies; ii) Rock samples employed for paleointensity determinations must obey the Thellier laws of reciprocity, independence and additivity of partial thermoremanent magnetisation (pTRM) acquired in non-overlapping temperature intervals (Thellier and Thellier, 1959). This behaviour is only verified for true SD particles, while multidomain (MD) grains do not obey these laws. Pseudo single-domain (PSD) grains carrying a TRM may approximately satisfy the requirements of the Thellier method for the smallest particles, but not for the larger ones (Shashkanov and Metallova, 1972; Levi, 1977; Bol'shakov and Shcherbakova, 1979; Worm *et al*., 1988); iii) During heating, irreversible chemical/mineralogical or physical (Kosterov and Prévot, 1998) changes can affect the magnetic phases, which results in erroneous paleointensity estimates.

If the geographic distribution of available absolute paleointensity determinations is taken into consideration, it can be recognised that the lack of data stemming from the former Soviet Union area at the beginning of the 1990s is rather ostensible. In fact, despite huge volcanic provinces and abundant lava flows, the Lesser Caucasus at that time could still be considered as terra incognita from the point of view of the abundance of paleointensity information. However, a trustworthy description of the changes with time of the EMF direction and intensity relies on less biased information of its characteristics, which includes the description of variations both with time and geographic location. The aforementioned lack of reliable absolute paleointensity data in the Caucasus and the abundance of Pliocene and Quaternary lava flows of apparently excellent characteristics for paleomagnetic and paleointensity determinations (as described in section 3) in the volcanic provinces of Georgia thus makes this region a most interesting subject of paleomagnetic and paleointensity research with the aim of describing the variations of the EMF.

### 4.1. A Pliocene polarity transition recorded in three neighbouring lava flow sequences in the Djavakheti volcanic province

With the aim of obtaining reliable observations of the transitional field during a reversal or excursion, Camps et al. (1996) undertook a paleomagnetic and paleointensity study on the 250 m thick Thoki lava flow sequence, located in the Djavakheti volcanic province in southern Georgia (Fig. 6). The Thoki section consists of 63 lava flows and is formed of two parts, the so-called lower and upper Akhalkalaki sequences, which are clearly separated by an erosion surface. Due to the time needed for erosion, there is no doubt that some period of quiescence occurred between the lava emissions of both sequences. In addition to paleomagnetic, rock-magnetic and paleointensity experiments, Camps et al. (1996) also performed two $^{40}Ar/^{39}Ar$ datings on plagioclase samples from the lower Akhalkalaki sequence, which yielded ages of 3.69 ± 0.04 Ma and 3.53

± 0.04 Ma. The upper Akhalkalaki sequence, however, probably formed during Quaternary. At the base of the lower Akhalkalaki sequence 16 consecutive flows recording intermediate directions were found. These 16 flows correspond to 3 directional groups (DG1 to DG3). The overlying flows (directional group DG4 in the lower Akhalkalaki sequence and all flows from the upper sequence) are all reversely magnetised. Paleointensities are particularly low in DG1 (<10μT), and tend to increase upwards in the lower Akhalkalaki section, though they still show weak values. The authors interpreted their results as either the partial record of an excursion or a record of the upper part of the normal to reversed Gilbert-Cochiti reversal.

Soon after, Goguitchaichvili *et al*. (1997) carried out a paleomagnetic study of the upper part of the nearby lying Tchuntchka section (Fig. 6). Its approximate thickness is estimated at 300 m, and it is constituted by at least 32 lava flows. The equivalent to the younger (probably Quaternary) upper Akhalkalaki sequence is not present in that section. Goguitchaichvili *et al*. (1997) reported reversely magnetised flows in the middle part of the sequence overlaid by thick normal polarity lavas and proposed a tentative magnetostratigraphic correlation between the Thoki and Tchunchka sites. The lower part of the latter section, consisting of six lava

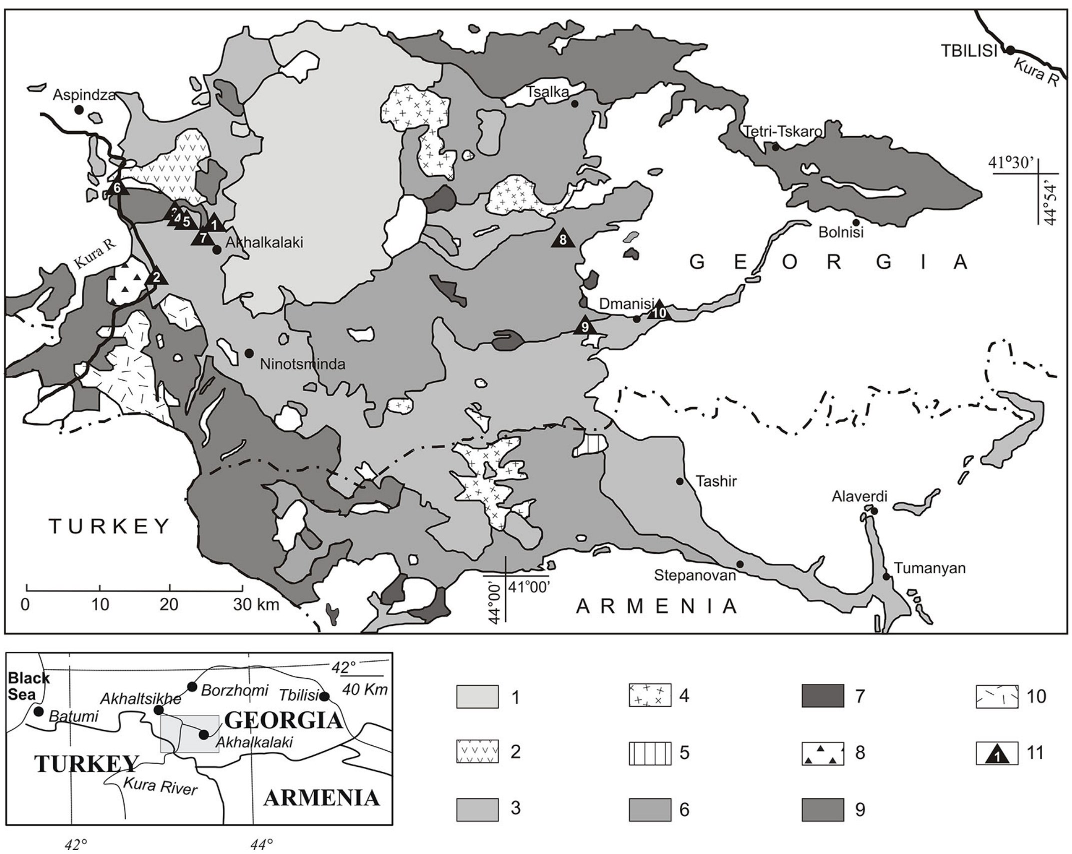


**Figure 6.** Schematic geological map (modified after Lebedev *et al*., 2008b and Calvo-Rathert *et al*., 2011) of the Pliocene-Quaternary magmatism in the Djavakheti Highland (Southern Georgia) showing the lava flow sequences mentioned in the present review. 1: Quaternary volcanics of the Samsari ridge (800-0 ka); 2: Basic lavas (1.75-1.55 Ma); 3: Basic lavas (2.15-1.95 Ma). 4: Dacitic lavas of the Djavakheti ridge (2.25 Ma); 5: Hyalodacite (2.5 Ma); 6: Basic lavas (2.65-2.45 Ma); 7: Rhyolites and dacites of the Chikiani, Agvorik and Busistsikhe volcanoes (2.85-2.6 Ma); 8: Dacites (3.15-3.11 Ma) of the Kumurdo lava flow (a) and Amiranisgora volcano (b); 9: Basic lavas (3.22-3.04 Ma); 10: Basic lavas (3.75-3.55 Ma); 11: Sampled lava flow sequences: (1) Korxi, (2) Apnia, (3) Thoki, (4) Tchunchka, (5) Khando, (6) Saro, (7) Akhalkalaki, (8) Zemo-Karabulaki, (9) Kvemo Orozmani, (10) Mashavera / Dmanisi paleoanthropologic site.

flows, was sampled in a new campaign in 2005. In addition, 16 consecutive flows were sampled in the lower part of the nearby lying Khando site (Fig. 6), which also lies at the Paravani River. As in the Thoki sequence, the upper part of the Khando section is clearly much younger than the lower part, and it is separated from the latter by a well-defined erosion surface. All flows belonging to the lower Tchuntchka section yielded intermediate polarity and the paleodirections found are rather similar to those obtained from the Thoki section by Camps et al. (1996). The Khando sequence, on the other hand, is also characterised by almost the same intermediate paleodirections in its lowermost eight flows, while the overlying lavas are characterised by unusually shallow negative inclinations and mean declinations corresponding to a stable reverse polarity geomagnetic regime (Goguitchaichvili et al., 2009). Results of paleointensity experiments performed with the Coe variant of the original Thellier experiment (Coe, 1967) on both sections yielded particularly weak values (< 10μT) in the lower Tchunchka and Khando sequences and somewhat higher, though still weak, values upwards in the lower Khando section.

Correlation of the results obtained in the three aforementioned Pliocene lava flow sequences allowed constructing the composite section shown in Figure 7. The paleomagnetic record starts at intermediate-polarity directional group NR1 defined by four lava flows from the Tchuntchka lower sequence. Transitional-polarity directional groups NR2 (six flows) and NR3 (three flows) yielded rather similar paleodirections and both are represented in Tchuntchka and Thoki sites while NR2 is absent in Tchuntchka. The same is true for the thick transitional NR4 zone. In contrast, the reverse polarity zone R1 is a common feature of all three sections. The relatively thick normal polarity zone N1, however, is only present in the Tchuntchka section. The mean paleointensity of all flows with intermediate field is low (12.8 ± 2.7 μT), while the reverse polarity flows have a paleointensity with a higher mean value of 27.3 ± 9.3 μT. Normal polarity flows yielded 34.2 ± 6.8 μT (Fig. 7b). For comparison, the present day field in Georgia is 47 μT. Considering all available radiometric ages (Camps et al., 1996) and paleomagnetic data it seems that the Gilbert-Gauss (R-N) reversal is recorded at

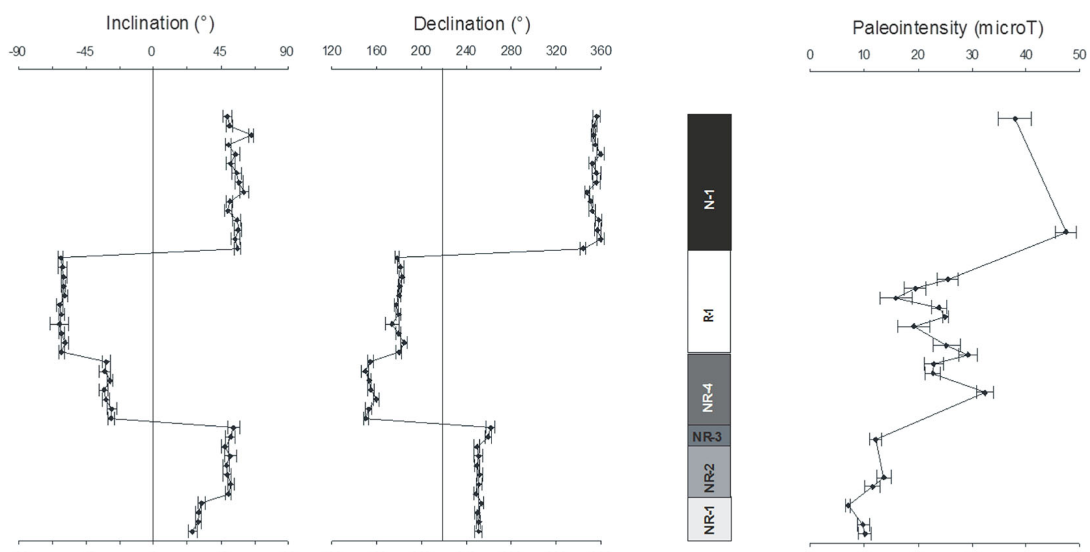


**Figure 7.** Composite section obtained from paleomagnetic results of the Thoki, Thuntchka and Khando sequences (Camps *et al*., 1996; Goguitchaichvili *et al*., 1997; Goguitchaichvili *et al*., 2009). Flow mean inclination, declination and absolute paleointensity for each flow of the Akhalkalaki composite section. Modified after Goguitchaichvili *et al*. (2009).

the upper part of the composite sequence. Moreover, Goguitchaichvili *et al*. (2009) suggest that the lower intermediate polarity flows possibly represent a kind of precursor of the Gilbert-Gauss reversal similarly to those observed by other authors in the Matuyama-Brunhes geomagnetic transition (*e.g.*, Quidelleur *et al*., 2002; Petronille *et al*., 2005). As shown by the results obtained in these three sequences the study of certain states of the Earth's magnetic field like polarity transitions is of particular interest, although due to their short duration in geological terms it is difficult to find a magnetisation record providing sufficently continuous and sound information about the characteristics of a polarity change.

### 4.2. Paleomagnetic and paleointensity results from the Apnia and Korxi lava flow sequences

Calvo-Rathert et al. (2013) performed a reconnaisance paleomagnetic and paleointensity study on 14 basaltic lava flows from two sequences of Pliocene age (K-Ar age between 3.09 ± 0.10 Ma and 4.00 ± 0.15 Ma; Lebedev et al., 2008a) from the eastern Djhavakheti Highland in southern Georgia, the Apnia and Korxi sections (Fig. 6). Samples used for the study had been taken in 1984–1986 sample collection campaigns. Oriented blocks were sampled from ten flows in the Apnia section and four flows in the Korxi section and prismatic specimens were cut in the laboratory from the blocks. Due to the long time elapsed since sampling had been carried out and the inadequate description of the 1984-1986 sampling, it was not possible to find out which specific lava flows from each sequence had been sampled. However, all four sampled Korxi flows belonged to the lowermost part of that section. Both sequences, however, have a significantly larger number of flows than those sampled for that preliminary study.

Paleomagnetic experiments allowed determining characteristic components for all flows and normal polarities (six flows), reversed polarities (seven flows) and intermediate polarities (one flow) could be observed. Paleomagnetic poles calculated using only those sites unequivocally showing normal or reversed polarities showed a good agreement with the 5 Ma window of the European synthetic polar wander path of Besse and Courtillot (2002). The paleomagnetic direction of the combined Apnia-Korxi flows thus agreed well with the expected one, showing no significant tectonic rotations, although the latter cannot be however, completely excluded in the Korxi section. Analysis of the angular dispersion of virtual geomagnetic poles yielded higher values than expected in both sequences. Paleointensity experiments using the Coe method were performed on 31 specimens from 10 flows and 19 samples from 8 flows provided successful determinations (Fig. 8), with mean flow values showing a wide scatter. If only flows with more than one successful paleointensity determination are taken into account, virtual dipole moments (VDM) vary between $3.5 \times 10^{22}$ $Am^2$ and $8.3 \times 10^{22}$ $Am^2$.

These preliminary results posed some interesting questions regarding the behaviour of the EMF recorded in both sequences. Moreover, the fact that flows with normal, reverse and intermediate polarity magnetisations could be all observed in flows of the Apnia sequence, pointed to a polarity transition being recorded in that section. For that reason, new samplings were carried out, this time on all individual flows of both sequences. 20 flows were sampled in the Pliocene Apnia sequence and 17 in the Pliocene lower part of the Korxi sequence. In addition, 10 flows were sampled in the upper part of the latter sequence, which is

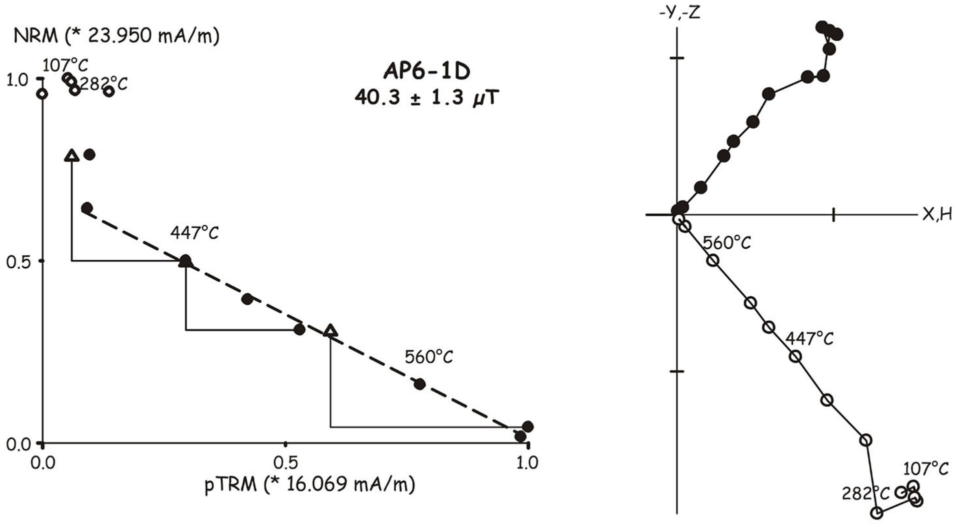


**Figure 8.** Paleointensity determination. Left: NRM-TRM plot of successful determination of specimen AP6-1D (Apnia). Right: Orthogonal vector plot of NRM demagnetisation during the paleointensity experiments. (Solid circles represent points used for the paleointensity determinations, open circles represent points excluded from paleointensity determinations and triangles represent pTRM-checks. Modified from Calvo-Rathert *et al*. (2013).

separated from the lower part by an erosional surface and has a K-Ar age of 1.09 ± 0.20 Ma (V.A. Lebedev, *personal communication*). This work is still in progress, although first rock-magnetic and paleomagnetic results have already been obtained (Sánchez Moreno *et al*., 2014). An interesting result arises from the analysis of the virtual geomagnetic pole (VGP) behaviour. Its mean value for the whole Apnia sequence agrees well with the 5 Ma window of the European synthetic polar wander path of Besse and Courtillot (2002). However, if the mean values of VGPs of the reverse polarity flows below the polarity transition and the normal polarity flows above transition are calculated, none of them agrees with the expected paleomagnetic pole, although all these normal and reverse VGPs individually still clearly show stable regime characteristics. Also interesting is the fact that eight flows from the Pleistocene upper Korxi flow record a polarity transition.

### 4.3. Paleomagnetic and paleointensity analysis of the Pleistocene Saro Lava Flow Sequence in the Djavakheti volcanic province

Another paleomagnetic investigation was carried out on 39 lava flows from a Pliocene lava flow sequence, named the Saro section, which is also located in the Djhavakheti Highland (Fig. 6). The sequence, which has a thickness of 200 m, is divided into two parts. The upper part consists of 3 volcanic flows and the lower part of 36. There is no evidence of intercalated sediments or paleosoils between any of the flows and from a petrological point of view, all lavas from the lower sequence are similar to the three upper sites. The paleomagnetic study of the Saro sequence also included a new $^{40}Ar/^{39}Ar$ dating of the uppermost flow of the sequence which yielded an age of 1.73 ± 0.03 Ma (Caccavari et al., 2014). Lebedev et al. (2008a) had analyzed and dated six samples from different horizons of the lower lava sequence obtaining ages which varied between 2.23 and 2.03 Ma and a K-Ar age of 1.67 ± 0.13 Ma was recently obtained by Lebedev (personal communication) on the same uppermost flow.

A ChRM direction could be isolated in all studied 39 lava flows, yielding reverse-polarity directions in all cases, a mean direction D = 202.2°, I = -60.6° being obtained. While the inclination agreed well with the expected one, the declination showed an eastward deviation of 19.2° ± 5.8°. This result will be discussed in section 5.2. The scatter of virtual geomagnetic poles (VGPs) $S_B$ of the sequence was also analysed finding that it was lower than the angular dispersion predicted for latitude 41° by the Model G-fit (McFadden et al., 1988) to data of paleosecular variation of lavas from the last 5 Ma. Caccavari et al. (2014) interpreted that paleomagnetic and radiometric results as well as petrologic characteristics of the sequence allowed two different explanations about the time of emplacement of the section: The first implies that the lower 36 flows of the sequence might have been emitted between the normal-polarity Reunion and Olduvai chrons, and the upper three flows after the Olduvai chron, with a long hiatus in volcanic activity of more than 150 ka. This interpretation agrees well with radiometric data but not with petrologic and paleomagnetic similarities between all flows. In fact, the lower flow of the upper section showed a paleomagnetic direction undistinguishable from the upper flow of the lower sequence. The second explanation implies that the whole sequence might have been emitted between 1.778 Ma and 1.73 $\pm$ 0.03 Ma, after the Olduvai chron. This explanation, however, disagrees with K-Ar data from Lebedev et al. (2008a) for the lower part of the sequence.

In a new study, Gogichaishvili et al. (2015 submitted), performed forty six successful absolute geomagnetic paleointensity determinations on samples from the Saro sequence using a Thellier-type double heating method. Flow-mean paleointensity values ranged from 16 ± 7.3 to 56.7 ± 15.8 μT, and corresponding VDM from 2.25 ± 1.03 to 8.44 ± 2.71 x $10^{22}$ $Am^2$. Especially interesting were the results obtained in two upper lying flows from the lower section, which yield rather low paleointensity values (16 and 19 μT) and could point towards a transitional regime. Although apparently no polarity transition could be recognized in the Saro section, as mentioned above, a long hiatus in volcanic activity might have taken place between the upper and lower sections of the sequence. The clear decrease of paleointensity in these two flows, which are very near to this possible hiatus, favours this interpretation. In this case, the Matuyama-Olduvai transition would have taken place during a long interruption of volcanic activity between the upper and lower part of the Saro section. As polarity transitions show an earlier start in the intensity record than in the directional record (Valet et al., 1999; Prévot et al., 1985a,b; Riisager and Abrahamsen, 2000), the onset of the transition would have been already recorded by the upper lying flows of the lower section, while the whole Olduvai subchron would not have been recorded in the Saro sequence.

### 4.4. Paleomagnetic and paleointensity results from other Pleistocene and Pliocene basaltic flows from the Djavakheti Highland

Paleomagnetic, rock-magnetic and paleointensity results were also obtained on other smaller lava flow sequences of Pleistocene and Pliocene age in the eastern Djavakheti Highland. Calvo-Rathert *et al*. (2011) analysed 23 basaltic lava flows belonging to four different sequences: Mashavera (twelve flows), Kvemo-Orozmani (four flows), Zemo-Karabulaki (three flows) and Diliska (five flows) (Fig. 6). K/Ar and $^{40}Ar/^{39}Ar$ ages for these sequences yield 1.8 ± 0.1 to 2.18 ± 0.14 Ma for the Mashavera sequence, 2.07 ± 0.11 Ma for the Zemo-Karabulakhi sequence, 3.15 ± 0.15 and 3.27 ± 0.15 Ma for the lower Diliska section and 2.12 ± 0.10 and 2.18 ± 0.10 Ma for the upper Diliska section (Maisuradze, 1991; Schmincke and van den Bogaard, 1995; Gabunia et al., 2000; Lebedev et al., 2008a,b). The Kvemo-Orozmani section is coeval to the Mashavera sequence (G. Maisuradze, personal communication). In 21 sites a characteristic component could be determined and in all except one it showed normal-polarity. The Plio-Quaternary paleomagnetic pole obtained (latitude $\phi$ = 82.1°, longitude $\lambda$ = 118.2°, $\alpha_{95}$=8.0°, k = 240.7) agrees with the position of both the 0 Ma and the 5 Ma windows of the synthetic Eurasian polar wander path from Besse and Courtillot (2002). In order to analyse the behaviour of secular variation, the scatter of paleosecular variation of virtual geomagnetic poles of both the Mashavera flow and all 18 studied flows of Pleistocene age was calculated. It could be observed that both data sets fit well the expected scatter at latitude 41°N.

Paleointensity experiments carried out with the Coe method (Coe, 1967) on 84 samples provided successful absolute paleointensity determinations in 25 cases, mainly in the Mashavera sequence. Most flows yielded paleointensity results in the 30-45 μT range, in accordance with expected Pliocene to present day intensities. Two flows, however, located near the top of the Mashavera sequence yielded high paleointensity values around 60 μT. Considering the available K/Ar and $^{40}Ar/^{39}Ar$ ages for the upper flow of this sequence, and the anomalous paleointensity results in the upper-lying Mashavera flows together with the steep inclinations observed in that sequence; these suggest the near onset of the Olduvai-Matuyama reversal.

## 5. Tectonic information obtained from paleomagnetic data in Georgia

The Caucasus is a region with a complex tectonic history due to its position between the converging Eurasian and Arabian plates (*e.g.*, Adamia *et al*., 2011). Paleomagnetic data are a useful tool to study tectonic deformation by analysing the deflection of paleomagnetic directions, which can give information about possible tectonic rotations experienced by the analysed units of an area in the geological past. This means that paleomagnetic analyses carried out on rocks from the Caucasus might be also of considerable geologic and tectonic interest.

### 5.1 Oroclinal bending in the Arabian syntaxis inferred from Eocene paleomagnetic data

Bazhenov and Burtman (2002) studied more than 300 samples of middle Eocene volcanics and volcano-sedimentary rocks from 31 sites belonging to 10 localities in the Adjaro-Trialet tectonic zone in the south-western part of the Caucasus in Georgia (Fig. 2), a zone which comprises a more than 5000 m thick pile of volcanic and volcano-sedimentary rocks. The aim of the study was to provide new paleomagnetic data to the limited set of available reliable data in the Caucasus area and to analyse the tectonic and geophysical implications of their results. A ChRM could be isolated in 19 of the 31 studied sites. The presence of two polarities and a positive fold test suggested its primary character. Correlation of their Tertiary declination data with the strike of Alpine folds in the Adjaro-Trialet zones and the Pontides in northern Turkey showed a relatively large scatter. The authors attempetd to reinforce their analysis by including other Tertiary and late Cretaceous data from the Lesser Caucasus and the Pontides after a strict selection of previously published data (Bazhenov and Burtman, 2002 and references therein). This procedure revealed a good correlation between paleomagnetic and structural data, indicating the occurrence of oroclinal bending in the Alpine structures but locally complicated with different deformation. The overall mean Tertiary inclination obtained from their measurements appeared to be slightly shallower than expected. This finding, however, agrees with geological evidence on moderate post-Eocene shortening across the Caucasus.

### 5.2. Paleomagnetic rotations observed in volcanic lava flow sequences

As mentioned in section 4, most paleomagnetic studies carried out on different Pliocene and Quaternary lava flow sequences in the Djavakheti Highland were mainly directed towards paleointensity determinations or the study of the behaviour of the EMF. In most cases, directional results from those studies yielded no significant rotations of the paleomagnetic vector in the analysed volcanic sequences. Nevertheless, as mentioned in section 3, the reconnaissance study performed by Goguitchaichvili *et al*. (2000) in three volcanic provinces in Georgia reports a slightly eastwardly deviated palaeodeclination in the Djavakheti region, although in Goguitchaichvili *et al*. (2001) this region appears to be non-rotated. In both cases, however, several individual units display palaeodeclinations clearly diverging from the North direction. These rotations, on the other hand, could be non-significant, as in many of the studied flows only very few samples (1 to 3) were analysed.

As reported in section 4.3, in the paleomagnetic and paleointensity analysis of the Pleistocene Saro Lava Flow Sequence in the Djavakheti volcanic province carried out by Caccavari et al. (2014), a ChRM direction could be isolated in all studied 39 lava flows from the sequence, yielding reverse-polarity directions in all cases, a mean direction D = 202.2°, I = -60.6° (N = 39; $\alpha_{95}$ = 2.0°; k = 138) being obtained. While the inclination agreed well with the expected one, the declination showed a significant eastward deviation of 19.2° ± 5.8°. The South/North relative motion between the Arabian and Eurasian plates is accommodated in the Southern Caucasus mainly by crustal shortening (Adamia *et al*., 2008 and references therein), and submeridional compression reaches its peak within the central segment of the Caucasus (Djavakheti-Dzirula salient), (Adamia *et al*., 2008). As previously mentioned, the Caucasus is characterised by a coexistence of compressional and extensional structures (*e.g.*, Rebaï et al, 1993). Among them, extensional structures with a considerable strike-slip component of either a NE–SW or a NW–SE strike (Adamia *et al*., 2011) can be found. This kind of faults with strike-slip component could be responsible for vertical-axis rotations like the ones detected in the Saro sequence.

Also in the paleomagnetic study carried out by Camps et al. (1996) in the Pliocene Thoki sequence a significant 22° deviation from the expected paleodeclination could be recognised in the upper part of the section (called upper Akhalkalaki Sequence in their study). In the lower part of the sequence, however, which is separated by an erosion surface from the upper sequence, apparently no rotation is observed. If this deviated paleodeclination has been produced by a 22° clockwise rotated paleodirection, the 22° rotation observed in the upper part of the sequence should then be included in the 180.3° declination measured in its lower part.

In the reconnaissance paleomagnetic and paleointensity study performed by Calvo-Rathert et al. (2013) in the Korxi sequence (section 4.2) a difference between the observed and expected paleodeclination of 23.9° ± 20.1° (confidence limits calculated after Demarest, 1983) was detected. This result means that although a significant clockwise rotation of the Korxi section cannot completely be ruled out, the result obtained can also be explained with the relatively high experimental uncertainty observed in this section. This high uncertainty is related to the fact that only four flows were available in that study in the Korxi section, resulting in a high value of the $\alpha_{95}$ radius of the confidence cone of its mean paleomagnetic direction. Not averaged secular variation could also be the cause of the apparently rotated paleodeclination observed in the Korxi section.

## 6. Archeomagnetic and archeointensity studies in Georgia

The study of the magnetisation found in archaeological objects, and mainly of the thermoremanent magnetisation (TRM) recorded in materials which have undergone firing at the time of their fabrication or use, can provide important information about the EMF in historic and prehistoric times and be useful as a dating tool. Despite its wealth in archeological remains related to its position between Europe and Asia, Georgia can still be considered almost *terra incognita* from the point of view of archeomagnetic and archeointensity research, as only few studies of this kind have been performed hitherto. It should also be borne in mind that Georgia is the site of the so far oldest hominid site found in Eurasia, the Dmanisi paleoanthropologic site.

### 6.1. A paleomagnetic study of the Dmanisi paleoanthropologic site

The Dmanisi paleo-anthropologic site is located in southern Georgia (Caucasus), near the village of Patara-Dmanisi. During excavations in the remains of a well preserved medieval village in Dmanisi, human fossil bones and artefacts started to appear at the site in 1983 and the following years (Djaparidze *et al*., 1991). K/Ar and $^{40}Ar/^{39}Ar$ dating of the lava flow underlying the site and of volcanogenic ashes in which a hominid mandible was found yielded ages between 1.8 and 2.0 M.a. (Schmincke and van den Bogaard, 1995; Maissuradze *et al*., 1991; Gabunia *et al*., 2000); Lumley *et al*., 2002), making the Dmanisi findings the most ancient human fossils outside Africa so far.

The site has been subject of several paleomagnetic studies. Sologashvili *et al*. (1995) studied samples from the sedimentary deposits and the underlying basalt flows. They obtained normal polarities in all litho-stratigraphic units and an anomalous direction in the basal lava, correlating the section with the Olduvai subchron. Most of the samples, however, were not fully demagnetised. Goguitchaichvili and Parès (2000) analysed cores from the basalt lava and 27 samples from the overlying sediments. The basalt flow yielded an intermediate polarity direction and the sedimentary samples provided reverse polarity directions. These results did not support an Olduvai age for the human remains, but suggested an age comprised between 1.77 Ma (Olduvai/Matuyama boundary) and 1.07 Ma (Matuyama/Jaramillo boundary). Gabunia *et al*. (2000) obtained normal polarities in samples from the lower lying litho-stratigraphic levels (unit A) and the underlying basalt flow, as well as reversed polarities in the upper-lying litho-stratigraphic levels (unit

B) and the infills of sedimentary lens-shaped features cross-cutting unit A, which therefore proved to be non-contemporaneous to unit A sediments. Scatter observed in results from unit B in this latter study was, however, extreme (k = 3.2).

Because of these rather contradictory results, Calvo-Rathert *et al*. (2008) started a new paleomagnetic and rock-magnetic study on 106 specimens from both units A and B and the uppermost underlying basalt flow. The lava and unit A provided normal polarities, while reversed polarities and anomalous directions were observed in the upper-lying unit B, the latter due to overlapping of a secondary and a primary reversed polarity component. This interpretation was supported by results of anisotropy of magnetic susceptibility, as unit B susceptibilities, in opposition to results from unit A, clearly showed a secondary, non-sedimentary fabric. These results indicate that the lower part of the section clearly correlates with the Olduvai subchron, but the upper levels could be as young as 1.07 Ma (Fig. 9). As human remains were found both in units with normal and reversed polarity, different non-contemporaneous human occupations might therefore have been possible.

### 6.2. New archeointensity data from Georgia

Shaar *et al*. (2013) carried out a Thellier-type paleointensity experiment using the IZZI protocol (Tauxe and Staudigel, 2004) with routine pTRM-check on 48 potsherds and fired clays, obtaining new data for Georgia from *ca*. 3000 BCE to 1500 CE. Their results showed a significantly high field maximum at 900 BCE with a Virtual Axial Dipole Moment (VADM) of $16 \cdot 10^{22}$ $Am^2$. This maximum field value appeared to be

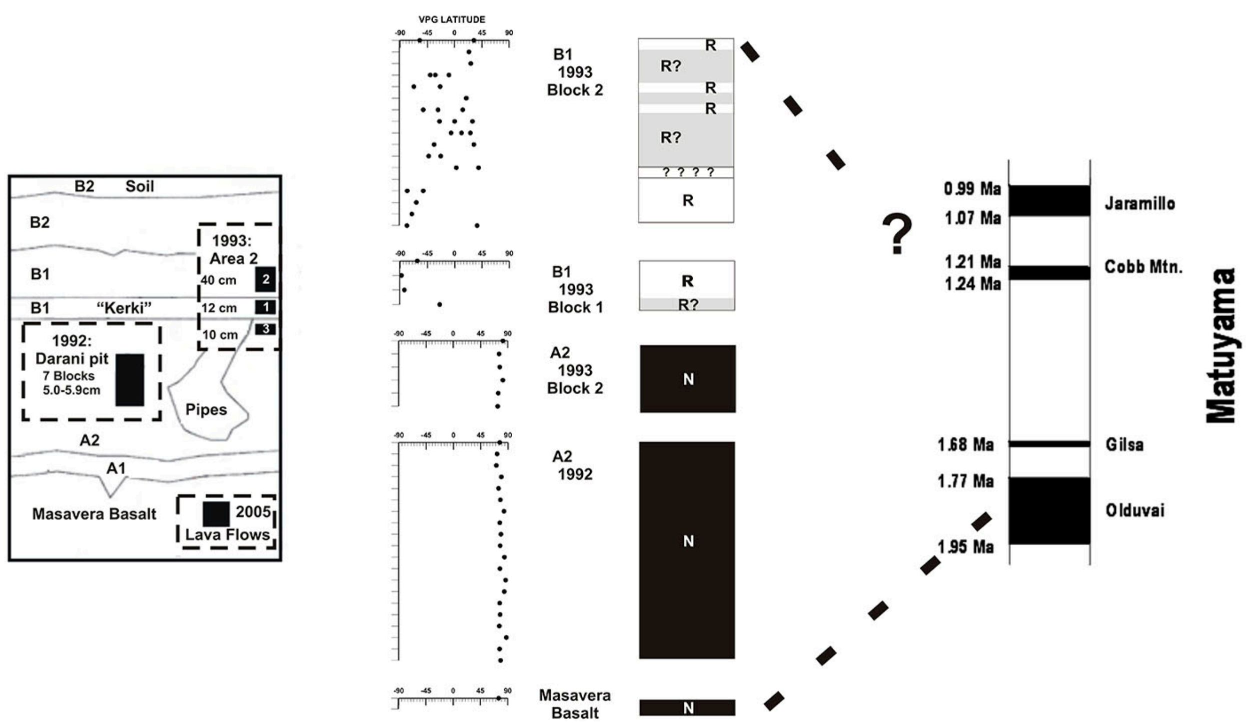


**Figure 9.** a) Schematic stratigraphic section of the Dmanisi site (modified from Gabunia *et al*., 2001). Main depositional units A1, A2, B1 and B2 (after Gabunia *et al*., 2001). Sampled units are shown with black rectangles. b) Latitudes of virtual geomagnetic poles and magnetic polarities of studied levels in all units. In grey, samples with anomalous directions, interpreted as reversed polarity directions. Comparison with the Geomagnetic Polarity Time Scale (Gradstein *et al*., 2004). Modified from Calvo-Rathert *et al*. (2008).

bounded by two low field minima around 1250 BCE and 400 BCE, with a VADM value of less than $6 \cdot 10^{22}$ $Am^2$. The authors also concluded that the decay of the field from 900 BCE was not steady, but showed great variability.

## 7. Conclusions

The Caucasus has already been the subject of several paleomagnetic studies, although reliable paleomagnetic data from that area are still sparse if compared to other regions belonging to the Alpine fold belt (Bazhenov and Burtman, 2002). This is due to the fact that many of those studies date back several decades and the methodology employed often does not fulfil the minimum reliability and quality criteria required for present-day paleomagnetic results. However, since the 1990's a number of new paleomagnetic studies based on a more up-to-date paleomagnetic methodology have been published, which have supplied new and in principle more trustworthy paleomagnetic results from the Caucasus.

In the present review, reults from paleomagnetic and paleointensity studies obtained on samples from the Republic of Georgia are reported. These paleomagnetic studies were directed towards different topics, including general paleomagnetic studies, paleomagnetism applied to tectonics, the study of the direction and intensity of the ancient geomagnetic field and archeomagnetic studies. Besides offering interesting new results related to the topics adressed in each of these studies, they provide a new data set which partially fills the gap of paleomagnetic and paleointensity results in this region. However still much paleomagnetic work appears to be necessary in this area.

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