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A reconnaissance magnetostratigraphy of Georgian Plio-Quaternary volcanic provinces (southern Caucasus)

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RESUMEN

Se presentan resultados de un estudio paleomagnético y de magnetismo de rocas en muestras de las regiones de Djavakheti, Khrami y Kazbeki, en Georgia (Cáucaso). Se tomaron muestras de 247 coladas volcánicas subaéreas y de 3 estratos sedimentarios lacustres intercalados entre éstas, pertenecientes a 44 localidades. El objetivo del trabajo consistía en el estudio de la estabilidad magnética y paleomagnética de muestras para determinar su potencial en estudios de magnetoestratigrafía y paleointensidad. Los experimentos de magnetismo de rocas demostraron que la magnetización remanente está asociada principalmente a la presencia de magnetita de tipo PSD. 113 coladas volcánicas y un estrato sedimentario dieron como resultado una magnetización de polaridad normal, mientras que otras 130 coladas volcánicas presentaron una magnetización de polaridad inversa. 4 coladas volcánicas y 2 estratos sedimentarios se caracterizan por mostrar direcciones correspondientes a una polaridad intermedia. Se determinó una dirección paleomagnética media para todas las unidades volcánicas, salvo las de polaridad intermedia, de D=4.7°, I=58.3°, k=28 y α_{95}=3.7° y se estableció una magnetoestratigrafía preliminar de las provincias volcánicas georgianas.

PALABRAS CLAVE: Magnetoestratigrafía, paleomagnetismo, Cáucaso sur, Plioceno.

ABSTRACT

A palaeomagnetic and rock magnetic study was carried out on samples of the Djavakheti, Khrami and Kazbeki regions in Georgia. Samples were taken from 44 localities from 247 subaerial lava flows and from 3 lacustrine sedimentary layers, interbedded between flows. Rock magnetic experiments showed that characteristic remanent magnetisation is mainly carried by magnetite of pseudo single domain size. 113 lava flows and 1 sedimentary layer yielded normal polarity magnetisation, 130 lava flows were reversly magnetised and 4 lava flows and 2 sedimentary layers displayed an intermediate polarity direction. A mean direction of D=4.7°, I=58.3°, k=28, α_{95}=3.7° was obtained for all volcanic units, except those of intermediate polarity. A preliminary magnetostratigraphy of the Georgian volcanic provinces is proposed.

KEY WORDS: Magnetostratigraphy, palaeomagnetism, southern Caucasus, Pliocene.

INTRODUCTION

Despite a considerable increase in quantity and quality of palaeomagnetic data during the last ten years, the geographical distribution of results is still uneven (e.g. Tanaka *et al.*, 1995; Perrin and Shcherbakov, 1997). Few reliable palaeomagnetic and palaeointensity results are available for large areas of the former Soviet republics. This lag impedes an accurate analysis of the fine-scale changes in the statistics of geomagnetic field variations (Jacobs, 1994). The present study was carried out on Plio-Quaternary doleritic and andesitic lava flows in the Georgian volcanic provinces. Continental volcanic rocks carrying thermoremanent magnetisation are suitable materials, both in terms of palaeodirection and palaeointensity determination. For this reason, the South Caucasus volcanic provinces offer good opportunities of palaeointensity and palaeomagnetic studies.

We present a reconnaissance palaeomagnetic and rock-magnetic investigation for choosing and selecting appropriate samples for their magnetic and palaeomagnetic stability and selecting suitable sites for magnetostratigraphic and palaeointensity studies. Previous palaeomagnetic studies in Georgia were carried out by Sologashvili (1986), who examined more than a hundred flows from the main volcanic regions in Georgia, including some flows sampled in the present work. The total amount of samples was small. Goguitchaichvili *et al.* (1997) and Camps *et al.* (1996) studied older volcanic sequences (~ 4 My) in a limited geographical area. We establish a preliminary Plio-Quaternary

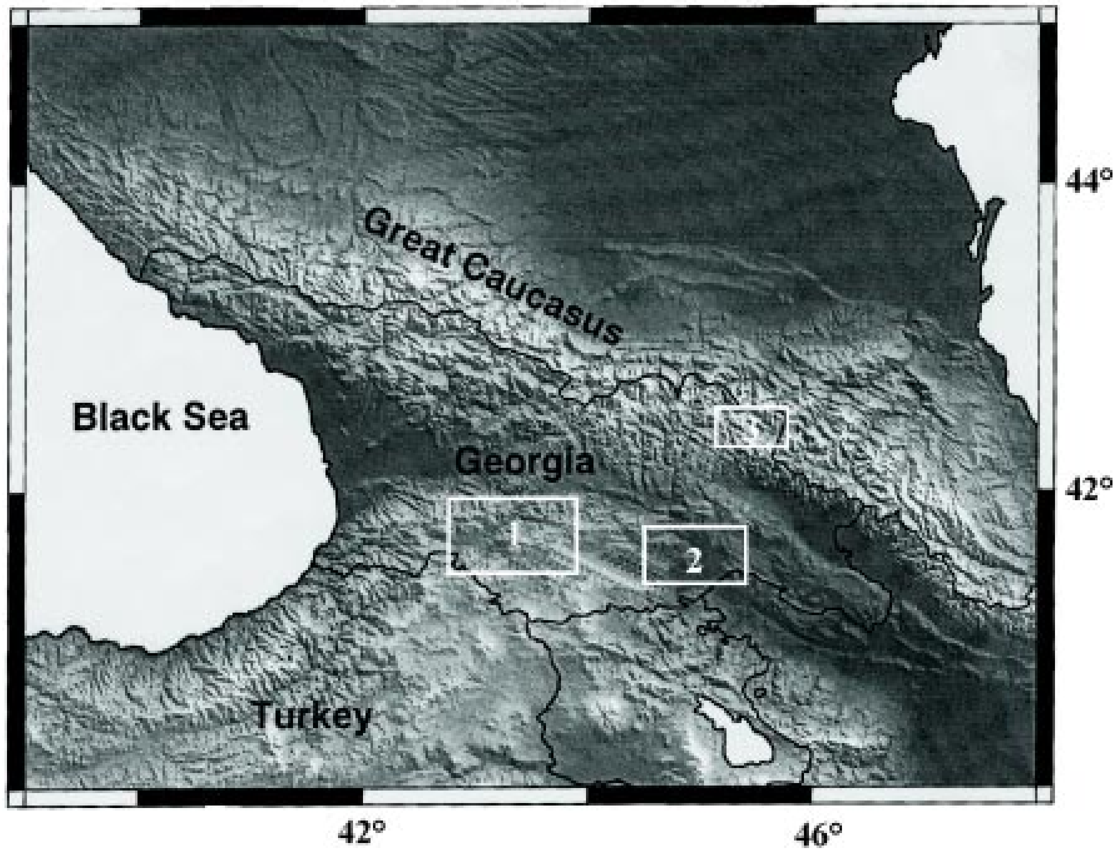

Fig. 1. The Georgia Plio-Quaternary volcanic provinces: 1 - Djavakheti Region; 2 - Khrami Bassin; 3 – Kazbeki. Solid lines refer to the national borders.

magnetostratigraphy of the Georgian volcanic provinces. Palaeointensity experiments are reported elsewhere (Goguitchaichvili *et al.,* 2000).

GEOLOGICAL SETTING AND SAMPLING

The Caucasus was formed by convergence between the Arabian and Eurasian plates, resulting in a complex tectonic setting (e.g. Rebaï *et al.,* 1993). Compressive and extensional structures are accompanied by right and left-lateral strike slip faults and an important Neogene to Quaternary volcanism. Few geological and petrologic studies are available. Three phases of volcanic activity can be distinguished in Georgia: (1) late Miocene to early Pliocene, (2) middle to late Pliocene or Pleistocene, and (3) Quaternary (Skhirtladze, 1958; Maissuradze *et al.,* 1980). Late-orogenic subaerial volcanism occurred mainly in the Djavakheti Mountains, the Khrami basin and the Kazbeki region (Figure 1).

Samples were taken from 44 localities, in 247 subaerial lava flows belonging to all three regions plus 3 lacustrine sedimentary layers, which were interbedded between the flows. In most cases, the sites included a sequence of up to 15 consecutive lava flows (Table 1). Most of them were doleritic or andesitic. One to three oriented blocks of different sizes were taken from each flow. Several 2cm cubes were cut from each block for remanence measurements. The blocks were oriented with respect to the Sun by means of a magnetic theodolite. All lava flows and interbedded lacustrine sedimentary layers were horizontal i.e. the dip was less than 4°. GPS geographical positions are shown in Table 1.

From available K-Ar dates (Rubinshtein *et al.,* 1972; Maissuradze *et al.,* 1980; Aslanian *et al.,* 1982 and Sologashvili, 1986), the flows cover the time interval from 2.5 My to 0.06 My.

PALAEOMAGNETIC AND ROCK MAGNETIC MEASUREMENTS

240 pilot specimens were taken and stepwise demagnetised, in most cases with alternating fields and in some

Table 1

Palaeomagnetic results from Georgia volcanic provinces: Lat/Long: Latitude/Longitude of the studied sites, N: Number of consecutive flows, n: Total number of samples from the consecutive flows yielding the same palaeodirections, D: Declination, I: Inclination, k and α_{95}, Precision parameter and radius of confidence cone of Fisher statistics, Plat/Plong: Latitude/Longitude of VGP position. Pol: Magnetic polarity, Age: K-Ar ages recalculated using decay constants by Dalrymple (1992). The references to original K-Ar results for Djavakheti region are from (4) Sologashvili, (1986) and (3) Maissuradze *et al.*, 1980; For Khrami basin (2) Aslanian *et al.*, 1982, and for Kazbeki (1) Rubinshtein *et al.*, 1972. Sedimentary units are labeled by asterics

Site	*Lat*	*Long*	*Code*	*N*	*n*	*D*	*I*	*k*	α_{95}	*Plat*	*Plong*	*Pol*	*Age*	*Ref.*
KAZBEKI														
Tkarcheti	42°35’47’’	44°33’56’’	*36*	3	8	13	47	133	4.2	72	186	**N**		
Gudauri	42°28’22’’	44°28’38’’	*38*	2	5	9	42	120	3.3	70	199	**N**		
Kvecheti	42°25’22’’	44°33’00’’	*39*	2	4	5	48	46	4.4	76	206	**N**		
Kazbegi	42°41’27’’	44°38’00’’	*40*	14	17	352	51	550	1.4	78	258	**N**		
Kumliscixe	42°27’16’’	44°29’01’’	*41*	2	4	352	54	40	5.8	80	265	**N**	**0.06**	***1***
Devdoraki	42°45’00’’	44°37’41’’	*43*	4	10	357	67	61	7.6	82	29	**N**		
Chkeri	42°39’30’’	44°37’58’’	*44*	2	4	350	67	950	1.4	80	4	**N**		
Mleta	42°25’36’’	44°29’34’’	*42*	6	14	332	55	220	5.3	67	306	**N**		
Bidara	42°32’11’’	44°28’32’’	*34*	7	11	16	69	112	2.3	75	85	**N**		
Mnadoni	42°35’02’’	44°29’07’’	*37*	4	9	328	64	116	5.8	67	334	**N**		
Okrokana	42°34’55’’	44°29’17’’	*35*	4	10	17	74	158	2.5	69	69	**N**		
kHRAMI														
Avranlo	41°39’10’’	43°53’34’’	*16*	1	1	312	48			49	312	**N**	**0.23**	***2***
Orozmani(1)	41°17’55’’	44°14’38’’	*28*	7	10	358	59	132	4.1	88	272	**N**		
Orozmani(2)	41°17’55’’	44°14’38’’	*28*	4	8	196	-31	122	7.6	-62	10	**R**		
Orozmani(3)	41°17’55’’	44°14’38’’	*28*	5	11	42	65	79	6.2	60	109	**N**		
Zurtaketi(1)	41°24’43’’	44°05’43’’	*24*	4	6	2	62	84	4.5	88	80	**N**		
Zurtaketi(2)	41°24’43’’	44°05’43’’	*24*	3	5	170	-41	267	2.6	-70	72	**R**	**0.31**	***2***
Zurtaketi(3)*	41°24’43’’	44°05’43’’	*24*		5	1	58	401	1.5	87	207	**N**		
Zurtaketi(4)*	41°24’43’’	44°05’43’’	*24*		8	207	56	25	11.3	-8	22	**I**		
Zurtaketi(5)	41°24’43’’	44°05’43’’	*24*	3	7	155	-51	651	2.3	-68	117	**R**		
Sarfisgele(1)	41°18’00’’	44°07’58’’	*23*	4	10	178	-35	43	8.8	-68	49	**R**		
Sarfisgele(2)	41°18’00’’	44°07’58’’	*23*	2	3	12	63	15	12.2	81	109	**N**		
Sarfisgele(3)	41°18’00’’	44°07’58’’	*23*	3	7	175	-57	256	2.2	-85	93	**R**	**2.18**	***2***
Gomareti	41°30’00’’	44°10’01’’	*17*	1	1	156	-57			-71	131	**R**	**0.43**	***2***
Machavera	41°22’30’’	44°23’56’’	*29*	15	28	19	60	968	1.1	76	129	**N**		
Dmanissi	41°31’42’’	44°17’54’’	*18*	1	1	25	71			68	85	**N**	**0.53**	***2***
Axa	41°27’00’’	44°05’52’’	*32*	8	13	155	-61	282	1.5	-71	145	**R**		
Bedeni	41°32’30’’	44°06’48’’	*30*	2	4	175	-64	125	4.6	-84	186	**R**		
Araxlo	41°28’18’’	44°41’06’’	*31*	10	19	178	-60	221	5.6	-88	121	**R**		
Disveli	41°30’02’’	44°31’40’’	*20*	1	2	185	-55			-83	9	**R**	**0.69**	***2***
Arnala	41°39’10’’	44°53’35’’	*33*	6	10	179	-53	53	7.9	-82	51	**R**		
Kakliani	41°19’42’’	44°17’30’’	*19*	1	1	181	-40			-72	41	**R**	**0.74**	***2***
Samchvilde	41°29’59’’	44°17’30’’	*25*	13	22	194	-59	456	4.3	-79	318	**R**		
Chvidsakrada	41°35’33’’	43°57’51’’	*26*	3	7	204	-55	329	2.2	-70	323	**R**		

(Table 1, continued).

Site	*Lat*	*Long*	*Code*	*N*	*n*	*D*	*I*	*k*	α_{95}	*Plat*	*Plong*	*Pol*	*Age*	*Ref.*
Tsalka	41°35'50''	44°05'22''	*27*	4	9	202	-63	229	2.9	-74	296	**R**		
Dachbashi	41°35'17''	44°07'30''	*21*	1	1	207	-62			-70	299	**R**	**1.05**	***2***
Trialeti	41°32'30''	44°06'48''	*22*	1	1	203	-48			-68	340	**R**	**2.35**	***2***
DJAVAKHETI														
Khertvissi	41°28'30''	43°17'30''	*4*	3	7	206	-56	190	2.6	-70	309	**R**		
Saro	41°30'17''	43°16'47''	*5*	4	11	213	-62	850	1.8	-66	297	**R**		
Aspindza	41°30'17''	43°16'47''	*3*	4	9	222	-56	213	3.1	-57	308	**R**		
Mtkvari	41°28'20''	43°17'32''	*6*	14	23	233	-63	954	2.3	-52	290	**R**		
Kumurdo	41°23'53''	43°21'04''	*2*	5	12	28	47	82	7.2	64	154	**N**	**1.12**	***3***
Korxi(1)	41°28'58''	43°22'30''	*7*	12	33	207	-67	833	3.6	-69	280	**R**		
Korxi(2)	41°28'58''	43°22'30''	*7*	7	16	17	52	318	2.9	74	160	**N**		
Varevani	41°30'48''	43°23'36''	*15*	3	8	215	-66	688	1.4	-64	285	**R**		
Diliska(1)*	41°25'04''	43°28'34''	*1*		12	160	20	21	18.8	-35	68	**I**		
Diliska(2)	41°25'04''	43°28'34''	*1*	4	10	356	59	129	3.8	87	289	**N**		
Bertakana(1)	41°23'53''	43°21'04''	*13*	2	3	297	58	42	8.5	43	332	**I**		
Bertakana(2)	41°23'53''	43°21'04''	*13*	4	7	182	-62	910	2.6	-88	259	**R**		
Bertakana(3)	41°23'53''	43°21'04''	*13*	2	2	137	-13			-38	103	**I**		
Apnia(1)	41°21'40''	43°16'02''	*14*	3	7	335	53	45	16.8	69	300	**N**	**1.69**	***4***
Apnia(2)	41°21'40''	43°16'02''	*14*	7	13	185	-55	156	3.5	-83	7	**R**		
Akhalkalaki	41°23'02''	43°00'05''	*12*	4	9	351	51	278	2.1	78	263	**N**		
Murjebi	41°32'08''	43°28'21''	*10*	3	7	193	-77	220	3.2	-65	236	**R**		
Sartxe(1)	41°14'00''	43°39'17''	*8*	1	2	3	-8			45	219	**I**		
Satxe(2)	41°14'00''	43°39'17''	*8*	2	4	224	-32	61	6.3	-46	332	**R**	**2.29**	***3***
Spasovka(1)	41°12'03''	43°39'42''	*11*	2	3	199	-39	29	10.8	-65	358	**R**		
Spasovka(2)	41°12'03''	43°39'42''	*11*	2	3	344	41	70	8.6	68	266	**N**		
Sagamo(1)	41°15'03''	43°15'01''	*9*	2	4	164	-62	112	6.3	-78	148	**R**		
Sagamo(2)	41°15'03''	43°15'01''	*9*	2	3	234	44	60	6.6	-4	359	**I**		
Sagamo(3)	41°15'03''	43°15'01''	*9*	3	7	348	63	156	3.8	81	338	**N**		

cases thermally (Figure 2). Thermal demagnetisation showed that most remanent magnetisation was removed at temperatures between 525° and 575°, pointing to magnetite as the main carrier of remanence. Characteristic directions of individual samples were calculated by means of principal component analysis (Kirschvink, 1980), four to ten points were taken for these determinations. Almost 70% of the samples carried a single palaeomagnetic component, both for thermal and alternating field treatment (Figure 2). In some cases a secondary component, probably of viscous origin, could be recognised. This component was easily removed by AF demagnetisation with a 10 mT peak field. Due to the simple demagnetisation behaviour of the pilot specimens, the remaining samples were subjected to only three alternating field demagnetisation steps at 10, 20 and 30 mT. After demagnetisation, the end points were taken as the characteristic direction.

Mean directions are listed in Table 1. All samples from consecutive flows belonging to all 44 localities were included. In some cases, flows belonging to a locality seem to cover a longer time interval, because different polarities were recognised in the locality. In these cases, mean directions were calculated for each polarity group. Mean directions of interbedded sedimentary layers were determined separately. Each independently determined mean directions will be colled a 'unit'. There were sixty-one units.

Continuous susceptibility measurements (k-T curves) showed a simple thermomagnetic behaviour indicating the

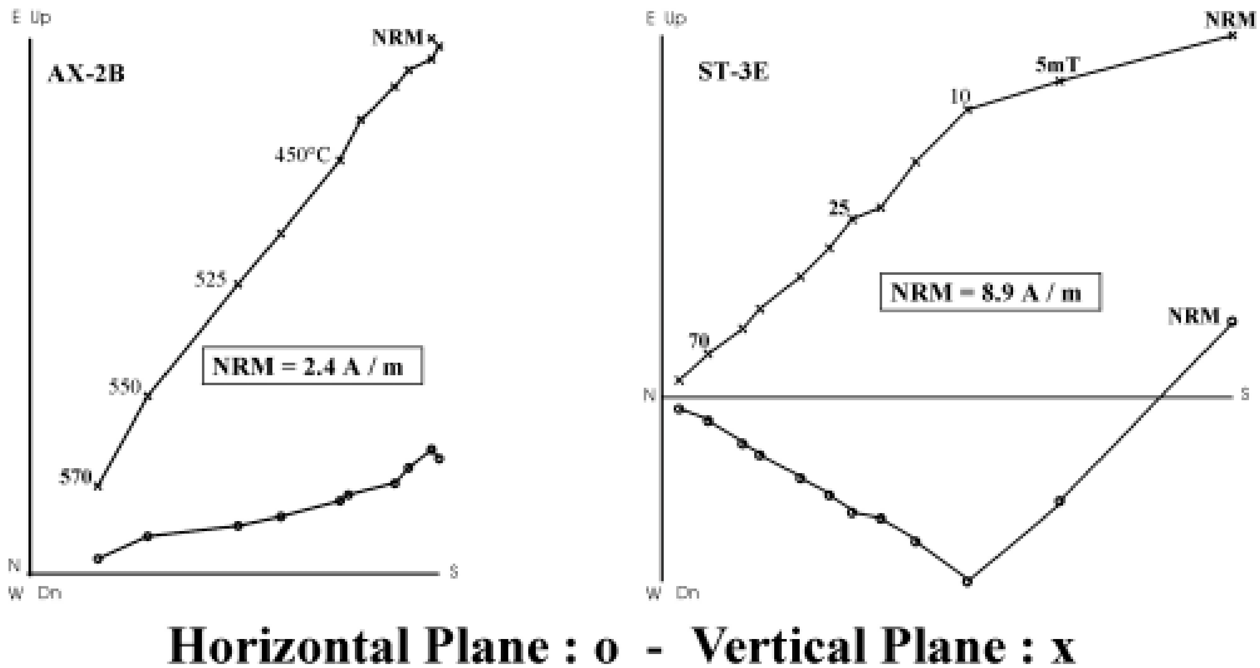

Fig. 2. Orthogonal vector plots of stepwise thermal or alternating field demagnetisation of representative samples (stratigraphic co-ordinates). The numbers refer to temperatures in °C or to peak alternating fields in mT. o – Projection on the horizontal plane.

presence of a single magnetic phase (Goguitchaichvili *et al.*, 2000), with Curie points ranging from 550 to 570°C. Titanomaghemite was detected in a few cases.

From earlier measurements of ratios of hysteresis parameters (Goguitchaichvili *et al.,* 2000), all measured samples seems to fall in the pseudo-single-domain (PSD) grain size. Median destructive fields (MDF) determined from AF demagnetisation curves range from 35 to 55 mT, thus suggesting that small PSD grains could be responsible for remanent magnetisation (Dunlop and Özdemir, 1997).

MAIN RESULTS AND DISCUSSION

Twenty-six units from 113 lava flows and 1 sedimentary layer yield normal polarity magnetisation, and 29 units from 130 lava flows are reversly magnetised (Figure 3). In six units (four lava flows and two sedimentary layers), anomalous directions characterised either by deviations of declinations from north or very shallow inclinations, were observed (Table 1 and Figure 3). Palaeolatitudes of these units are below 45°. Also, two palaeointensity (Goguitchaichvili *et al.,* 2000) results yield anomalously weak values. These palaeomagnetic directions are interpreted as corresponding to intermediate directions. Six sites (including two for intermediate directions) consist of only one sample, with doubtful reliability, although their palaeomagnetic directions do not differ significantly from those of other nearby units. The mean direction of all volcanic units, excluding those of intermediate polarity, yields the following values: D=4.7°, I=58.3°, k=28, α_{95}=3.7°, N= 54.

We suggest that the single palaeomagnetic component determined in these samples is of primary origin. The presence of normal and reversed polarities and some intermediate polarity directions supports this interpretation. Continuous thermomagnetic curves show that the remanence is carried in most cases by magnetite or low-Ti titanomagnetite due to oxi-exsolution of original titanomagnetite during initial cooling. This most probably indicates a thermoremanent origin of characteristic remanent magnetisation. Moreover, unblocking temperature spectra and relatively high MDF values point to small pseudo-single domain low-Ti titanomagnetite as responsible for remanent magnetisation. Some trace of titanomaghemite were observed in a few units, but the remanence was fairly stable. Single-component, linear magnetisation was detected in most cases.

If the palaeomagnetic directions obtained can be considered to be of primary origin, and since normal**,** reversed and intermediate polarities were recognised, we may attempt to establish a preliminary magnetic stratigraphy for the Geor-

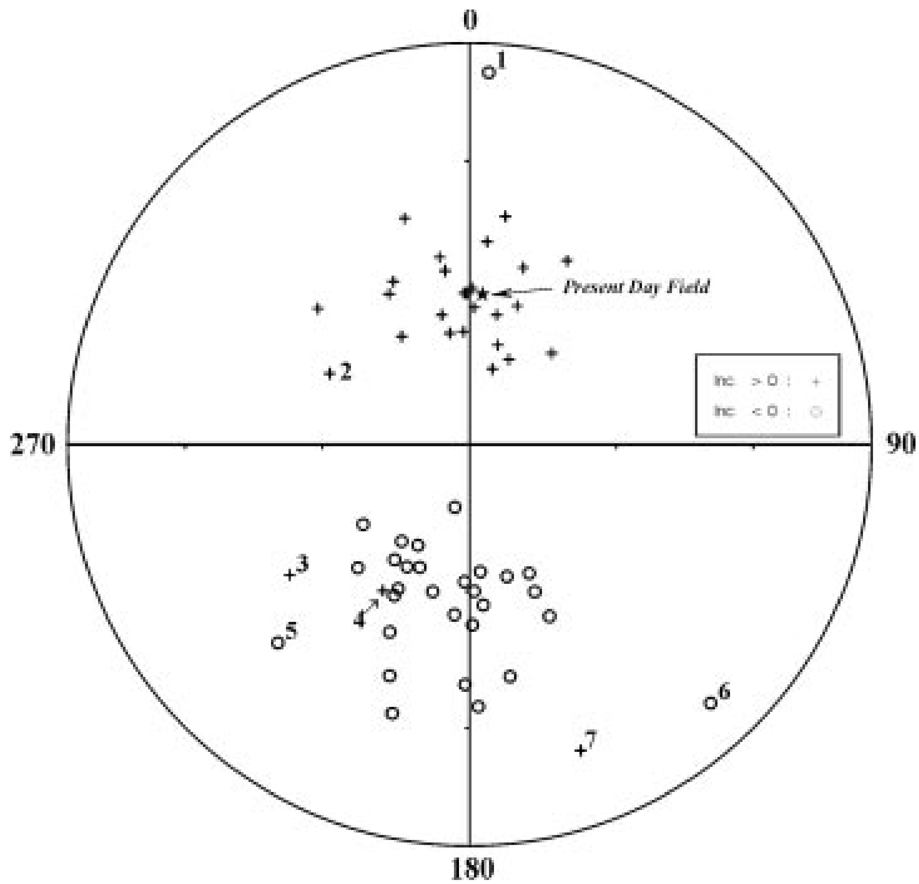

Fig. 3. Equal-area projections of unit mean palaeodirections from Georgian Plio-Quaternary units (see text and Table 1). Units with palaeodirections deviating from the mean are: (1) Satxe-1; (2) Bertakana-1; (3) Sagamo-2; (4) Zurtaketi-4; (5) Satxe-2; (6) Bertakana-3; (7) Diliska-1.

gian volcanic provinces (Figure 4). We attempted to build a composite section. In several cases, field observations allow matching of adjacent sections. Note that, due to detrital remanence acquisition and conservation problems (Dunlop and Özdemir, 1997), the intermediate directions from the lacustrine sedimentary units Zurtaketi-4 and Diliska-1 (Table 1 and Figure 4) may have no geomagnetic significance. In the case of Zurtaketi-4, the sedimentary layer is interbedded between lava flows of normal and reversed polarity. The intermediate polarity of this layer may thus be considered to be significant. The available K-Ar data come from earlier Russian studies (Rubinshtein *et al.,* 1972, Maissuradze *et al.*, 1980, Aslanian *et al.*, 1982 and Sologashvili, 1986); they were recomputed with the more recent decay constants by Dalrymple (1992). Two reverse polarity units dated as 0.31 My and 0.43 My were detected in the Brunhes geomagnetic chron (Figure 4). Possibly these units may correspond to the Levantine (Biwa2) event or to the Emperor geomagnetic event (Champion *et al.,* 1988). However, no intermediate directions related to these events were found. Five consecutive lava flows from the Kumurdo site (Table 1 and Figure 4), dated at 1.105 My, yield normal polarity magnetisations. They may correspond probably to the radiometrically dated Cobb Mountain event (Singer *et al.,* 1999). The Olduvai event seems to be present in several sites of the Djavakheti region, as suggested by normal polarity flows at the Apnia site, dated at 1.69 My (Figure 4). The lower units of the radiometrically dated Satxe, Trialeti and Sarfisgele sites seem to correspond to the end of the Matuyama chron. If so, an intermediate palaeodirection found in the Sagamo section might correspond to the Gauss-Matuyama transition. Another transitional flow which overlies the reverse-polarity Satxe flows dated at 2.29 My, probably corresponds to the Matuyama-Reunion boundary, which has been recently dated at around 2.07 My (Harland *et al.,* 1989; Cande and Kent 1992; Van Velzen, personal communication).

These results only represent a preliminary reconnaissance magnetostratigraphy of the Georgian volcanic provinces. The studied rocks a good magnetic and palaeomagnetic

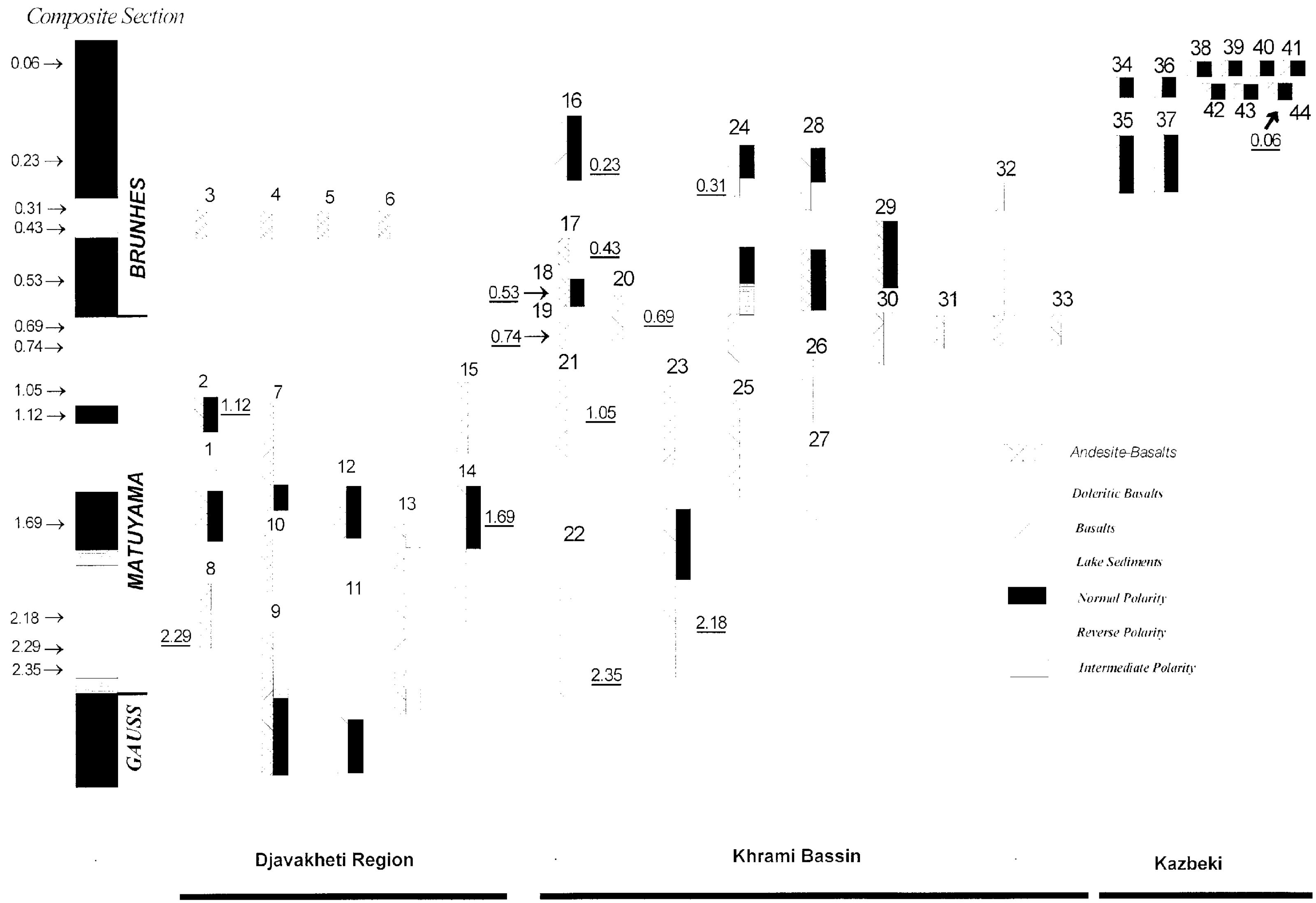

Fig. 4. Suggested magnetostratigraphy of the Georgia volcanic provinces. The underlined numbers refer to the K-Ar ages (table 1) are underlined. *Djavakheti Region:* 1. Diliska, 2. Kumurdo, 3. Aspindza, 4. Khertvissi, 5. Saro, 6. Mtkvari, 7. Korxi, 8. Satxe, 9. Sagamo, 10. Murjebi, 11. Spasovka, 12. Akhalkalaki, 13. Bertakana, 14. Apnia, 15. Varevani. *Khrami Bassin:* 16. Avranlo, 17. Gomareti, 18. Dmanissi, 19. Kakliani, 20. Disveli, 21. Dachbashi, 22. Trialeti, 23. Sarfisgele, 24. Zurtaketi, 25. Samchvilde, 26. Chvidsakdara, 27. Tsalka, 28. Orozmani. 29. Machavera, 30. Bedeni, 31. Araxlo, 32. Axa, 33. Arnala. *Kazbeki:* 34. Bidara, 35. Okrokana, 36. Tkarcheti, 37. Mnadoni, 38. Gudauri, 39. Kvecheti, 40. Kazbeki, 41. Kumliscixe, 42. Mleta, 43. Devdoraki, 44. Chkeri. Dashed lines indicate the middle part of some sequences that could not be sampled due to lack of accessibility.

stability, and appear to be suitable for future more detailed palaeomagnetic and magnetostratigraphic studies.

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