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Palaeomagnetism of Georgian Plio-Quaternary volcanic provinces (Southern Caucasus): a pilot study

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Abstract – A preliminary palaeomagnetic and rock magnetic study was carried out on 248 Plio-Quaternary lava flows and three interbedded lacustrine sedimentary layers from Georgia (Caucasus). Most samples are characterised by a single palaeomagnetic component, carried by magnetite, as confirmed by susceptibility–temperature curves. Normal, reversed and in a few cases intermediate polarities were recognised. A palaeomagnetic mean direction of $D = 6.0°$, $I = 57.8°$, $k = 30$, $\alpha_{95} = 3.8°$ was obtained. Considering the three sampled volcanic provinces separately, differences with the expected palaeodeclination are non-significative (Kazbeki and Khzami) or small (Djavakheti). A mean palaeointensity value of 41.5 ± 11.3 μT, corresponding to a mean VDM of $7.8 \pm 3.7 \cdot 10^{22}$ A·m^2 is obtained. © 2000 Académie des sciences / Éditions scientifiques et médicales Elsevier SAS

palaeomagnetism / palaeointensity / Pliocene / Quaternary / Southern Caucasus

Résumé – Paléomagnétisme des régions volcaniques plio-quaternaires de la Georgie (Caucase du Sud) : une étude pilote. Une étude préliminaire du paléomagnétisme et du magnétisme des roches a été effectuée sur 248 coulées volcaniques plio-quaternaires et sur trois niveaux sédimentaires lacustres interstratifiés de Géorgie (Caucase). La plupart des échantillons sont caractérisés par une seule composante paléomagnétique, portée par la magnétite, comme le confirment les courbes de susceptibilité en fonction de la température. Des polarités normales, inverses et intermédiaires dans certains cas, ont été reconnues. Une direction paléomagnétique moyenne de $D = 6{,}0°$, $I = 57{,}8°$, $k = 30$, $\alpha_{95} = 3{,}8°$ a été obtenue. Considérant séparément les trois provinces volcaniques échantillonnées, on observe que les différences avec la paléodéclinaison attendue sont non significatives (Kazbeki et Khzami), ou faibles (Djavakheti). Une valeur moyenne de paléointensité de $41{,}5 \pm 11{,}3$ μT, correspondant à une valeur moyenne de VDM de $7{,}8 \pm 3{,}7 \cdot 10^{22}$ A·m^2 a été obtenue. © 2000 Académie des sciences / Éditions scientifiques et médicales Elsevier SAS

paléomagnétisme / paléointensité / Pliocène / Quaternaire / Caucase du Sud

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Version abrégée

1. Introduction

La formation des chaînes de montagne du Caucase est à relier à la convergence entre plaque Arabique et plaque Eurasiatique. La conséquence en est que la zone comprise entre les deux plaques est comprimée, tandis qu'il y a simultanément éjection latérale du bloc Anatolien vers l'ouest et du bloc Iranien vers l'est (par exemple [10], *figure 1*). Il en résulte une tectonique actuelle complexe, avec association de structures compressives nord–sud (charriages et plis est–ouest) et extensives est–ouest (failles normales nord–sud et dykes), accompagnées par un important volcanisme néogène à quaternaire et des décrochements sénestres NE–SW et dextres NW–SE.

On a montré que les rotations de blocs autour d'axes verticaux jouaient un rôle important dans l'accommodation des déformations de plaques lithosphériques (par exemple [6]) et que les déclinaisons paléomagnétiques étaient un bon indicateur de ce type de rotation. Aussi, des sites appartenant aux provinces volcaniques de Géorgie ont-ils été échantillonnés dans le but de déterminer les directions paléomagnétiques.

Les échantillons ont été prélevés dans 244 coulées subaériennes de laves à 44 endroits appartenant aux trois régions. Au total, 501 carottes paléomagnétiques standard ont été obtenues. Dans la plupart des cas, plusieurs coulées consécutives sont présentes à chaque site (de 1 à 15, voir *tableau*) ; elles ont en général une composition basaltique ou andésitique et comportent de temps à autre des niveaux sédimentaires lacustres interstratifiés entre les coulées.

2. Résultats paléomagnétiques

240 échantillons représentatifs de la plupart des coulées ont été démagnétisés graduellement, dans la plupart des cas en champs alternatif et, dans certains cas, thermiquement (*figures 2A* et *2B*). Les directions caractéristiques de chaque échantillon ont été calculées par analyse en composantes principales, 4 à 10 points étant utilisés pour les déterminations. Il est montré que près de 70 % des échantillons étudiés ne comportent qu'une seule composante magnétique, portée par la magnétite, comme le confirment les courbes de susceptibilité en fonction de la température (*figures 2C* et *2D*) – voir plus loin.

Les directions moyennes de site, répertoriées dans le tableau, ont été calculées à partir des directions caractéristiques de tous les échantillons des coulées consécutives. Les directions moyennes des niveaux sédimentaires interstratifiés ont été déterminées séparément de celles des laves. On appellera unité magnétique chaque formation caractérisée par de telles directions moyennes, déterminées indépendamment.

26 unités (113 laves et 1 niveau sédimentaire) fournissent une polarité normale, 29 unités (130 coulées) sont aimantées de façon inverse et 6 unités (4 coulées de lave et 2 niveaux sédimentaires) ont une polarité intermédiaire.

3. Expériences de paléointensité et de magnétisme des roches

Deux types de comportement magnétique ont été détectés, à partir de mesures de la susceptibilité en fonction de la température (courbe *k–T*). Dans la plupart des cas, les courbes montrent une unique phase magnétique (*figure 2C*), avec des points de Curie entre 350 et 570 °C, ce qui est indicatif d'une titanomagnétite. Dans les autres cas (14 échantillons), deux phases magnétiques peuvent être reconnues (*figure 2D*) : il s'agirait de titanomaghémite, se transformant en magnétite au chauffage.

28 échantillons ont été sélectionnés pour des expériences de paléointensité et 17 ont donné des estimations acceptables (*figures 3A* et *3B*). Les intensités géomagnétiques absolues obtenues sur les unités volcaniques de Géorgie se situent entre 16,6 et 54,7 μT. Si l'on écarte les échantillons à polarité intermédiaire, la valeur moyenne est de 41,5 ± 11,3 μT.

4. Discussion et conclusions.

Les constituants paléomagnétiques déterminés dans les roches étudiées sont considérés comme d'origine primaire, ce que confirment les polarités normales et inverses, de même que certaines directions intermédiaires de polarité. Dans la plupart des cas, la rémanence est portée par la magnétite résultant de l'oxy-exsolution d'une titanomagnétite originelle, lors du refroidissement de la coulée.

La présente étude paléomagnétique indique une direction caractérisée par D = 6,0°, I = 57,8°, k = 30, α_{95} = 3,8° et peu différente de celle attendue en Géorgie au Plio-Quaternaire, à savoir D = 4,9° et I = 59,8° [13].

Si l'on considère séparément les trois provinces volcaniques échantillonnées (*tableau*), la différence de 5° par rapport à la paléodéclinaison attendue est non significative pour les provinces de Kazbeki et Khzami, faible pour celle de Djavankheti. Si certaines unités individuelles présentent des paléodéclinaisons déviant plus nettement, ces dernières ont une origine tectonique.

Cependant, des rotations tectoniques de grande envergure ne semblent pas avoir pris place entre ces trois régions volcaniques, depuis le Pliocène. La compression entre les plaques Arabique et Eurasiatique n'a pas été accommodée par des mouvements latéraux au niveau de décrochements. Néanmoins, des rotations locales peuvent être observées dans certains sites.

1. Introduction

The formation of the mountain ranges of the Caucasus is related to the convergence between the Arabian and Eurasian plates. As a consequence, the region located between both plates is squeezed, while simultaneously a westward lateral ejection of the Anatolian block and an eastward lateral ejection of the Iranian block is produced (e.g. [10], *figure 1*). This results in a complex present-day tectonic setting, with an association of both north–south compressive (east–west thrusts and folds) and east–west extensional (north–south normal faults and dykes) structures, accompanied by considerably Neogene to Quaternary volcanism and NE–SW left-lateral and NW–SE right-lateral strike-slip faults [10].

Block rotations about vertical axes have been shown to play an important role in accommodating lithospheric plate deformations (e.g. [6]). Palaeomagnetic

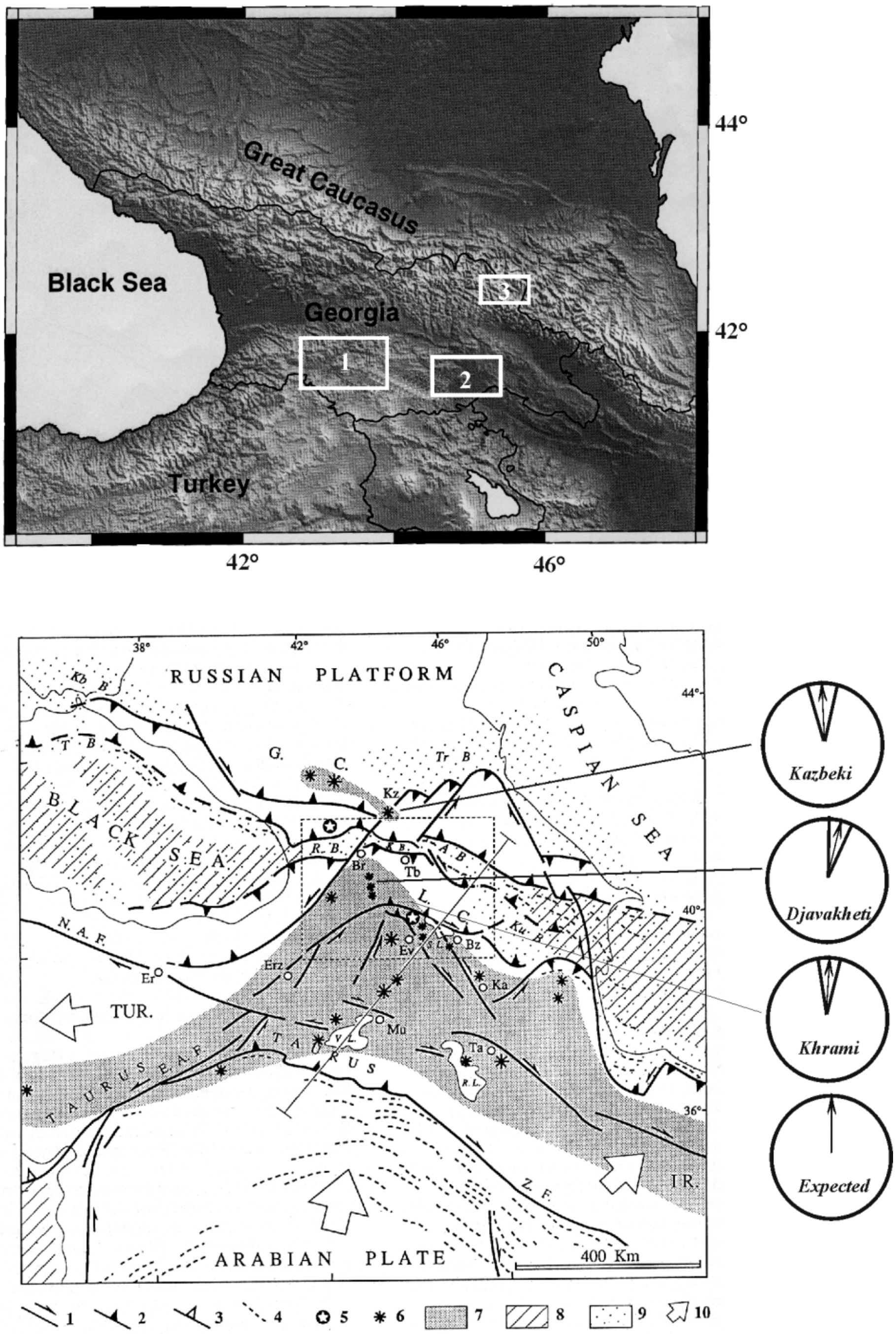

Figure 1. Georgian Plio-Quaternary volcanic provinces. **Top:** Geographical location. **1**: Djavakheti Region; **2**: Khrami Basin; **3**: Kazbeki. **Bottom:** Palaeomagnetic results and active tectonics in the front of the Arabian collision and the Caucasus, after [10]. Circles with arrows indicate mean palaeodeclinations and α_{95} for each volcanic region. Lower circle indicates expected Plio-Quaternary palaeodeclination [13]. **Key. 1**, major strike-slip fault; **2**, major thrust fault; **3**, subduction trench; **4**, recent folding; **5**, epicentral zones of the recent earthquakes; **6**, recent volcanic cones; **7**, Plio-Quaternary volcanic zones; **8**, oceanic and intermediate crust; **9**, main Neogenic and Quaternary basin; **10**, relative motion of blocks with respect to Eurasia. **Letter key: Br**, Bordjomi; **Bz**, Bazargechar; **Er**, Erzincan; **Erz**, Erzerum; **Ev**, Erevan; **Ka**, Kaphen; **Kz**, Kazbeki; **L.C.**, Lesser Caucasus; **Mu**, Muradiyé; **Ta**, Tabriz; **Tb**, Tbilissi.

Figure 1. Provinces volcaniques plio-quaternaires de Géorgie. En haut : situation géographique. **1**: région de Djavakheti ; **2** : bassin de Ktami, **3** : Kazbeki. En bas : résultats paléomagnétiques et tectonique active en avant de la collision arabique et en arrière du Caucase [10]. Les cercles avec les flèches indiquent les paléodéclinaisons moyennes et α_{95} pour chaque région volcanique. Le cercle inférieur indique la paléodéclinaison plio-quaternaire attendue [13]. **1** : décrochement majeur ; **2** : faille majeure ; **3** : fosse de subduction ; **4** : plissement récent ; **5** : épicentres de récents tremblements de terre ; **6** : cônes volcaniques récents ; **7** : zones volcaniques plio-quaternaires ; **8** : croûte océanique et intermédiaire ; **9** : principaux bassins néogènes et quaternaires ; **10** : mouvement relatif de blocs par rapport à l'Eurasie. Signification des lettres : **Br**, Bordjomi ; **Bz**, Bazatgechar ; **Er**, Erzincan ; **Erz**, Erzerum ; **Ev**, Erevan ; **Ka**, Kaphen ; **Kz**, Kazebi ; **L.C.**, Lesser Caucasus ; **Mu**, Muradfiyé ; **Ta**, Tabriz ; **Tb**, Tbilissi.

declinations are a good indicator of these kinds of rotations. As palaeomagnetic data in the Caucasus region are scarce, the first aim of the present study was to increase the amount of available data in that region, in order to obtain more information about its recent Pliocene to Quaternary tectonic development. For this purpose, sites belonging to the Georgian volcanic provinces were sampled for a reconnaissance palaeomagnetic and rock-magnetic study.

The geographical distribution of palaeointensity results is still uneven (e.g. [9]), and only few reliable data exist from the Southern Hemisphere and large areas from the former Soviet Union. This impedes an accurate analysis of the fine-scale changes in the statistical characteristics of geomagnetic field variations [5]. As in most cases continental volcanic rocks carrying thermoremanent magnetisation seem to be the most suitable material for palaeointensity determination, the second aim of the present study was to ascertain the suitability of volcanic rocks from the South Caucasus volcanic provinces for such studies.

In Georgia, Alpine (Late Miocene to Holocene) compression is responsible for orogenesis and intensive volcanic activity. Three phases of volcanic activity can be distinguished: (1) Late Miocene to Early Pliocene, (2) Middle to Late Pliocene, and (3) Quaternary [7, 12]. Late-orogenic subaerial volcanism in Georgia occurred mainly in the Djavakheti Mountains, the Khrami basin and the Kazbeki region. Their location is schematically shown in *figure 1*.

Samples were taken from 248 subaerial lava flows at 44 localities (sites) belonging to all three regions. In total, 501 standard palaeomagnetic cores were obtained. In most cases, several consecutive flows are present at each site (from 1 to 15 consecutive lava flows, *table*). They are generally of basaltic or andesitic composition. Occasionally, lacustrine sedimentary layers are interbedded between the flows (*table*). In general, 1–3 oriented blocks of different size were taken from each flow. Several 2 cm cubes were cut from each block for remanence measurements. The blocks were oriented relating their position to the Sun by means of a magnetic theodolite. All lava flows sampled as well as interbedded lacustrine sedimentary layers were horizontal (dip less than 3°). Exact GPS geographical positions are reported for all sites in the *table*.

The flows studied approximately cover the time interval from 2.5 to 0.06 Myr according to the available K–Ar dating [1, 7, 11, 13]. A magnetostratigraphic study on more than a hundred flows from the main volcanic regions in Georgia, also including flows sampled for the present work, had already been carried out by [13], but due to the small amount of samples analysed it had only a preliminary character. Older volcanic sequences (~4 Myr) from Georgia have been studied by [2] and [4]. These studies, however, are restricted to a very limited geographical area.

2. Palaeomagnetic results

240 pilot specimens were taken from almost all flows and stepwise demagnetised, in most cases with alternating fields and in some cases thermally (*figures 2A* and *2B*). Characteristic directions of individual samples were calculated by means of principal component analysis, 4 to 10 points being taken for these determinations. Almost 70 % of the studied samples carry essentially a single component of magnetisation, observed both upon thermal and alternating field treatment (*figures 2A* and *2B*). Remanence was mainly removed at temperatures between 525 and 575 °C (*figures 2A*), which points to almost pure magnetite as the carrier of remanence. Median destructive fields (MDF) range from 35 to 55 mT suggesting that 'small' pseudo-single domain grains are responsible for remanent magnetisation [3]. In some cases, a secondary viscous component was present and easily removed after a 10 mT peak demagnetising field. Due to the simple demagnetisation behaviour of the pilot specimens, the rest of the samples were subjected to only 3 alternating field demagnetisation steps (10, 20 and 30 mT), and after analysis of the results of the demagnetisation procedure, end points (30 mT points) were taken as the characteristic direction.

Mean site directions (listed in the *table*) were calculated from the characteristic directions of all samples from the consecutive flows. In some cases, however, flows belonging to a single locality seem to cover a longer time interval since different polarities were recognised in the same locality. In these cases, mean directions were calculated for each polarity group. Mean directions of interbedded sedimentary layers were determined separately from those obtained from lava flows. We will call each formation characterized by such independently determined mean directions a magnetic unit. Six units (Zurtaketi 4, Doliska 1, Bertakana 1, Bertakana 3, Satxe 1 and Sagamo 2) show aberrant directions characterised either by strong deviations of declinations from north or very shallow inclinations (*table*). As the other units from the same localities did not show similar directions, tectonic rotations can be excluded. As the VGP (virtual geomagnetic poles) palaeolatitudes obtained from these units are less than 45° and, in addition, the two palaeointensity results obtained from them (see section 3) are anomalously weak, we interpret these palaeomagnetic directions as being intermediate directions. They are not taken into account in the following discussion.

26 units (113 lava and 1 sedimentary layer) yield normal polarity, 29 units (130 lava flows) are reversely magnetised and 6 units (4 lava flows and 2 sedimentary layers) display intermediate polarity. We note that 8 sites from the 61 studied correspond only to one or two samples. Thus, their reliability can be questioned. However, their palaeomagnetic directions do not differ significantly from those of other nearby lying units.

Table. Palaeodirectional and palaeointensity results from Georgian volcanic provinces. *Lat*/*Long*: latitude/longitude of the studied sites, *N*: number of consecutive flows, *n*: total number of samples of each unit (see text), *D*: Declination, *I*: Inclination, *k* and α_{95}: precision parameter and radius of confidence cone, *Plat*/*Plong*: latitude/longitude of VGP position. *Pol*: Magnetic polarity, *Pint* (st): Palaeointensity in µT and associated standard error. *Age*: K–Ar ages in My [1, 7, 11, 13]. Sedimentary units are labelled by stars.

Tableau. Données sur les paléodirections et paléointensités des provinces volcaniques de Géorgie. *Lat/Long* : latitude/longitude des sites étudiés ; *N* : nombre de coulées consécutives ; *n* : nombre total d'échantillons de chaque unité (voir texte) ; *D* : déclinaison ; *I* : inclinaison, *k* et α_{95} : paramètre de précision et rayon du cône de confiance ; *Plat/Plong* : latitude/longitude de la position VGP ; *Pol* : polarité magnétique ; *Pint* (st) : paléointensité en µT et erreur standard correspondante ; *Age* : âges K–Ar en Ma [1, 7, 11, 13]. Les unités sédimentaires sont indiquées par des étoiles.

Site	*Lat*	*Long*	*N*	*n*	*D*	*I*	*k*	α_{95}	*Plat*	*Plong*	*Pol*	*Pint (st)*	*Age*
Tkarcheti	42°35′47″	44°33′56″	3	8	13	47	133	4.2	72	186	**N**		
Gudauri	42°28′22″	44°28′38″	2	5	9	42	120	3.3	70	199	**N**		
Kvecheti	42°25′22″	44°33′00″	2	4	5	48	46	4.4	76	206	**N**		
Kazbegi	42°41′27″	44°38′00″	14	17	352	51	550	1.4	78	258	**N**		
Kumliscixe	42°27′16″	44°29′01″	2	4	352	54	40	5.8	80	265	**N**	26.6 (1.2)	**0.06**
Devdoraki	42°45′00″	44°37′41″	4	10	357	67	61	7.6	82	29	**N**		
Chkeri	42°39′30″	44°37′58″	2	4	350	67	950	1.4	80	4	**N**		
Mleta	42°25′36″	44°29′34″	6	14	332	55	220	5.3	67	306	**N**		
Bidara	42°32′11″	44°28′32″	7	11	16	69	112	2.3	75	85	**N**		
Mnadoni	42°35′02″	44°29′07″	4	9	328	64	116	5.8	67	334	**N**		
Okrokana	42°34′55″	44°29′17″	4	10	17	74	158	2.5	69	69	**N**		
KAZBEKI	***11 Sites***				***357***	***59***	***36***	***8***					
Avranlo	41°39′10″	43°53′34″	1	1	312	48			49	312	**N**	48.3 (5.3)	**0.23**
Orozmani (1)	41°17′55″	44°14′38″	7	10	358	59	132	4.1	88	272	**N**		
Orozmani (2)	41°17′55″	44°14′38″	4	8	196	–31	122	7.6	–62	10	**R**		
Orozmani (3)	41°17′55″	44°14′38″	5	11	42	65	79	6.2	60	109	**N**		
Zurtaketi (1)	41°24′43″	44°05′43″	4	6	2	62	84	4.5	88	80	**N**	54.7 (6.2)	
Zurtaketi (2)	41°24′43″	44°05′43″	3	5	170	–41	267	2.6	–70	72	**R**		**0.31**
Zurtaketi (3)	*41°24′43″*	*44°05′43″*		*5*	*1*	*58*	*401*	*1.5*	*87*	*207*	***N***		
Zurtaketi (4)	*41°24′43″*	*44°05′43″*		*8*	*207*	*56*	*25*	*11.3*	*–8*	*22*	***I***		
Zurtaketi (5)	41°24′43″	44°05′43″	3	7	155	–51	651	2.3	–68	117	**R**		
Sarfisgele (1)	41°18′00″	44°07′58″	4	10	178	–35	43	8.8	–68	49	**R**	50.0 (5.6)	
Sarfisgele (2)	41°18′00″	44°07′58″	2	3	12	63	15	12.2	81	109	**N**		
Sarfisgele (3)	41°18′00″	44°07′58″	3	7	175	–57	256	2.2	–85	93	**R**		**2.18**
Gomareti	41°30′00″	44°10′01″	1	1	156	–57			–71	131	**R**	47.2 (2.6)	**0.43**
Machavera	41°22′30″	44°23′56″	15	28	19	60	968	1.1	76	129	**N**		
Dmanissi	41°31′42″	44°17′54″	1	1	25	71			68	85	**N**	48.8 (2.5)	**0.53**
Axa	41°27′00″	44°05′52″	8	13	155	–61	282	1.5	–71	145	**R**	23.4 (3.2)	
Bedeni	41°32′30″	44°06′48″	2	4	175	–64	125	4.6	–84	186	**R**		
Araxlo	41°28′18″	44°41′06″	10	19	178	–60	221	5.6	–88	121	**R**		
Disveli	41°30′02″	44°31′40″	1	2	185	–55			–83	9	**R**		**0.69**
Arnala	41°39′10″	44°53′35″	6	10	179	–53	53	7.9	–82	51	**R**		
Kakliani	41°19′42″	44°17′30″	1	1	181	–40			–72	41	**R**	48.1 (5.7)	**0.74**
Samchvilde	41°29′59″	44°17′30″	13	22	194	–59	456	4.3	–79	318	**R**		
Chvidsakrada	41°35′33″	43°57′51″	3	7	204	–55	329	2.2	–70	323	**R**		
Tsalka	41°35′50″	44°05′22″	4	9	202	–63	229	2.9	–74	296	**R**		
Dachbashi	41°35′17″	44°07′30″	1	1	207	–62			–70	299	**R**	51.5 (3.6)	**1.05**
Trialeti	41°32′30″	44°06′48″	1	1	203	–48			–68	340	**R**	18.9 (2.2)	**2.35**
KHRAMI	***19 Sites***				***4***	***56***	***39***	***6***					
Khertvissi	41°28′30″	43°17′30″	3	7	206	–56	190	2.6	–70	309	**R**		
Saro	41°30′17″	43°16′47″	4	11	213	–62	850	1.8	–66	297	**R**		
Aspindza	41°30′17″	43°16′47″	4	9	222	–56	213	3.1	–57	308	**R**		
Mtkvari	41°28′20″	43°17′32″	14	23	233	–63	954	2.3	–52	290	**R**		
Kumurdo	41°23′53″	43°21′04″	5	12	28	47	82	7.2	64	154	**N**	39.1 (2.5)	**1.12**
Korxi(1)	41°28′58″	43°22′30″	12	33	207	–67	833	3.6	–69	280	**R**		
Korxi (2)	41°28′58″	43°22′30″	7	16	17	52	318	2.9	74	160	**N**		
Varevani	41°30′48″	43°23′36″	3	8	215	–66	688	1.4	–64	285	**R**		
Diliska(1)	*41°25′04″*	*43°28′34″*		*12*	*160*	*20*	*21*	*18.8*	*–35*	*68*	***I***		
Diliska(2)	41°25′04″	43°28′34″	4	10	356	59	129	3.8	87	289	**N**		
Bertakana (1)	41°23′53″	43°21′04″	2	3	297	58	42	8.5	43	332	**I**		
Bertakana (2)	41°23′53″	43°21′04″	4	7	182	–62	910	2.6	–88	259	**R**		
Bertakana (3)	41°23′53″	43°21′04″	2	2	137	–13			–38	103	**I**	18.5 (0.8)	
Apnia (1)	41°21′40″	43°16′02″	3	7	335	53	45	16.8	69	300	**N**	33.4 (2.3	**1.69**
Apnia (2)	41°21′40″	43°16′02″	7	13	185	–55	156	3.5	–83	7	**R**		
Akhalkalaki	41°23′02″	43°00′05″	4	9	351	51	278	2.1	78	263	**N**		
Murjebi	41°32′08″	43°28′21″	3	7	193	–77	220	3.2	–65	236	**R**	52.2 (4.1)	
Satxe (1)	41°14′00″	43°39′17″	1	2	3	–8			45	219	**I**		
Satxe (2)	41°14′00″	43°39′17″	2	4	224	–32	61	6.3	–46	332	**R**	45.3 (7.9)	**2.29**
Spasovka (1)	41°12′03″	43°39′42″	2	3	199	–39	29	10.8	–65	358	**R**		
Spasovka (2)	41°12′03″	43°39′42″	2	3	344	41	70	8.6	68	266	**N**	35.9 (2.5)	
Sagamo (1)	41°15′03″	43°15′01″	2	4	164	–62	112	6.3	–78	148	**R**		
Sagamo (2)	41°15′03″	43°15′01″	2	3	234	44	60	6.6	–4	359	**I**	16.3 (1.2)	
Sagamo (3)	41°15′03″	43°15′01″	3	7	348	63	156	3.8	81	338	**N**		
DJAVAKHETI	**19 sites**				**13.7**	**58**	**24**	**7**					

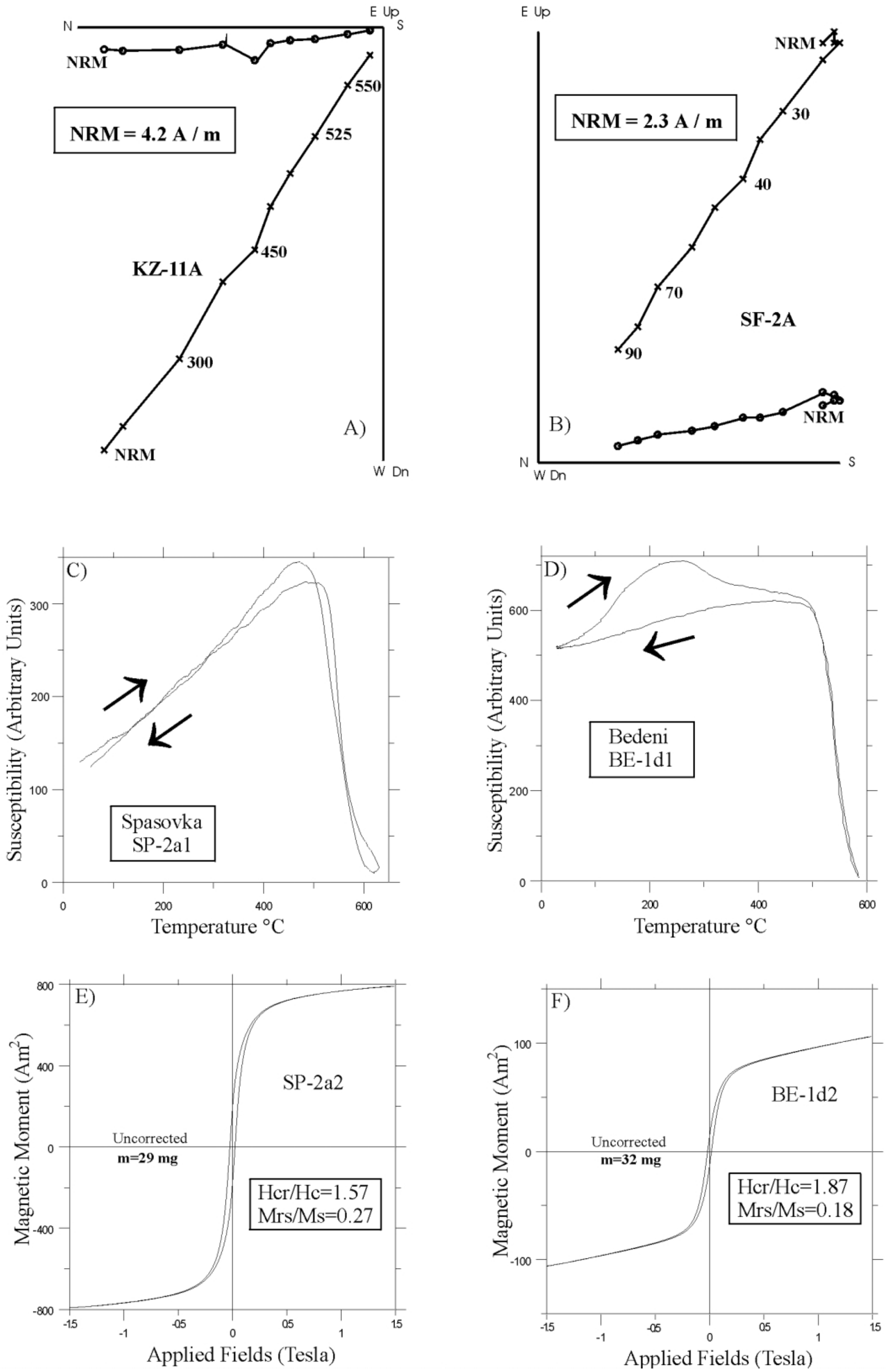

Figure 2. Orthogonal vector plots of stepwise thermal (**A**) or alternating field demagnetisation (**B**) of representative samples. Numbers refer either to temperatures in °C or peak alternating fields in mT. ○: horizontal projection; ×: vertical projection. Susceptibility versus temperature curves (**C** and **D**) and corresponding hysteresis plots (**E** and **F**) of representative samples. Arrows indicate heating and cooling branches.

Figure 2. Graphiques en coordonnées orthogonales montrant la désaimantation thermique graduelle (**A**) ou en champs alternatifs (**B**) d'échantillons représentatifs. Les nombres renvoient, soit aux températures en °C, soit aux pics de champs alternés en mT. ○ : projection horizontale; × : projection verticale. Courbes de susceptibilité en fonction de la température (**C** et **D**) et diagrammes de l'hystérésis correspondante (**E** et **F**) d'échantillons représentatifs. Les flèches indiquent le sens de chauffe ou de refroidissement.

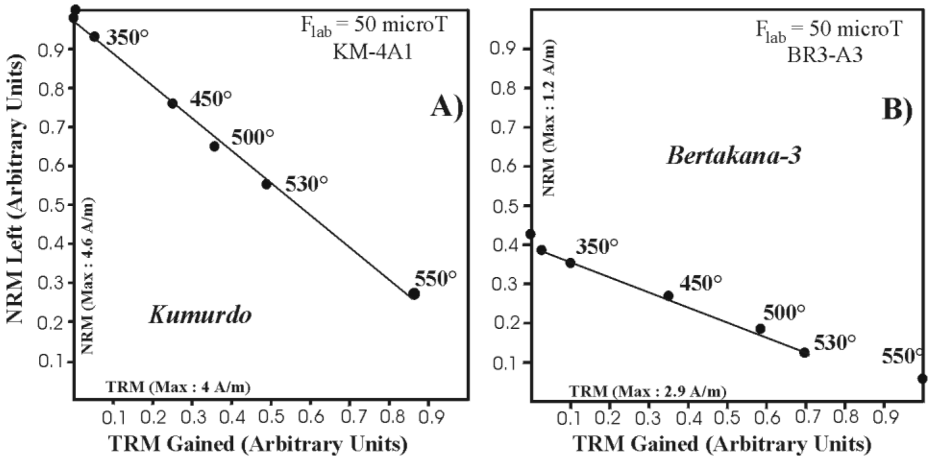

Figure 3. Examples of Arai-Nagata (NRM–TRM) plots.

Figure 3. Exemple de diagrammes NRM–TRM d'Arai-Nagata.

3. Rock magnetic and palaeointensity experiments

To identify the magnetic minerals carrying remanent magnetisation and check their thermal stability, continuous susceptibility versus temperature measurements (*k–T* curves) were carried out in air. Two different types of behaviours were detected. In most cases, the curves show a simple thermomagnetic behaviour indicating a single magnetic phase (*figure 2C*) with Curie points ranging from 550 to 570 °C. This is indicative of low-Ti titanomagnetite content, which is compatible with a magnetic mineralogy resulting from deuteric oxidation. In other cases (14 samples), two thermomagnetic phases could be recognized during heating (*figure 2D*). The lower Curie point does not exceed 400 °C, while the highest one reaches almost 570 °C. The cooling curve shows only a single phase, with a Curie temperature close to that of magnetite. Such irreversible *k–T* curves can be due to the presence of titanomaghemite, which transforms into magnetite (e.g. [8]) during heating.

Hysteresis curves were found to be rather similar for all studied samples (*figures 2E* and *2F*). The ratios of hysteresis parameters indicate that all studied samples fall in the pseudo-single-domain (PSD) grain size, which might suggest a mixture of multi-domain (MD) and a significant amount of single-domain grains.

In order to check the suitability of the studied volcanic flows for palaeointensity determinations, preliminary palaeointensity experiments using the Thellier–Thellier method in its classic form [14] were carried out, although no pTRM-checks were used in this study. All heatings were performed in air, and at each temperature step samples were heated twice with an applied laboratory field of 50 μT. Only 28 specimens with stable and single magnetisation components and with reasonably reversible thermomagnetic curves were selected for palaeointensity experiments. We only accepted determinations which were made from at least 5 points with a linear distribution of NRM–TRM points up to 520–550 °C. Only 17 samples yielded an acceptable palaeointensity estimate (*figures 3A* and *3B*).

The absolute geomagnetic intensities obtained from Georgian volcanic units vary between 16.3 to 54.7 μT. Two intermediate polarity samples provided significantly reduced palaeointensities. After discarding the latter, a mean value of 41.5 ± 11.3 μT is obtained.

4. Discussion and conclusions

We consider the palaeomagnetic components determined in this study to be of primary origin. This is confirmed by the fact that normal and reversed polarities as well as some intermediate polarity directions were determined. In addition, thermomagnetic curves show that the remanence is carried in most cases by magnetite resulting from oxy-exsolution of original titanomagnetite during the initial flow cooling, which most probably indicates thermoremanent origin of the primary magnetisation. Moreover, unblocking temperature spectra and relatively high MDF values point to small pseudo-single domain low-Ti titanomagnetite as responsible for remanent magnetisation, and single-component, linear demagnetisation plots which were observed in most cases.

Palaeomagnetic results (after rejecting for calculation those units with a single sample and those showing intermediate polarity) of the present study yield a $D = 6.0°$, $I = 57.8°$, $k = 30$, $\alpha_{95} = 3.8°$ direction. After comparing our results with the expected Plio-Quaternary direction in Georgia of $D = 4.9°$ and $I = 59.8°$ [13], no significant difference can be recognised. Nevertheless, if palaeodeclinations of individual sites are considered, some stronger deviations from the expected direction of declination can be observed, which can amount to as much as 48° (site Mtkvari, in the Djavakheti volcanic region, *table*).

Considering separately the three sampled volcanic provinces (*table*), it can be recognised again that differences with the expected palaeodeclination of 5° are either non-significative (units from volcanic provinces Kazbeki and Khzami) or small (volcanic province of Djavakheti). In the latter case, in which a slightly eastward deviated palaeodeclination ($D = 13.7$, $I = 58.1$, $\alpha_{95} = 7.0$, $k = 24$, $N = 19$) was obtained, several individual units display palaeodeclinations clearly deviating eastward from the northern direction. Though these directions might be due to secular variation, some units should include enough lava flows to average out most of this perturbation effect (Mtkvari, Korxi1). Most probably, these large deviations in declination have a tectonic origin.

However, no large tectonic rotations seem to have occurred between these three volcanic regions since the Pliocene. Compression between the Arabian and Eurasian plates has not been accommodated in the studied areas through lateral movements at strike slip faults. However, in certain sites local rotations are observed. A better knowledge of the local tectonic setting of those areas is needed for a deeper analysis of these rotations.

As far as the preliminary palaeointensity experiments are concerned, absolute geomagnetic intensities obtained from Georgian volcanics from the Pliocene to present day, vary from 16.3 to 54.7 μT. After discarding intermediate polarity samples the mean value is 41.5 ± 11.3 μT, which corresponds to a mean virtual dipole moment (VDM) of $7.8 \pm 3.7 \cdot 10^{22}$ $A \cdot m^2$. This value is very close to the Plio-Quaternary mean VDM recently determined by [9]. Two samples from intermediate polarity flows yield a significantly reduced palaeointensity, as expected for transitional fields [5].

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