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Cenozoic Volcanism of the Caucasian Mobile Belt in Georgia, its Geological-Petrological Peculiarities and Geodynamic Conditions

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Abstract: The Caucasian mobile belt is situated in the area of Late Cenozoic collision of the large Afro-Arabian and Eurasian lithospheric plates. Extensive volcanic activity in the Georgian part of the Caucasian mobile belt took place during the Late Miocene–Holocene. Five volcanic regions have been identified in Georgia; each of them reveals in a greater or lesser degree similarity of tectonic and magmatic processes. Volcanic products are represented by basaltic, doleritic, andesitic basaltic, andesitic dacitic, rhyolitic lavas and their pyroclastics with andesites and dacites prevailing. Using petrochemical and geochemical data the volcanics can be divided into two main rock groups: calc-alkaline and subalkaline series. The marker petrogeochemical series is presented by the medium- to high-K calc-alkaline volcanics. Relative to the heavy elements (HFSE) Y, Nb they are enriched in some large ion lithophile elements (LILE) Rb, Sr, Ba and light rare earth elements (REE) La, Ce. This confirms the leading role of fractional crystallization in forming the volcanics of the study area. These volcanics have the characteristics of pre-collision subduction (increased LILE content and high La/Nb ratios) geodynamic regimes. Volcanic rocks derived from sources displaying different tectonic environments show close petrogeochemical resemblance, indicating the similarity of the melting substrates of magmatic chambers. The findings also allow us to give priority to the magma generation conditions, to its periodical renewal and depths of inception in comparison with the geodynamical factors. Isotopic data ($^{87}Sr/^{86}Sr$) have confirmed that the subduction-enriched lithospheric mantle material was more important than that of the continental crust components. Sr isotopic ratios do not show marked dependence on the values of the petrochemical composition of the enclosing rocks and on the time of their formation.

Key Words: geodynamics, collision, volcanism, subalkaline, calc-alkaline, late Cenozoic

Kafkas Dağ Kuşağı'nın Gürcistan Kesiminde Tersiyer Volkanizmasının Jeolojik-Petrolojik Özellikleri ve Jeodinamik Ortamı

Özet: Kafkas Dağ Kuşağı Afrika-Arabistan ile Avrasya levhalarının çarpışma bölgesinde yer alır. Bu bölgenin Gürcistan kesiminde yaygın volkanik faaliyet Geç Miyosen–Holosen zaman aralığında meydana gelmiştir. Gürcistan'da ortak tektonik ve magmatik özellikler gösteren beş volkanik bölge tanımlanmıştır. Bu bölgelerde volkanizma bazaltik, andezitik, dasitik, riyolitik lavlar ve onların piroklastik eşdeğerleri ile temsil edilir; en yaygın volkanik kayalar andezit ve dasitlerdir. Jeokimyasal verilere göre volkanik kayalar iki grup tarafından temsil edilir: kalk-alkalen ve subalkalen. En yaygın volkanik seri orta-yüksek potasyum içerikli kalk-alkalen seridir. Bu serideki volkanik kayalar ağır elementlere göre (HFSE, Y, Nb) büyük iyon çaplı litofil elementler (LILE, Rb, Sr, Ba) ve hafif nadir toprak elementler (La, Ce) tarafından zenginleşmiştir. Bu durum bu volkanik kayaların oluşumunda fraksiyonel kristallenmenin önemine işaret eder. Jeokimyasal olarak bu volkanik kayalar çarpışma öncesi dalma-batma ortamının özelliklerini taşır (yüksek miktarda iyon litofil (LILE) elementler ve yüksek La/Nb oranı). Diğer farklı tektonik ortamlarda oluşan volkanik kayalar da ortak petrokimyasal özellikler sunar; bu durum bölgede magma haznesinin altında benzer bir temelin varlığına işaret eder. İzotopik veriler ($^{87}Sr/^{86}Sr$) magma oluşumunda dalma-batma olayları ile zenginleşmiş litosferik mantonun, kıtasal kabuk bileşeninden daha önemli olduğunu göstermektedir. Sr izotop oranları volkanik kayanın bileşimine ve yaşına göre önemli değişiklik göstermez.

Anahtar Sözcükler: jeodinamik, çarpışma, volkanizma, subalkalin, kalk-alkalen, geç Tersiyer

Introduction

The Georgian part of the Caucasian mobile belt is one of the best examples of continental collision volcanism related to the plate boundary zones (between the Eurasian and Afro-Arabian plates). The Late Cenozoic (Miocene to Quaternary) volcanic products have been studied by a large number of authors (Skhirtladze 1958; Milanovski & Koronovski 1973; Dzotsenidze 1972; Popov *et al.* 1987; Tutberidze 1990, 2001, 2004). The volcanic association of the Georgian part of the Caucasian mobile belt has many petrological and geochemical similarities to post-collisional (Miocene to Quaternary) calc-alkaline volcanics in neighbouring areas – Turkey, Azerbaijan, Armenia and Iran (Karapetian 1963; Innocenti *et al.* 1982; Yılmaz 1990; Imamverdiev & Mamedov 1996; Keskin *et al.* 1998; Temel *et al.* 1998; Yılmaz *et al.* 1998; Elburg *et al.* 2002; Alpaslan *et al.* 2004; Aydın *et al.* 2008; Ekici *et al.* 2009; Dilek *et al.* 2010; Kaygusuz *et al.* 2011).

There are many predominantly monogenic and polygenetic central type volcanoes forming eruption centres in Georgia. Often arranged linearly and spatially, they are connected with the intersections of faults of different orientations. The region is characterized by five volcanic cycles: Late Miocene–Early Pliocene, Late Pliocene–Early Pleistocene, Middle Pleistocene, Late Pleistocene and Holocene. The eruption products are represented by lavas and their pyroclastic equivalents. Volcanic activity results in the formation of the calc-alkaline (predominantly) and subalkaline series. The calc-alkaline series was formed under the subhorizontal continental collisional compression geodynamical regime, although subalkaline volcanism is connected with local tear-type rift-forming structures (Koronovski & Demiha 2000; Tutberidze 2001, 2004).

The main objective of the paper is to present a systematic compositional classification of the rock association, based on the existing geochemical and petrological data, to consider the composition of the initial magmatic melt and the factor of crystallization differentiation in the process of magma evolution, and to evaluate the role of crustal components and lithospheric mantle sources in the formation of the volcanic rocks.

Analytical Methods

In order to investigate the petrographic and petrogeochemical characteristics of the volcanics, samples were collected from the Georgian part of the Caucasian mobile belt. Their structure was studied using a polarizing microscope. Major element analyses were conducted in the petrochemical analytical laboratory at the Department of Geology of Tbilisi State University; in the central complex analytical laboratory at the Geological Department of Georgia (Tbilisi) and in the analytical laboratory of the Institute of the Caucasian Mineral Resources (Tbilisi). Results of chemical analyses are shown in Table 1.

Li, Rb were determined by the method of Flame Photometric Analyses, Ba, Sr – by the method roentgeno-spectral analyses, Ni, Co, Cr, V, Cu, Pb, Zn, Zr – through quantitative spectral analyses, La, Ce, Sm, Eu, Tb, Yb, Lu, Hf, Ta, V, Th – through instrumental neutron-activation analyses, and Nb, Y – by the method of roentgeno-radiometric analyses. These analyses were conducted in the physico-chemical analytical methods laboratory of the Bronitsky analytical centre at the Institute of Mineralogy, Geochemistry and Crystallochemistry of Rare Elements of the Russian Academy of Sciences (Moscow). Sr isotope analyses were carried out at the Institute of Geology of the Russian Academy of Sciences (Moscow) using the mass-spectrometer MAT-260 (determination accuracy is about 0.0001%). The age differentiation of the volcanic rocks is based on geomorphological, floral and faunal determination, palaeomagnetic and tephrochronologic methods. K-Ar isotope analyses were conducted using the mass-spectrometer MI-1201, IG laboratory of isotopic geochemistry and geochronology at the Institute of Geology Ore Deposits, Petrography, Mineralogy and Geochemistry of the Russian Academy of Sciences (Moscow, Chernishev *et al.* 1999).

Geological Setting

The Caucasian mobile belt is situated in continental collision zone between the Afro-Arabian and Eurasian lithospheric plates. This region constitutes one of the most important structural elements in the Alpine-Himalayan mountain belt. In the study area,

Table 1. Whole-rock major (wt%) and trace element analyses of representative samples from the Cenozoic volcanics of the Georgian part of the Caucasian mobile belt.

Volcanic Region Sample №	SGH 1195	SGH 111	SGH 1220	SGH 1216	SGH 1213	SGH 1595	SGH 123	SGH 1491	SGH 96	SGH 392	CG 1576	CG 29	SGH 1516	SGH 316	SGH 168	SGH 427	SGH 504
Age	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	◆	◆	◆	◆	◆
Major Elements (wt %)																	
SiO_2	48.25	60.4	64.65	66.3	68.36	73.44	63.68	67.2	75.0	71.5	47.9	55.90	51.82	55.96	56.99	58.91	64.82
TiO_2	1.13	0.32	0.3	0.4	0.42	0.18	0.5	0.45	0.21	0.23	1.81	1.34	1.08	1.20	0.7	0.58	0.82
Al_2O_3	14.69	16.66	16.32	14.79	15.3	13.77	16.35	17.86	13.14	14.62	15.6	16.70	16.3	15.69	15.83	16.16	15.89
Fe_2O_3	7.05	5.23	2.43	2.67	2.64	1.12	3.72	2.38	1.3	0.74	4.27	7.1	2.96	7.28	2.04	6.63	2.8
FeO	2.87	0.5	1.5	1.2	0.5	0.13	0.27	0.42		1.02	5.44		6.33	0.44	5.58	0.54	1.44
MnO	0.14	0.07	0.07	0.14	0.01	0.12	0.06	0.06	0.06	0.11	0.17	0.20	0.12	0.13	0.18	0.14	0.07
MgO	7.92	1.6	1.67	1.2	0.4	0.36	2.11	1.32	0.40	0.24	6.9	3.9	6.15	4.46	5.47	3.53	1.7
CaO	9.82	5.48	5.11	5.5	4.5	1.11	5.53	3.65	1.4	1.94	9.52	7.4	9.21	7.98	7.22	6.24	4.76
Na_2O	4.4	4.5	4.6	5	4	4.78	4.5	2.6	4.1	4.5	4.2	4.1	3.83	3.89	3.6	3.88	3.8
K_2O	1.8	2.8	2.1	2	1.7	3.65	2.1	2.88	4.1	4.1	2	2.7	1.35	1.82	1.3	2.19	2.7
P_2O_5	0.59	0.58	0.2	0.25	0.22	0.07	0.22	0	0.05	0.08	0.37	0.62	0.41	0.62	0.27	0.38	0.25
Trace Elements (ppm)																	
Ba	350	710	480	310	360	320	470	500	700	760	1100	933	200	140	160	240	220
Sr	650	740	560	230	320	80	540	430	89	290	1200	1469	290	230	220	250	190
Ni	170	14	25	20	36	7	14	20	7	5	33	29	100	30	38	34	23
Co	160	8	11	5	8	3	7	10	0.6	3	14	25.5	25	11	17	16	6
Cr	40	12	40	42	46	17	46	60	5	11	47	97	160	32	64	40	27
V	160	50	130	54	76	5	43	120	6.5	17	120	110	180	84	94	13	67
Cu	65	36	80	31	58	7	24	38	9	5	35	13	28	24	24	24	28
Pb	30	28	31	34	100	55	19	42	24	24	15	23	53	20	26	15	27
Zn	130	230	90	70	100	30	60	90	50	30	100	93	150	90	110	80	80
Zr	170	240	140	150	130	110	170	180	70	320	150	210	140	180	170	190	140
Li	9.8	6.4	8.4	14	12	11	14	11	36	29	48	18	8.6	8.5	11	7.2	15
Rb	28	44	50	61	55	83	28	49	125	95	67	63	0	33	22	37	70
Ni/Co	1.06	1.75	2.27	4	4.5	2.33	2	2	11.67	1.67	2.36	1.14	4.00	2.73	2.24	2.13	3.83
Ba/Sr	0.54	0.96	0.857	1.35	1.13	4	0.87	1.16	7.87	2.62	0.92	0.64	0.69	0.61	0.73	0.96	1.16
K/Na	0.41	0.62	0.46	0.40	0.43	0.76	0.47	1.11	1	0.91	0.48	0.66	0.35	0.47	0.36	0.56	0.71

Table 1. Continued.

Volcanic Region Sample №	SGH 1241	SGH 1583	CPLC 1476	CPLC 1461	CPLC 1471	CG 1488	CG 1789	Kaz 1804	Kaz 1354	Kaz 1341	KeH 1670	KeH 1674	KeH 1645	SGH 1284	SGH 1565	SGH 1509	SGH 1583
Age	◆	◆	◆	◆	◆	◆	◆	■	■	■	■	■	■	●	●	●	●
Major Elements (wt %)																	
SiO_2	67.62	66.02	60.9	62.67	63.45	50.24	46.6	59.20	66.98	50.12	62.04	65.24	67.96	51.3	60.1	64.1	66.02
TiO_2	0.82	0.35	0.4	0.38	0.47	1.26	1.84	0.98	0.06	1.15	0.31	0.83	0.47	0.82	0.92	0.31	0.35
Al_2O_3	14.62	12.62	16.55	17.54	15.85	17.54	15.3	17.30	16.15	16.38	17.48	15.93	16.01	16.15	17	16.19	12.62
Fe_2O_3	0.9	1.74	1.25	4.13	0.85	2.56	3	1.92	1.79	3.39	0.39	1.06	2.37	2.56	1.22	2.26	1.74
FeO	2.94	3.07	5.2	1.22	3.95	5.11	6.84	2.24	1.62	5.65	4.33	2.65	0.46	7.46	3.9	3	3.07
MnO	0.07	0.1	0.17	0.09	0.1	0.15	0.19	0.14	0.11	0.08	0.14	0.07	0.04	0.48	0.17	0.05	0.1
MgO	1.21	2.64	2.55	2.81	2.5	8.13	9.3	4.10	4.11	9.18	3.96	2.16	2.3	7.39	3.2	2.16	2.64
CaO	3.32	6.87	6.25	5.95	5.7	7.56	10.23	5.30	1.72	7.08	4.62	4.62	3.92	8.73	6.5	6.04	6.87
Na_2O	4.5	3.86	3.7	2.6	3.5	3.75	3.3	4.20	4.05	3.08	3.69	3.89	3.26	4	3.2	3.52	3.86
K_2O	3.2	3.32	2.1	1.89	2.1	1.79	1.61	1.70	2.28	2.71	1.75	2.75	2.32	0.9	1.7	1.49	3.32
P_2O_5	0.18	0.33	0.6	0.24	0.6	0.71	0.19	0.37	0	0.01	0.57	0.57	0.4	0.28	0.28	0.12	0.33
Trace Elements (ppm)																	
Ba	420	220	500	410	280	510	450	480	300	300	850	270	520	320	280	230	220
Sr	140	240	500	600	220	1000	280	210	230	270	650	390	480	500	340	340	240
Ni	19	17	13	22	18	92	28	88	14	96	14	60	35	100	22	20	17
Co	8	6	10	10	11	28	7	14	7	18	9	18	19	29	11	8	6
Cr	35	36	28	50	47	74	50	130	80	70	14	95	20	130	53	70	36
V	110	56	86	100	100	210	58	100	44	90	60	130	78	180	150	96	56
Cu	34	31	27	30	35	92	26	31	24	56	50	52	50	54	60	45	31
Pb	47	56	62	19	24	38	19	31	31	28	17	21	15	23	33	32	56
Zn	100	70	100	90	70	130	50	70	70	80	90	70	130	130	150	71	70
Zr	220	180	210	180	170	180	150	130	170	230	130	160	180	120	210	180	180
Li	22	14	8.6	32	12	9.4	41	14	35	24	11	37	11	6.8	14	15	14
Rb	83	71	30	37	37	25	43	47	67	92	56	67	29	0	35	40	71
Ni/Co	2.38	2.83	1.30	2.20	1.64	3.29	4.00	6.29	2.00	5.33	1.56	3.33	1.84	3.45	2.00	2.50	2.83
Ba/Sr	3.00	0.92	1.00	0.68	1.27	0.51	1.61	2.29	1.30	1.11	1.31	0.69	1.08	0.64	0.82	0.68	0.92
K/Na	0.71	0.86	0.57	0.73	0.60	0.48	0.49	0.40	0.56	0.88	0.47	0.71	0.71	0.23	0.53	0.42	0.86

Table 1. Continued.

Volcanic Region Sample № Age	Kaz 1388 ●	Kaz 1594 ●	Kaz 1331 ●	Kaz 1302 ●	Kaz 1429 ●	Kaz 1417 ●	KeH 1628 ●	KeH 1656 ●	KeH 1657 ●	KeH 1653 ●	KeH 1723 ●	Kaz 1798 Δ	Kaz 1410 Δ	Kaz 1379 Δ	Kaz 1650 Δ	KeH 1658 Δ	KeH 1659 Δ
Major Elements (wt %)																	
SiO_2	63.33	66.88	64.55	67.27	57.68	62.38	65.35	57.81	63.16	67.22	71.85	59.8	63.1	60.84	64.4	63.38	62.98
TiO_2	0.6	0.12	0.41	0.41	0.55	0.6	0.38	0.86	0.73	0.37	0.15	0.76	0.85	0.5	0.63	0.56	0.5
Al_2O_3	15.81	15.94	15.81	15.98	14.72	17.38	15.47	16.38	15.24	15.64	14.96	16	17.8	16.5	17.15	15.84	15.3
Fe_2O_3	2.132	3.01	1.51	0.82	2.57	3.91	3.94	2.76	2.81	1.1	0.34	3.73	2.41	2.67	2.37	2.79	1.14
FeO	3.08	0.18	3.08	3.01	3.37	0.9	0.28	3.29	3.52	2.59	0.56	1.6	2.61	2.72	0.89	1.19	3.38
MnO	0.14	0.07	0.14	0.18	0.14	0.01	0.07	0.07	0.12	0.07	0.07	0.1	0.71	0.14	0.08	0.14	0.14
MgO	2.75	3.99	2.29	1.46	6.25	3.51	2.45	5.67	1.94	1.99	0.38	4.6	2.4	5.17	2.95	3.52	4.05
CaO	5.07	2.54	4.43	3.46	7.09	5.15	4.91	7.68	4.9	4.37	2.87	5.92	5	6.68	4.48	5.54	5.43
Na_2O	4.3	4.2	4.4	4.3	4.1	4.52	4	4.80	4.38	4.6	4.6	3.6	4	3.6	3.61	3.9	3.9
K_2O	2	1.6	2	2.6	2.8	1.97	1.8	1.40	2.18	1.6	3	2.4	1.9	2.6	2.83	1.8	1.8
P_2O_5	0.28	0	0.16	0.15	0.25	0.01	0.28	0.31	0.49	0.13	0.09	0.03	0.15	0.16	0.32	0.2	0.19
Trace Elements (ppm)																	
Ba	460	270	350	320	410	120	420	440	180	200	390	270	370	270	290	290	280
Sr	360	360	260	240	430	160	490	680	180	410	280	330	360	280	200	350	370
Ni	60	18	20	16	89	18	34	66	21	20	25	45	44	44	24	56	46
Co	11	6	7	7	13	9	15	22	9	6	10	11	9	14	13	17	16
Cr	100	53	50	37	200	37	65	65	41	52	47	170	82	160	54	120	130
V	100	36	41	40	100	38	100	200	40	41	62	100	92	88	50	110	130
Cu	20	14	44	18	19	22	57	70	30	40	40	13	24	14	25	60	37
Pb	20	21	34	35	20	44	20	19	39	40	50	24	35	33	28	20	22
Zn	50	30	90	70	60	50	80	100	100	100	100	70	80	70	70	100	90
Zr	170	180	170	120	200	260	180	170	150	200	140	110	160	120	140	110	130
Li	14	23	41	51	24	30	22	36	27	32	66	37	33	31	45	33	31
Rb	56	56	77	77	46	55	54	42	60	72	72	61	49	58	71	54	58
Ni/Co	5.45	3.00	2.86	2.29	6.85	2.00	2.27	3.00	2.33	3.33	2.50	4.09	4.89	3.14	1.85	3.29	2.88
Ba/Sr	1.28	0.75	1.35	1.33	0.95	0.75	0.86	0.65	1.00	0.49	1.39	0.82	1.03	0.96	1.45	0.83	0.76
K/Na	0.47	0.38	0.45	0.60	0.68	0.44	0.45	0.29	0.50	0.35	0.65	0.67	0.48	0.72	0.78	0.46	0.46

Symbols: volcanics: 1▲– Late Miocene–Early Pliocene, 2◆– Late Pliocene–Early Pleistocene, 3■– Middle Pleistocene, 4●– Late Pleistocene, 5Δ– Holocene.

intense tectonic and seismic movements and large-scale continental magmatism occurred during the last 11 Ma of the Late Cenozoic. Cenozoic volcanic activity in the region lasted from the Late Miocene to the Holocene. Volcanism occupies a wide area and is manifested in different structural-morphological units (SMU) of Georgia. These are: I Fold (fold-nappe) system of the Greater Caucasus (Kavkasioni); II Transcaucasian intermontane area and III Fold (fold thrust) system of the Lesser Caucasus (Antikavkasioni) (Gamkrelidze 2000). Hence five volcanic regions are defined: (1) South Georgian highland (SGH.-III SMU), (2) Central part of the Lesser Caucasus folded system (CPLC, III SMU), (3) Central Georgia (CG,II SMU); (4) Kazbegi (Kaz. I SMU) and (5) Keli highlands (KeH. I SMU) (Figure 1).

Each of the volcanic regions has a definite degree of autonomy in the development of tectonic and magmatic processes (Skhirtladze 1958; Tutberidze 2004).

Volcanic Region of the South Georgian Highland

The Volcanic region of the South Georgian Highland occurs in the northen zone of Armenia and the Eastern Anatolian volcanic upland. The study area is characterized by three volcanic and volcano-sedimentary sequences: Late Miocene–Early Pliocene, Late Pliocene–Early Pleistocene and Late Pleistocene (Milanovski *et al.* 1973; Skhirtladze 1958; Tutberidze 2004).

In the Late Miocene–Early Pliocene, volcanism began with explosive activity and ended with eruptions that mainly produced lava flows. Powerful volcanic action occurred in the Arsiani range where a pyroclastic-effusive complex – the 'Goderdzi suite' was formed. This suite is divided into lower and upper parts based on their lithological characters (Skhirtladze 1958; Tutberidze 2004). The lower part consists completely of pyroclastic rocks (crystalline, vitroclastic and mixed tuffs) of andesitic and dacitic composition. The upper part consists of calc-alkaline lava flows compositionally ranging from basalt to rhyolite, with prevailing andesites and dacites.

Volcanics of this age group are widespread on the Erusheti uplands. Here, rocks analogous to the 'Goderdzi suite' are also represented by pyroclastic and lava sub-suites with the lava flows dominant. The lava flows include calc-alkaline andesites, dacites and rhyolites, perlites and obsidians, and, in lesser quantities basaltic, basaltic-andesitic lavas and their pyroclastics. Their eruption centres are in Turkey (Skhirtladze 1958; Tutberidze 2004).

Late Miocene–Early Pliocene volcanic activity is comparatively scarce in the Javakheti uplands in the eastern part of the South Georgian Highland, but the study area comprises rocks of this stage, with 'Goderdzi suite' lavas dominant. The eruptions of these rocks took place along the approximately N–S-trending Samsari fault, forming a set of polygenetic and monogenetic volcanic centres; the latter commonest. The biggest stratovolcanoes of the Javakheti uplands are Didi Abuli (3350 m) and Didi Samsari (3305 m). Their eruption products are mainly calc-alkaline andesites, dacites, rhyolites and rhyolitic dacites, with subordinate obsidians, perlites and marecanites.

The Late Miocene–Early Pliocene age of the volcanic rocks was determined using floral and faunal remnants (Uznadze 1963), by tephrochronological data (Skhirtladze 1964) and K-Ar data (10–11 Ma: Gabunia & Rubinshtein 1977; 9.4–9.8 Ma: Aslanian *et al.* 1982).

In the Late Pliocene–Early Pleistocene stage, in the volcanic highlands of southern Georgia the character and location of volcanism abruptly changed: it became confined to the Javakheti upland.

The initial stage of magmatic development was connected with faults and occurred as an immense eruption of non-differentiated basaltic melt, with very powerful lava streams of dolerite-basaltic plateau effusives and very protracted gorge-type lava streams.

In the next pulse of this stage, fault-related volcanic eruptions were replaced by central-type eruptions, mainly producing basaltic andesitic, and andesitic lavas and their pyroclastic equivalents together with minor dacites. More acid members of differentiation are not characteristic. The eruption centres form major stratovolcanoes (Emlikli 3050 m, South Dalidag 2930 m) and many polygenetic and monogenetic extinct volcanoes, dated at 1.9–2.9 Ma (Vekua 1961; Ferring *et al.* 1996; Gabunia *et al.* 2000).

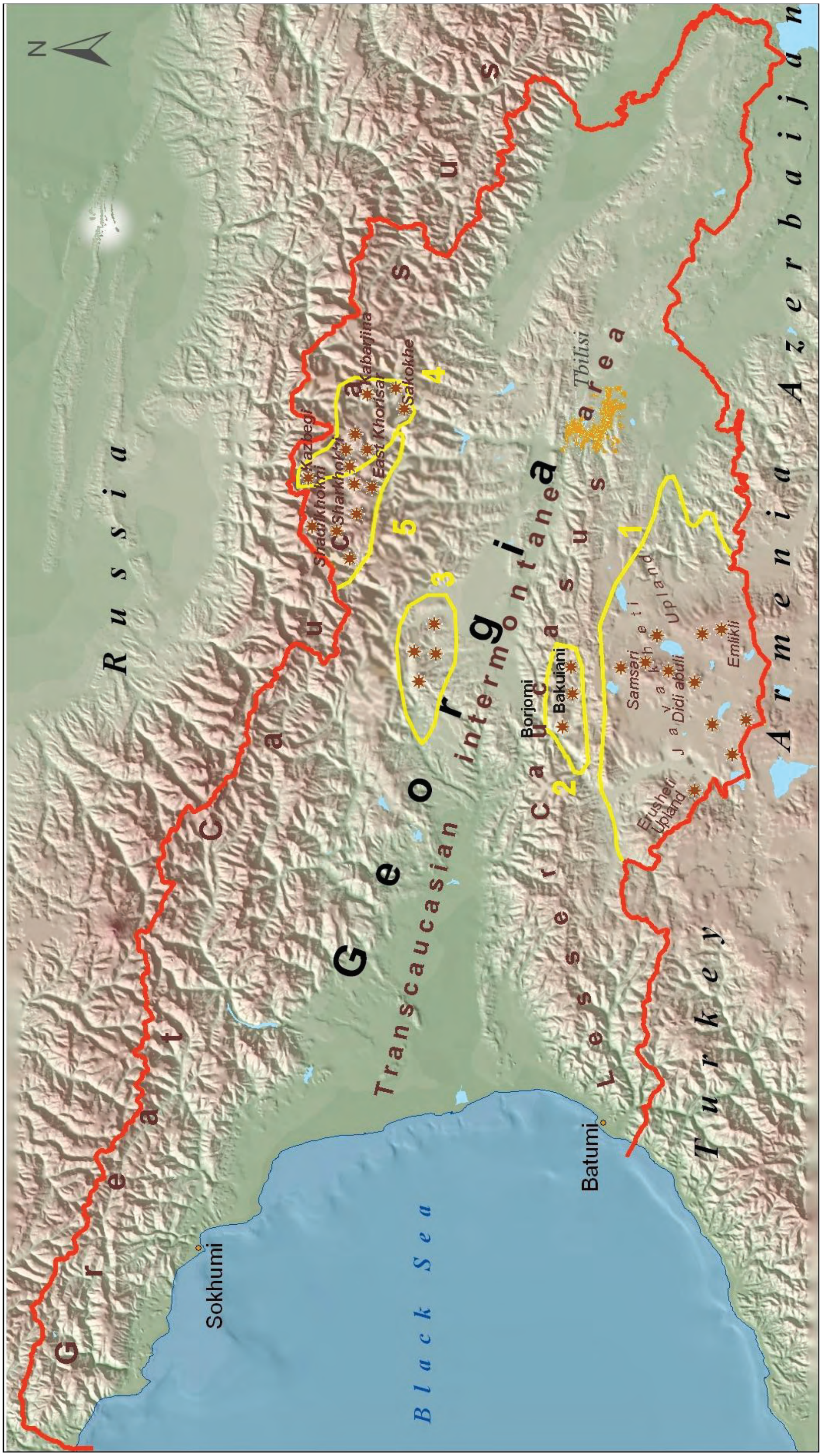

Figure 1. Cenozoic volcanic areas in the Georgian part of the Caucasian mobile belt. Volcanic areas: 1– South Georgian highland, 2– Central part of the Lesser Caucasus folded system, 3– Central Georgia, 4– Kazbegi and 5– Keli highland; ✶– volcanic centres.

The Late Pleistocene stage is the latest volcanic stage in the South Georgian Highland, and is confined to the Javakheti upland. Volcanism is characterized by andesitic and doleritic lavas and associated, subordinate pyroclastic rocks.

The Volcanic Region of the Central Part of the Lesser Caucasus Folded System

This region is not distinguished in the scale of manifestation of Cenozoic volcanism. Volcanic activity, encompassing the volcanic regions of Borjomi and Bakuriani, is restricted to the central part of this zone and occurred during the Late Pliocene–Early Pleistocene stage. The volcanic products include andesitic, minor basaltic and basaltic-andesite lavas and associated pyroclastics. The erupted magmatic products formed valley-type lava flows.

Volcanic Region of Central Georgia

In this region two phases of volcanic activity are distinguished: an earlier one during the Late Miocene–Early Pliocene and the later one in the Late Pliocene–Early Pleistocene. In the first phase volcanic products ranging from basalts to minor basaltic andesites were formed, mostly comprising lava flows, with minor pyroclastic rocks. In the second phase only basaltic lavas and minor pyroclastic material were erupted.

The Kazbegi Volcanic Region

Located in the axial zone of the major anticlinorium of the Greater Caucasus at the junction of the eastern and central segments of the Greater Caucasus Main Range, the Kazbegi volcanic region contains two volcanic areas: the Kazbegi volcanic area, and the central part of the Greater Caucasus Main dividing ridge. Four main phases of volcanic activity have been identified in this region: Early Pleistocene, Middle Pleistocene, Late Pleistocene and Holocene.

Early Pleistocene Stage – In the Kazbegi volcanic area this stage is characterized by relatively low-level volcanic activity, consisting mainly of andesite lavas and minor pyroclastics. Dacitic rocks are also present in lesser amounts. Volcanic lava streams descended from the Kazbegi (Mkinvartsveri, 5033 m) stratovolcanic centre. The andesites are dated at 455,000±40 a (Chernishev *et al.* 1999).

Middle Pleistocene Stage – The Kazbegi stratovolcano became incomparably more active. The first impulse of this stage of volcanic activity began with explosive eruptions and production of minor pyroclastic material. The following impulse produced great volumes of andesitic lavas, which form the valley-type system of flows. The volcanic rocks consist mainly of andesites and their pyroclastic equivalents, with minor dacites and basaltic-andesites. The age of the andesites ranges from 235,000±40 to 185,000±30 a (Chernishev *et al.* 1999).

The volcanic products of this stage are widespread across the volcanic area of the central part of the Greater Caucasus main watershed. They have a wide range of chemical composition, being represented by andesitic and dacitic lavas and their pyroclastic equivalents with minor basaltic and basaltic-andesite lavas and their pyroclastics. Initial products of the Kabarjina stratovolcano are characterized by emissions of significant volumes of lava flows, lahars, dacitic tuffs and tuffites: the dacites are dated at 225,000–295,000 a.

Dacites of the subvolcanic complex of Kabarjina are younger, being dated at 225,000±40 a. In the study area basaltic andesitic lavas (from Sakokhe volcano) were dated at 185,000±30 a and andesites (from East Khorisar volcano) were dated at 135,000±25 a (Chernishev *et al.* 1999).

Late Pleistocene Stage – Volcanic rocks of this age in the Kazbeki volcanic area are scarce and are represented only by andesites, dated at 50,000±20 a.

In the Holocene stage substantial volcanic eruptions only took place in the Kazbegi volcanic area. The volcanoes mostly produced andesitic lavas with minor pyroclastic rocks, dated by radiocarbon at 6,000 a (Janelidze 1975; Burchuladze *et al.* 1976).

The Volcanic Region of the Keli Highland

The area studied covers the Erman-Akhubati and Keli plateaus, where three major phases of volcanic activity have been identified: Middle Pleistocene, Late Pleistocene and Holocene. The volcanic products consist mostly of andesitic and dacitic lavas and pyroclastic deposits, with minor rhyolitic and rhyodacitic lavas and their pyroclastic equvalents. They show a wide range of chemical compositions.

Middle Pleistocene Stage – The volcanic activity on the Keli Plateau began with several eruptions. During the first impulse a large volume of cordierite andesites and their pyroclastic equivalents was ejected. The final impulse of this stage of volcanism was characterized by strong effusive eruptions, ending with the formation of series of andesitic lava flows. Andesites (from Shadilkhokh volcano) are dated at 215,000±35 a (Chernishev *et al.* 1999). In the volcanic area of the Keli and Erman-Akhubati plateaus Middle Pleistocene volcanics are mainly of dacitic and rhyolitic composition.

Late Pleistocene Stage – The volcanic sequence is built up of andesites and minor basaltic andesites, dacitic and rhyolitic lava flows and pyroclastic deposits. The age of these volcanic rocks (from the Sharkhokh volcano) is from 20,000±15 a to 15,000±15 a (Pleistocene–Holocene boundary; Chernishev *et al.* 1999).

Holocene volcanic and pyroclastic rocks dominate the Erman-Akhubati Plateau. They consist of andesitic with minor dacitic and rhyolitic lava flows and their pyroclastic equivalents. The age of volcanism was determined by a morphological method of stratigraphic studies (Dzotsenidze 1972).

Geochemistry

The results of major (wt%) and trace (ppm) element chemical analyses of representative samples are presented in Table 1.

The volcanic rocks in the region were classified using the classification diagram of Le Bas *et al.* (1986), based on the total alkali (Na_2O+K_2O) vs SiO_2 (TAS) diagram (Figure 2). In this diagram the dashed line dividing the calc-alkaline and subalkaline magma series was taken from Irvine & Baragar (1971).

On the $Na_2O+K_2O–SiO_2$ diagram (TAS) most samples plot in the calc-alkaline field and show a wide compositional spectrum from basalts to rhyolites. A few rocks plot in the field of trachybasalts and trachyandesites (Figure 2).

In the $K_2O–SiO_2$ discrimination diagram (Ewart 1982) volcanic rocks of the Georgian part of the Caucasian mobile belt belong to the medium- to high-K calc-alkaline petrogeochemical series. A few

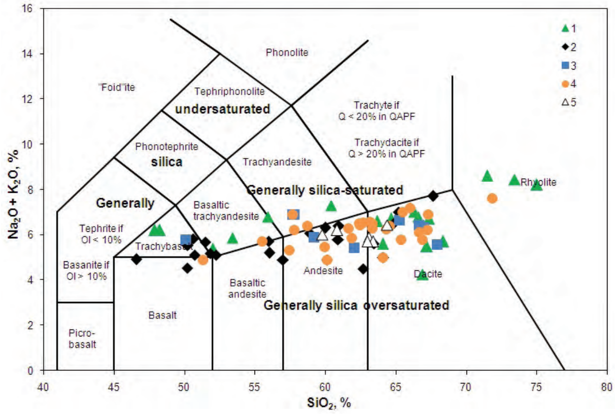

Figure 2. Total alkali-silica diagram (Le Bas *et al.* 1986) for the Cenozoic volcanics of the Georgian part of the Caucasian mobile belt. Dividing line between the alkaline and subalkaline fields is from Irvine & Baragar (1971). Symbols as for Table 1.

basaltic samples plot in the alkaline petrogeochemical area (Figure 3).

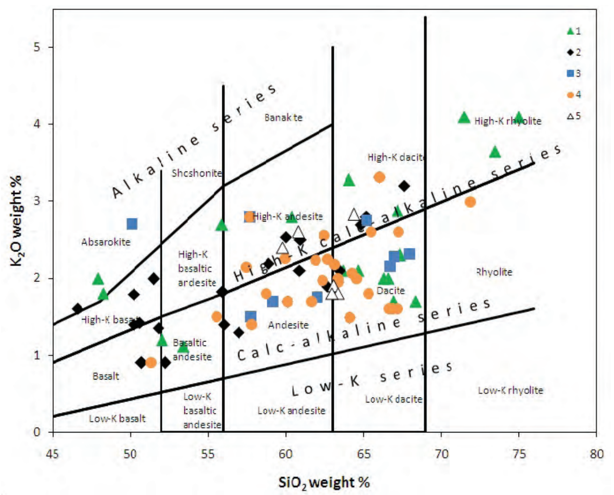

Figure 3. $K_2O–SiO_2$ diagram (Ewart 1982) for the Cenozoic volcanics of the Georgian part of the Caucasian mobile belt. Symbols as for Table 1.

On the total alkali (Na_2O+K_2O)–total FeO–MgO (AFM) diagram proposed by Irvine & Baragar (1971) the calc-alkaline series can be discriminated from the tholeiitic series. In Figure 3 the volcanic rock samples mostly plot in the calc-alkaline field. A few plot in the tholeiitic field (Figure 4).

In the $FeO/MgO–SiO_2$ diagram (Miyashiro 1974) the rocks plot mainly in the calc-alkaline field and

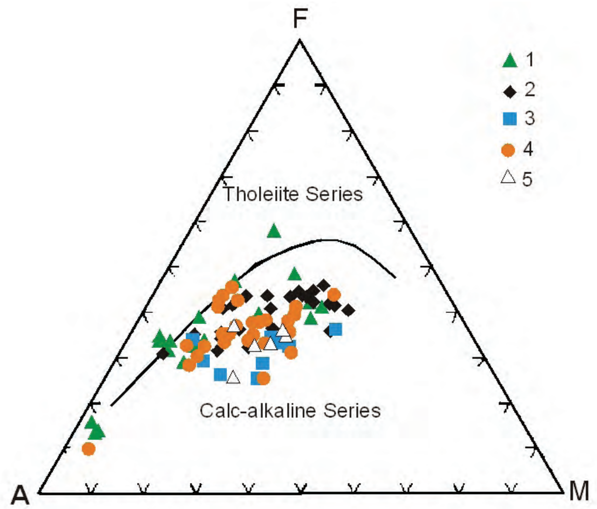

Figure 4. AFM ternary diagram for the Cenozoic volcanics of the Georgian part of the Caucasian mobile belt. Dividing line between the tholeiitic and calc-alkaline dividing curve is from Irvine & Baragar (1971). Symbols as for Table 1.

along the dividing line between the calc-alkaline and tholeiite fields (Figure 5).

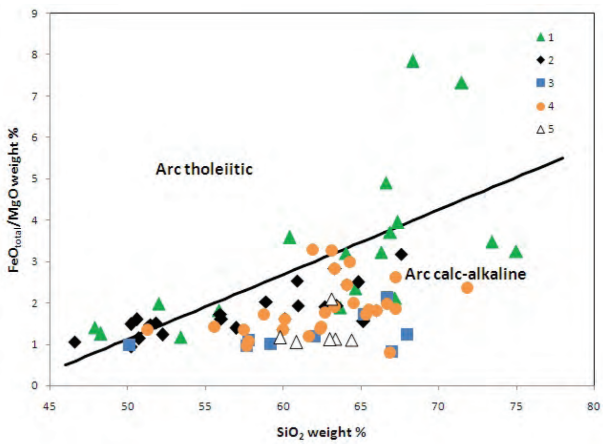

Figure 5. FeO*/MgO–SiO_2diagram (Miyashiro 1974) for the Cenozoic volcanics of the Georgian part of the Caucasian mobile belt. Symbols as for Table 1.

The geochemistry of the late Cenozoic volcanic rocks from the Georgian part of the Caucasian mobile belt indicates that they belong to the medium- to high-K calc-alkaline petrogeochemical series. Volcanics of the region show a wide compositional spectrum from basalts to rhyolites, mainly comprising andesites, dacites, dolerites and minor basaltic-andesites and rhyolites with SiO_2 contents ranging from 45 to 75 wt% (Table 1). The major oxides such as TiO_2, Al_2O_3, MgO, CaO, FeO and Fe_2O_3 show negative correlation with increasing SiO_2 and positive correlation with K_2O. The table shows that in all samples Na_2O is more abundant than K_2O, as mainly seen in the basic and middle acid rocks (Table 1).

Trace Element Geochemistry

The results of major and trace element analyses of the representative whole rock samples from the Georgian part of the Caucasian mobile belt are given in Table 1.

With increasing SiO_2 there is an increase in most large ion lithophile elements (LILE) such as Ba, Sr, Li, Rb, Th and a decrease in compatible trace elements such as Ni, Co, Cr, V. On chondrite-normalized diagrams (Figure 6) trace element patterns of the Georgian part the Caucasian mobile belt volcanic rocks generaly exhibit a positive correlation between SiO_2 and Ba, Th, Rb, Sr, Th, La, Ce and negative correlations in some high field strength elements such as Nb and Ta.

Some basaltic rocks show characteristic variations in composition with their geographic position. For example, subalkaline basalts from Central Georgia and the Kazbegi region exhibit a positive correlation between K_2O and LILE such as Rb, Ba, La and Ce (Figure 6).

Rare Element Geochemistry

In the studied volcanics the contents of some rare earth elements have been taken from the literature sources (Popov *et al.* 1987) and are given in Table 2. Chondrite-normalized spider diagrams of rare earth elements are shown in Figure 7.

In the volcanic rocks of the Georgian part of the Caucasian mobile belt, the rare earth elements, normalized to chondrite composition, show enrichment in light REE (La to Sm) with respect to heavy REE (Tb to Lu). The volcanic rocks studied have similar K, Rb, Ba, Sr, Ba/La contents to those from subduction zones (Thompson *et al.* 1984;

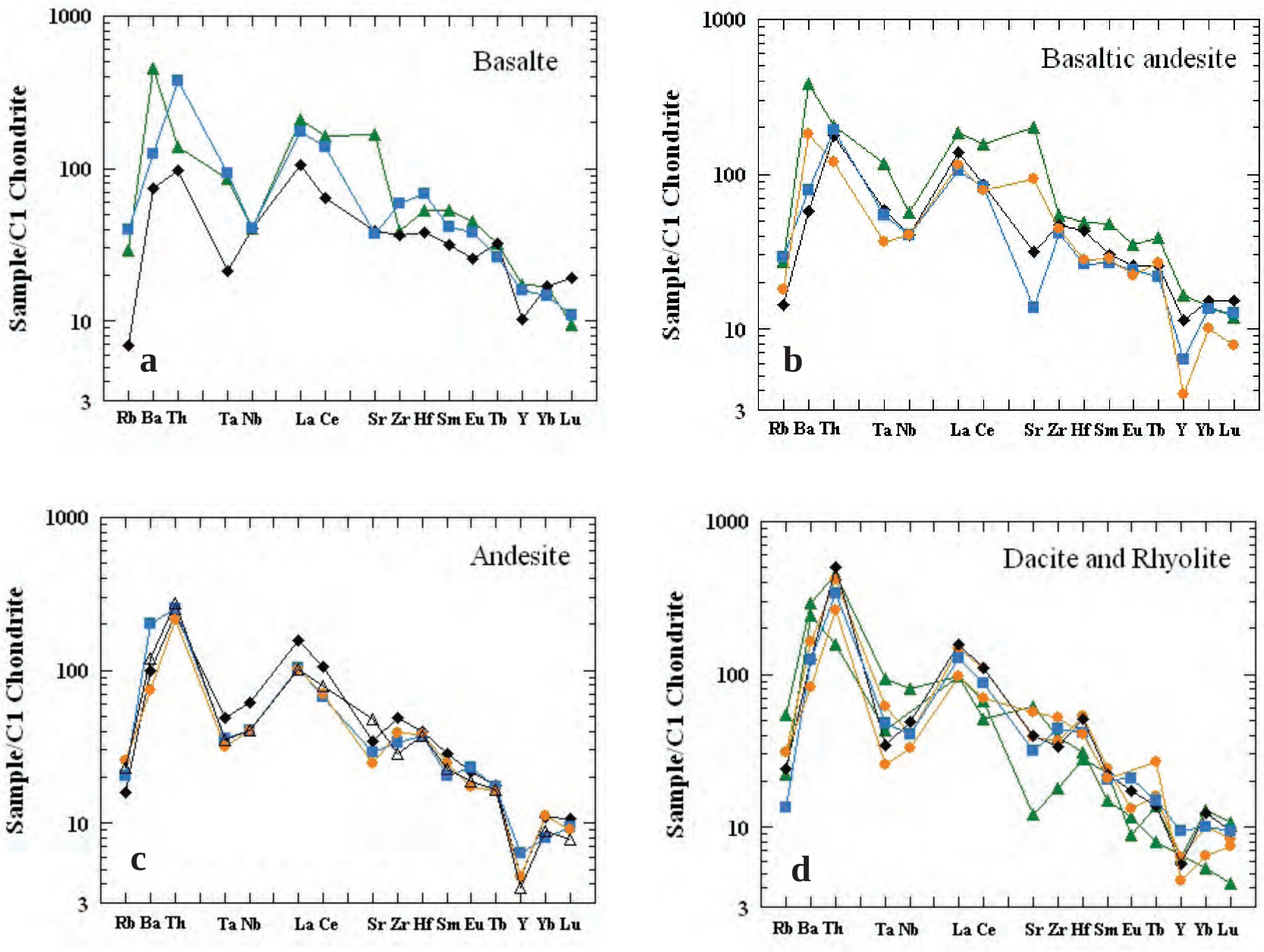

Figure 6. Chondrite-normalized (Sun &McDonough 1989) multi-element patterns for the Cenozoic volcanics of the Georgian part of the Caucasian mobile belt. Symbols as for Table 1.

Elburg *et al.* 2002). The high alkalinity of basalts and high contents of the light spectrum of the rare earth elements (La-Eu) and of lithophile elements (Li, Rb, Sr, Ba, Pb, U, Th), which are correlated, geochemically resemble alkaline basalts of oceanic island arcs and continental rift zones.

High La/Yb ratios are characteristic of basalts from the Kazbegi region and the central area of Georgia (16.40–17.24 Ma), compared to the dolerites and basalts of the volcanic upland of South Georgia (8.62 Ma); the high alkalinity of basalts and high contents of the light rare earth elements (La, Eu) and of lithophile elements (Li, Rb, Sr, Ba, Pb, U, Th), which are correlated with them, geochemically resemble alkaline basalts from oceanic island arcs and continental rift zones.

However, the above-mentioned basalts differ from each other in having low values of the siderophile elements (Ni, Co, Cr, V), thus evincing an affinity with the basalts of island arcs and active continental zones. Basalts of Central Georgia are characterized by the increased Ba/La ratio, similarity to orogenic rocks, and lower Nb/La ratio compared to MORB and intra-plate basalts (Sun & Mcdonough 1989).

Sr Isotope Geochemistry

Results of Sr isotope analyses (Skirtladze *et al.* 1990) of Cenozoic volcanic rocks of the Georgian part of the Caucasus mobile belt are presented in Table 3. All samples show a small range of Sr isotope ratios; volcanics of the investigated region, in spite of their

Table 2. Rare earth element analyses of the Cenozoics volcanics from the Georgian part of the Caucasian mobile belt (Popov *et al.* 1987) .

Rocks	Basaltic			Basaltic andesite				Andesite				Dacite				Rhyolite	
Age	6 ▲	7 ◆	5 ■	29 ▲	30 ◆	27 ■	28 ●	40 ◆	37 ■	52 ●	51 Δ	71 ▲	70 ◆	68 ■	69 ●	96 ▲	89 ●
Elements																	
La	50.0	25	41	44.0	33	25	27	37	24.5	24	24	23	37.5	30	23	23	35
Ce	100	39	84	96.5	52.5		48	64	41	43	48	31	68	54	43	41	67
Sm	8.1	4.8	6.4	7.3	4.6	4.1	4.4	4.35	3.1	3.8	3.5	2.3	3.4	3.1	3.2	3.5	3.7
Eu	2.60	1.5	2.2	2.05	1.5	1.4	1.3	1.25	1.35	1.0	1.1	0.68	1.0	1.2	1.0	0.51	0.76
Tb	1.20	1.20	0.99	1.45	0.95	0.81	1.00	0.66	0.64	0.61	0.62	0.30	0.51	0.56	0.49	0.55	0.59
Yb	2.9	2.9	2.5	2.4	2.6	2.3	1.7	1.85	1.35	1.9	1.5	0.91	2.1	1.7	1.1	2.2	1.7
Lu	0.24	0.49	0.28	0.30	0.39	0.32	0.20	0.27	0.24	0.23	0.20	0.11	0.24	0.24	0.19	0.27	0.21
Y	27	16	25	26	18	< 10	< 6	< 7	<10	<7	< 6	-	<9	15	< 7	10	< 10
Hf	5.7	4.1	7.3	5.2	4.6	2.8	3.0	4.25	4.0	<4.1	4.0	3.3	5.45	4.4	4.7	3 .0	5.7
Nb	10	<10	<10	14	<10	10	<10	15	<10	< 10	<10	-	12	<10	< 8	2 0	< 10
Ta	1.20	0.30	1.30	1.65	< 0.82	0.76	0.51	0.68	0.50	0.44	0.49	<0.6	<0.48	0.67	0.36	1.30	0.86
U	4.8	<3.0	<3	< 4.2	< 2.8	2.4	< 3.0	<2.0	3.35	< 2.0	2.9	4.6	3.9	<3.6	<3.2	4.3	<3.20
Th	4.0	2.8	11	5.9	5.2	5.6	3.5	6.7	7.35	6.2	7.9	4.5	14.5	9.8	7.6	13.0	12.0
La/Yb	17.24	8.62	16.40	18.33	12.69	10.87	15.88	20.00	18.15	12.63	16.00	25.27	17.86	17.65	20.91	10.45	20.59
Nb/La	0.2	0.4	0.24	0.32	0.30	0.40	0.37	0.41	0.41	0.42	0.42		0.32	0.33	0.35	0.87	0.29
Nb/Y	0.37	0.63	0.40	0.54	0.56	1.00	1.67	2.14	1.00	1.43	1.67		1.33	0.67	1.14	2.00	1.00

Symbols are the same as for Table 1.

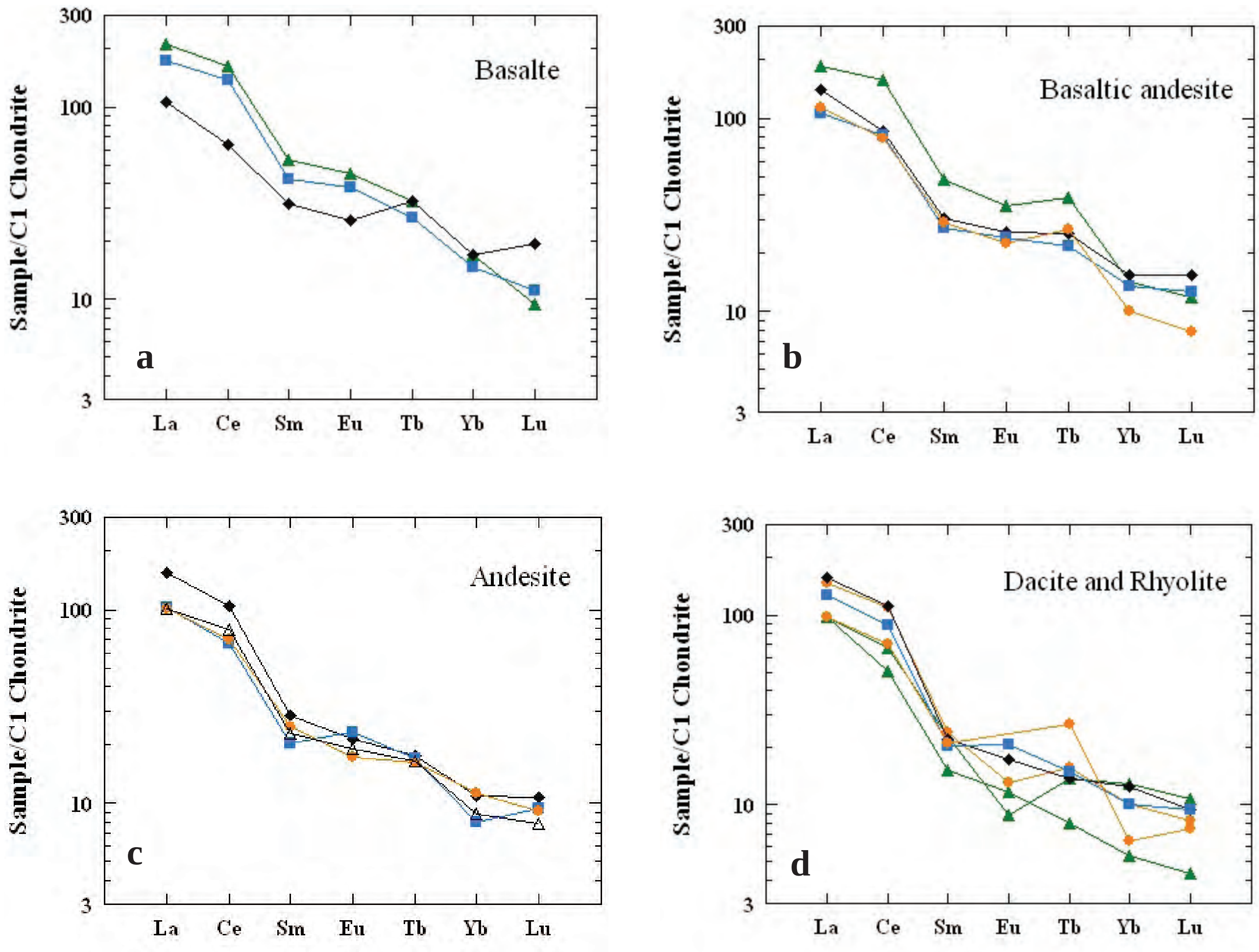

Figure 7. Chondrite- normalized (McDonough & Sun 1995) rare earth element patterns for the Cenozoic volcanics of the Georgian part of the Caucasian mobile belt. Symbols as for Table 1.

different ages, petrographical composition and spatial separation, reveal their genetical relations by their Sr ratios: 0.703920–0.704195 (dolerites); 0.703683–0.704531 (basalts); 0.704107–704305 (basaltic andesites); 0.704373–0.705320 (andesites); 0.704115–0.705460 (dacites); 0.704890 (rhyolites). Some andesites (sample 1354) and dacites (sample1422) from the calc-alkaline rocks of the Kazbegi volkanic zone have higher $^{87}Sr/^{86}Sr$ ratios: 0.70500 (for andesite) and 0.70460 (for dacite) than for calc-alkaline series rocks from other zones (Table 3).

Isotope data ($^{87}Sr/^{86}Sr$) have confirmed that mantle material played a leading role during magma generation. Sr isotopic ratios do not show dependence on the values of the petrochemical composition of the enclosing rocks and on the time of their formation. Sr isotope ratios and the geochemical characteristics of the investigated volcanics show that the parent magma was derived from both the upper lithospheric mantle and lower crust.

Geodynamics

The Cenozoic history of the Caucasus, in particular the Alpine-Himalayan folded belt, is a history of the approach and final collision of the Afro-Arabian and Eurasian lithospheric plates. The collision of the plates followed the closure of the Neo-Tethyan basin through subduction beneath the Eurasian plate.

Table 3. Sr isotope analyses from the Cenozoic volcanics of the Georgian part of the Caucasian Mobile belt (Skirtladze *et al.* 1990)

rocks	sample	$^{87}Sr/^{86}Sr$	volcanic region
dolerite	1181	0.703920	
dolerite	1812	0.704195	
basaltic andesite	104	0.704305	
andesite	556	0.704373	SGH
dacite	954	0.704308	
dacite	1145	0.704162	
dacite	1817	0.704115	
andesite	1469	0.704690	ATFS
basaltic andesite	1783	0.704107	
basalt	1488	0.703683	CG
basaltic andesite	1778	0.704531	
andesite	1630	0.705510	
andesite	1638	0.705320	Kaz.
andesite	1659	0.704770	
rhyolite	1723	0.704890	
andesite	1852	0.704370	
dacite	1354	0.705460	KeH
andesite	1422	0.705000	
dacite	1677	0.704920	

The scientists are at variance about the time of collision between the Afro-Arabian and Eurasian plates and about the final closure of the Neo-Tethyan oceanic basin. It might be in the Jurassic (Adamia *et al.* 1977); Early Miocene (Kazmin *et al.* 1986); Late Miocene (Koçyiğit *et al.* 2001); Late Cretaceous (Alavi 1994); Late Miocene and Oligocene (Jolivet & Fassena 2000); Miocene (Şengör *et al.* 1985; Robertson *et al.* 2007); Middle–Late Miocene (Okay *et al.* 2011) and Pliocene (Lordkipanidze 1980).

Within the limits of the investigated region and across most of the Caucasian mobile belt the Late Miocene tectonic and extensive volcanic activity is closely linked to the approach and final collision of the Afro-Arabian and Eurasian lithospheric plates. In the Late Miocene (10–11 Ma) a strong orogenic movement (Attic orogeny) occurred, causing structural changes in the Caucasus. Strong subaereal volcanic activity and formation of the Caucasus and Achara-Trialeti young mountain systems are connected with this phase. In the Late Miocene (10 Ma ago) the speed of convergence of the plates abruptly increased (3 cm/year) compared to during the interval of 40–10 Ma (1cm/year). The maximum speed of convergence occurred between 60 Ma and 40 Ma (Eocene, 6–7 cm/year) (Zonenshain & Savostin 1979).

Geochemical and Sr isotope data from the Late Cenozoic volcanics of the Georgian part of the Caucasian mobile belt has revealed the heredity of the imprints characteristic of subduction zone magmatism (enrichment with the subduction components – K, Rb, Li, Ba, La, Ce, etc., and high La/Nb). The abundance of calc-alkaline rocks and participation of the subduction components is indicative of the presence of subduction zones (Zonenshain & Savostin 1979; Lordkipanidze 1980; Tutberidze 2004). On the tectonic discrimination diagrams (Yb+Ta-Rb; Pearce *et al.* 1984) most samples plot near the VAG, Syn-COLG and WPG triple junction (Figure 8).

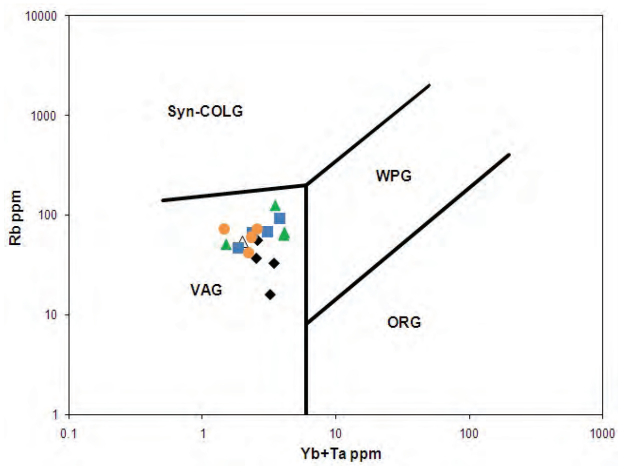

Figure 8. Tectonic discrimination diagram (Pearce *et al.* 1984) for the Cenozoic volcanics of the Georgian part of the Caucasian mobile belt. Symbols as for Table 1.

In the studied volcanics it is very difficult to single out indicators, which would separate collisional from precollisional magmatic products. The question of a genetic link between the composition of volcanic products and the geodynamic regime must be the subject of further detailed study.

Conclusions

- Within the limits of Georgia Late Cenozoic volcanism of the Caucasian mobile belt is present between the convergent hinterlands of the Afro-Arabian and Eurasian collision zone.
- The studied volcanic rocks were formed between 10 Ma and 6 Ma ago. Volcanism took place in the geodynamic conditions of horizontal compression.
- The volcanic eruptives include andesitic basalts, andesites, dacites and minor basalts and rhyolites, both as lavas and their pyroclastic equivalents. The volcanic rocks are divided into two magmatic series: calc-alkaline and sub-alkaline. Medium- and high-K calc-alkaline volcanics are dominant.
- The studied volcanics are enriched in large ion lithophile and light rare earth elements (LILE, LREE) and are depleted in high field strength elements (HFSE).
- The volcanics, in spite of their petrographical and age differences and spatial disconnection, are characterized by low mantle values of Sr isotopic composition. All rock types of the studied area show a limited range of $^{87}Sr/^{86}Sr$ ratios, ranging from 0.703683 to 0.705510.
- The main role in the formation of volcanic series in the investigated region was played by mantle sources. Fractional crystallization of magma was decisive in the process of forming the volcanic series. Continental crust played a insignificant role during the formation of the volcanic rocks in the studied area.
- Geochemical data show that all the Cenozoic volcanics of the Georgian part of the Caucasian mobile belt are characterized by the properties of a pre-collisional geodynamical regime

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