

Major, Volatile, Ore, and Trace Elements in Magmatic Melts in the Earth's Dominant Geodynamic Environments.

I. Mean Concentrations

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Abstract—Data from our original database, which includes more than 2600000 analyses for 75 elements of mineral-hosted melt inclusions and quench glasses in volcanic rocks, are generalized to calculate the mean concentrations of major, volatile, ore, and trace elements in magmatic melts from the following dominant geodynamic environments: (I) spreading zones of oceanic plates (mid-oceanic ridges), (II) environments affected by mantle plumes in oceanic plates (oceanic islands and lava plateaus), (III, IV) environments related to subduction processes (III is zones of arc magmatism on the oceanic crust, and IV is zones of magmatism in active continental margins in which magma-generating processes involve the continental crust), (V) environments of continental rifts and areas with continental hotspots, and (VI) environments of backarc spreading. A histogram of SiO₂ distribution in natural magmatic melts shows a bimodal distribution: one of the maxima falls onto SiO₂ concentrations of 50–52 wt % and the other onto 72–76 wt %. The most widely spread melts contain 62–66 wt % SiO₂. Mean temperatures and pressures are calculated for each of the environments. The normalized multielemental patterns presented for environments I through VI show the ratios of the mean concentrations of elements in magmatic melts of mafic, intermediate, and felsic composition to the concentrations in the primitive mantle. Mean ratios of incompatible, trace, and volatile components (H₂O/Ce, K₂O/Cl, Nb/U, Ba/Rb, Ce/Pb, etc.) are evaluated for the melts of each of the environments. The variations in these ratios are calculated, and it is demonstrated that the ratios of incompatible elements are mostly statistically significantly different in the different environments. The differences are particularly significant between the ratios of the most differently incompatible elements (e.g., Nb/Yb) and some ratios involving volatile components (e.g., K₂O/H₂O).

Keywords: melt inclusions, volatile components, ore and trace elements, geodynamic environments

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We were the first to publish in 2004 a review of mean concentrations of major components and volatile and trace elements in magmatic melts in the Earth's dominant geodynamic environments based on our database, which had been composed starting from 1994 in the system Paradox for Windows. Data in the database are analyses of glass in naturally quenched and experimentally homogenized melt inclusions in minerals and quench glasses in volcanic rocks (Naumov et al., 2004). The total number of analyses in the database was then almost 14000, and the database comprised 190500 determinations of 60 elements. Our next review included 33000 analyses for 73 elements and was published in 2010 (Naumov et al., 2010). The number of measurements in the database amounted to

480000. The further intensification of such studies is well illustrated by data in Table 1.

The total number of the publications was 1936, and the overall number of the objects was 145000, which were analyzed for 75 elements. Nowadays the database comprises more than 2600000 measurements: 1312000 analyses for major components, 225000 analyses for volatiles (H₂O, Cl, F, S, and CO₂), 640000 analyses for ore and trace elements, 415500 analyses for REE, and the database additionally contains 24500 measurements of homogenization temperatures and >7700 measurements of pressures in natural magmatic melts.

Acute interest of many researchers in mineral-hosted inclusions is explained by that these inclusions

Table 1. Number of publications on mineral-hosted melt inclusions and quench glasses in rocks included in our database during various periods of time

Period of time	Number of publications	%	Number of analyses	%
1970–1979	26	1.3	318	0.2
1980–1989	115	6.0	1749	1.2
1990–1999	366	18.9	9113	6.3
2000–2009	603	31.1	27593	19.0
2010–2022	814	42.7	106413	73.3
1970–2022	1936	100.0	145186	100.0

provide likely the most straightforward and reliable means of estimating the composition and physico-chemical parameters of natural magmatic melts. These studies were even more activated after quantitative analytical methods of high spatial resolution were invented: electron, ion, and proton probes; Raman spectroscopy; laser ablation–inductively coupled plasma–mass spectrometry, local IR spectroscopy, etc. Some lately published papers present data even on the isotopic composition of some elements in individual melt inclusions (e.g., Eiler et al., 2007; Bouvier et al., 2008; Le Voyer et al., 2008; Harlou et al., 2009; Layne et al., 2009; Wittenbrink et al., 2009; Anderson et al., 2021; Hartley et al., 2021; Li et al., 2021; Kawaguchi et al., 2022).

Our work was centered on analysis of similarities and differences between the behaviors of elements in

natural magmatic systems and factors that control the most general features of the geochemistry of rocks in the Earth’s dominant geodynamic environments. This analysis was carried out based on evaluation of the mean concentrations of elements in corresponding melts of mafic, intermediate, and felsic composition.

CHARACTERISTICS OF THE EARTH’S DOMINANT GEODYNAMIC ENVIRONMENTS

Herein we distinguish the following geodynamic environments that differ from one another in the parameters of generation and evolution of magmatic melts: (I) spreading environments of oceanic plates (mid-oceanic ridges), (II) environments in which effects of mantle plumes are discernible (on oceanic islands and lava plateaus), (III and IV) environments related to subduction processes (III is environments of arc magmatism, and IV is zones of magmatism on active continental margins in which continental crust is involved in the magma-generating processes), (V) environments of continental rifts and continental hotspots, and (VI) environments of backarc spreading.

Figure 1 presents a histogram of the distribution of SiO₂ concentrations in mineral-hosted homogeneous melt inclusions and in quenched glasses in volcanic rocks from all of the aforementioned geodynamic environments.

The distribution is obviously bimodal, with one of the maxima occurring at SiO₂ = 50–52 wt % and the other at 72–74 wt %. The falls on um SiO₂ concentra-

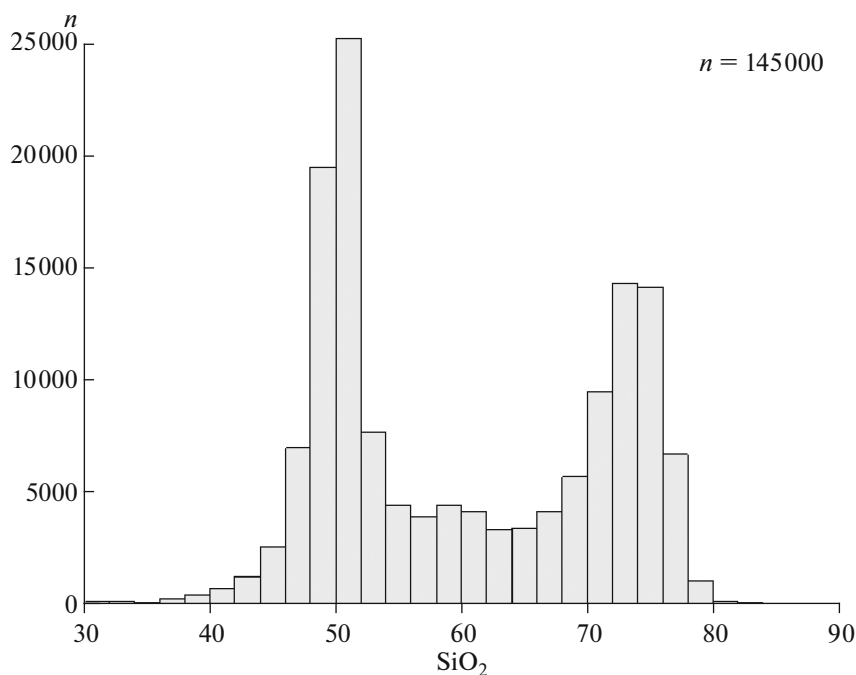


Fig. 1. Histogram showing the distribution of SiO₂ concentrations in magmatic melts from all of the Earth’s principal geodynamic environments: data on mineral-hosted inclusions and quench glasses (*n* is the number of determinations).

tions of 62–64 wt %. We have previously mentioned the bimodal character of naturally occurring magmatic melts, with this conclusion based on 3465 analyses (Naumov et al., 2004), and later confirmed this based on 33000 analyses (Naumov et al., 2010). It seems to be reasonable to conclude that the further amassing of the analytical data will not any significantly modify this conclusion.

The histograms shown in Fig. 2 demonstrate how SiO₂ concentrations are distributed between magmatic melts in the various geodynamic environments (I–VI).

Melts in environment I (mid-oceanic ridges) are mostly of mafic composition. Environment II (oceanic islands) is also dominated by mafic melts, and ultramafic ones are quantitative strongly subordinate. Similar distribution types are characteristic of environments III and IV (island arcs and active continental margins). Intraplate continental environments (V) are characterized by a trimodal SiO₂ distribution. The magmatic melts show broad variations in SiO₂ concentration from 40 to 80 wt %. Data on backarc basins (environment VI) are still relatively sparse (2150 determinations), but they still show the dominance of mafic melts. In general and with regard to this distribution of the SiO₂ concentrations (Figs. 1 and 2), the mean concentrations of major components and volatile, trace, and rare-earth elements were calculated for three types of magmatic melts: mafic and ultramafic ones (SiO₂ = 40–54 wt %), intermediate and low-SiO₂ felsic melts (SiO₂ = 54–66 wt %), and felsic ones (SiO₂ > 66 wt %).

For each of the melt types, mean concentrations were calculated separately for each of the geodynamic environments (see above). Our earlier publications (Naumov et al., 2004, 2010, 2016, 2022) demonstrated that it is more reasonable to calculate geometric (but not arithmetic) mean concentrations, because the distributions of many elements are closer to lognormal ones. Lognormal distributions of trace elements and, hence, more adequate usage of geometric means have also been stressed by other researchers (Gale et al., 2013). Geometric mean concentrations were calculated at 95% confidence level. Determinations that did not meet this criterion were rejected, and the mean values were recalculated. The calculated mean concentrations of major oxides and volatile and trace elements are summarized in Tables 2–5.

How much the mean concentrations of elements have changed when new data were added and the number of the determinations has been significantly increased compared to the earlier ones? To estimate these changes, we compared data on mafic melts from all of the geodynamic environments published in (Naumov et al., 2010) with data on melts from the same environments in Table 2. The difference for major elements was 6.8 rel. %, that for volatile elements (H₂O, Cl, F, S, and CO₂) was 19.2 rel. %, that

for nine trace elements (Li, V, Rb, Sr, Y, Zr, Ba, Th, and U) was 10.7 rel. % and that for REE was 9.4 rel. %.

Figures 3 and 4 show primitive mantle-normalized multielemental patterns for the mean concentrations of elements (Tables 2–4) in magmatic melts from geodynamic environments I–VI.

No such analysis of the distribution of trace elements in melts of different composition from different geodynamic environments extend beyond the scope of this paper. Many related issues have been discussed in papers on the analysis of data on some of these environments (e.g., Kovalenko et al., 2006, 2007, 2009). Herein we would only like to stress some issues commonly emerging when the whole data set on mineral-hosted inclusions and glasses in rocks is analyzed.

(1) The mean compositions of mineral-hosted inclusions and glasses in rocks confirm the presence of characteristic geochemical fingerprints of mafic, intermediate, and felsic melts in each of the environments. First of all, this is the fan-shaped configuration of the normalized patterns of trace elements in mafic and intermediate melts. The greatest differences were found between the melts of environments I and V.

(2) The normalized trace-element patterns of intermediate and mafic melts are generally similar and differ from those of felsic rocks. This may indicate that the sources of intermediate and mafic melts were similar in each environment. It is also reasonable to hypothesize that the leading mechanism generating intermediate melts is the differentiation of mafic (mantle) magmas, whereas the sources and generation mechanisms of felsic magmas were different (derivation from crustal rocks).

(3) A remarkable feature of the patterns, first of all, those of mafic melts, is the very narrow range of the concentrations of the least incompatible elements in the right-hand parts of the patterns (from Tb through Lu). This uniformity indicates that the mantle sources and generation parameters of the magmas were generally similar, because the concentrations and ratios of HREE and other mildly incompatible elements most strongly depend on the generation parameters of the melts, in contrast to those of the most incompatible elements, whose concentrations in mantle sources significantly vary when even small melt and fluid portions are transferred (mantle metasomatism). It should be kept in mind that the relative concentrations of the least incompatible elements are least significantly affected by processes of crustal contamination, changes in the source compositions under the effect of fluid- and melt-assisted material transfer, etc. The small differences in these parts of the patterns are the most illustrative in this context. These components are most significantly enriched in the melts of mid-oceanic ridges, a fact that may indicate that the degrees of melting were the lowest, and the magma generation depths were the shallowest, in this environment.

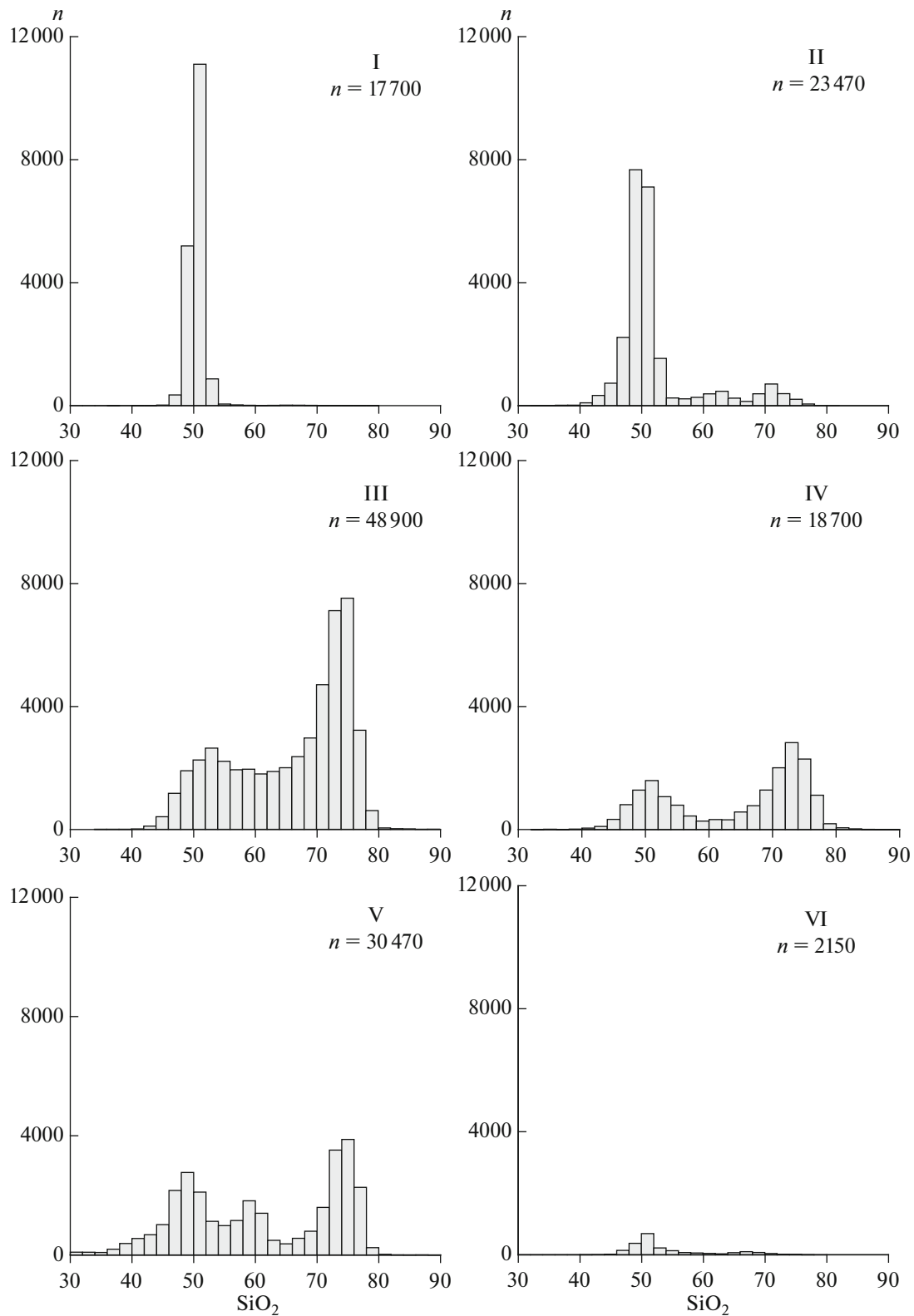


Fig. 2. Histograms showing the distribution of SiO₂ concentrations in natural magmatic melts from all of the Earth's geodynamic environments (I–IV): data on mineral-hosted homogeneous inclusions and quench glasses (*n* is the number of determinations). Environments: (I) mid-oceanic ridges, (II) oceanic islands, (III) island arcs, (IV) active continental margins, (V) continental rifts and hotspot areas, (VI) backarc basins.

Table 2. Mean concentrations of major components and volatile, ore, and trace elements in ultramafic and mafic magmatic melts ($\text{SiO}_2 = 40\text{--}54$ wt %) in the dominant geodynamic environments (I–VI): data on mineral-hosted melt inclusions and quench glasses in volcanic rocks

Component	n	I	n	II	n	III	n	IV	n	V	n	VI
SiO_2 , wt %	17556	50.39	19701	49.79	8148	50.70	5278	50.04	10458	48.66	1464	50.35
		+1.02/–1.00		+1.98/–1.91		+3.05/–2.88		+2.89/–2.74		+3.26/–3.06		+1.83/–1.77
TiO_2 , wt %	14740	1.21	17363	2.13	7828	1.00	5167	1.20	10010	1.58	1254	1.06
		+0.48/–0.34		+0.99/–0.67		+0.64/–0.39		+0.56/–0.38		+1.15/–0.67		+0.51/–0.35
Al_2O_3 , wt %	14509	15.61	17371	13.86	7772	15.45	5175	16.70	10059	14.45	1249	15.64
		+1.51/–1.37		+1.57/–1.41		+2.45/–2.11		+2.38/–2.08		+4.53/–3.45		+2.01/–1.78
FeO , wt %	14590	9.22	17447	11.22	7832	9.47	5177	9.24	10042	9.90	1249	8.63
		+1.59/–1.36		+2.19/–1.83		+2.66/–2.08		+2.76/–2.13		+3.74/–2.72		+2.50/–1.94
MnO , wt %	12632	0.16	15791	0.18	7367	0.17	5019	0.16	9439	0.16	1123	0.16
		+0.05/–0.04		+0.06/–0.05		+0.10/–0.06		+0.09/–0.06		+0.12/–0.07		+0.06/–0.05
MgO , wt %	12965	8.02	17634	7.10	7953	6.15	5168	5.90	10024	6.22	1317	7.12
		+1.50/–1.26		+2.57/–1.89		+3.57/–2.26		+2.94/–1.96		+5.25/–2.84		+2.29/–1.73
CaO , wt %	14535	11.80	17365	11.15	7800	10.34	5171	9.78	10059	10.10	1249	11.56
		+1.19/–1.08		+1.84/–1.58		+2.92/–2.28		+2.30/–1.86		+4.54/–3.13		+1.71/–1.49
Na_2O , wt %	14589	2.57	17355	2.39	7771	2.53	5170	3.15	10069	2.81	1249	2.62
		+0.63/–0.50		+0.62/–0.49		+1.06/–0.75		+1.09/–0.81		+2.16/–1.22		+0.67/–0.53
K_2O , wt %	15185	0.13	17305	0.48	7854	0.74	5170	0.89	10092	1.22	1310	0.55
		+0.19/–0.08		+0.61/–0.27		+0.91/–0.41		+0.73/–0.40		+2.34/–0.80		+0.94/–0.35
P_2O_5 , wt %	13288	0.13	16310	0.27	6823	0.17	4917	0.30	9011	0.46	1147	0.18
		+0.16/–0.07		+0.30/–0.14		+0.28/–0.11		+0.37/–0.16		+0.67/–0.27		+0.15/–0.08
H_2O , wt %	3927	0.25	6127	0.43	2716	1.87	1887	1.82	1993	1.12	458	0.76
		+0.27/–0.13		+0.56/–0.24		+1.67/–0.88		+1.72/–0.88		+2.36/–0.76		+0.76/–0.38
Cl , ppm	5752	90	8446	200	5396	830	4178	730	4659	1220	519	630
		+250/–70		+410/–130		+810/–410		+830/–390		+3810/–920		+1420/–430
F , ppm	2625	170	4694	440	1936	370	1245	680	2221	1400	220	160
		+160/–80		+630/–260		+570/–220		+650/–330		+3940/–1030		+160/–80
S , ppm	5721	1070	10558	750	4713	900	4026	1040	4656	960	380	990
		+390/–290		+1170/–460		+2450/–660		+1590/–630		+1840/–630		+570/–360
CO_2 , ppm	2908	210	5504	270	1103	250	1070	590	1234	990	184	180
		+260/–120		+910/–210		+1260/–210		+1550/–430		+2880/–740		+320/–110
Total		99.65		99.17		98.83		99.48		97.14		98.83
Li , ppm	3744	5.52	2722	4.41	1395	5.78	796	8.34	632	10.21	264	5.65
		+1.84/–1.38		+3.00/–1.78		+4.15/–2.41		+6.82/–3.75		+19.70/–6.72		+2.65/–1.80
Be , ppm	2815	0.52	676	0.87	555	0.61	94	0.68	325	2.43	242	0.58
		+0.31/–0.19		+0.72/–0.40		+0.34/–0.22		+0.70/–0.34		+4.68/–1.60		+0.46/–0.26
B , ppm	1270	1.30	1907	1.28	1019	12.80	464	6.79	420	10.50	22	5.29
		+1.30/–0.45		+1.41/–0.67		+9.47/–5.44		+13.17/–4.48		+32.13/–8.03		+9.63/–3.41
Sc , ppm	5343	38.87	2991	31.33	828	37.14	796	30.56	828	30.48	280	40.41

Table 2. (Contd.)

Component	n	I	n	II	n	III	n	IV	n	V	n	VI
V, ppm	5057	+6.05/-5.24 281	3253	+9.89/-7.52 295	1064	+12.51/-9.36 289	974	+12.32/-8.78 242	898	+16.42/-10.67 271	414	+7.15/-6.07 291
Cr, ppm	5486	+73/-58 278	3459	+102/-76 311	1248	+103/-76 120	495	+77/-59 80	1294	+163/-102 384	597	+95/-71 301
Co, ppm	3852	+186/-111 43.4	1733	+427/-180 42.9	555	+522/-98 33.8	445	+158/-53 35.2	372	+1287/-296 42.8	301	+646/-205 40.4
Ni, ppm	4387	+5.2/-4.6 97.3	2685	+12.5/-9.7 107	827	+11.5/-8.6 41.0	492	+19.9/-12.7 35.9	1041	+34.7/-19.2 233	301	+14.0/-10.4 90.9
Cu, ppm	4380	+55.2/-35.2 75.6	2023	+118/-56 93.5	743	+86.0/-27.8 92.1	432	+87.6/-25.4 125	464	+706/-175 124	382	+78.4/-42.1 100.3
Zn, ppm	4078	+20.8/-16.3 86.8	1745	+60.8/-36.8 108.9	683	+66.6/-38.7 81.5	313	+185/-29 106.9	332	+297/-87 108.5	267	+64.4/-39.2 88.5
Ga, ppm	3548	+28.7/-21.5 17.4	1052	+48.3/-33.5 21.2	260	+29.1/-21.5 16.5	146	+39.8/-29.0 23.4	157	+59.3/-38.3 20.3	161	+35.2/-25.2 16.3
Ge, ppm	1183	+3.0/-2.5 1.54	272	+5.3/-4.2 1.67	59	+4.4/-3.5 1.68	—	+5.9/-4.5 —	23	+7.1/-5.3 1.76	31	+2.4/-2.1 1.77
As, ppm	974	+0.11/-0.11 0.18	207	+0.34/-0.29 0.58	314	+0.27/-0.23 1.12	—	—	20	+0.94/-0.61 1.41	40	+0.12/-0.12 0.24
Se, ppb	783	+0.13/-0.07 310	118	+0.53/-0.27 230	41	+1.70/-0.67 202	—	—	—	+1.82/-0.80 —	39	+0.17/-0.10 368
Br, ppb	98	+119/-86 0.42	—	+191/-104 —	—	+148/-85 —	—	—	20	— 6.56	94	+107/-83 1.04
Rb, ppm	5749	+0.91/-0.29 1.55	5144	+12.10/-4.96 8.42	1266	+14.58/-5.03 7.69	1176	— 13.3	1413	+16.60/-4.70 29.5	579	+3.61/-0.80 3.00
Sr, ppm	6859	+2.76/-0.99 123	6469	+288/-137 260	1845	+369/-164 297	1375	+25.7/-8.7 488	2190	+86.6/-22.0 552	585	+6.40/-2.04 176
Y, ppm	6478	+63.7/-42.0 27.5	6227	+288/-137 24.6	1946	+369/-164 18.8	1327	+342/-201 19.3	1927	+838/-333 25.4	576	+115/-70 24.2
Zr, ppm	6548	+10.1/-7.4 85.9	6317	+10.2/-7.2 132	1914	+9.1/-6.1 57.2	1388	+9.3/-6.3 90.1	2099	+12.6/-8.4 178	569	+12.9/-8.4 68.8
Nb, ppm	6370	+62.8/-36.3 2.83	6697	+145/-69 11.54	1969	+64.0/-30.2 1.30	1324	+67.3/-38.5 4.29	1996	+204/-95 26.76	616	+55.3/-30.6 1.36
Mo, ppm	1994	+4.90/-1.80 0.56	791	+19.00/-7.18 0.95	308	+1.73/-0.74 0.46	158	+7.72/-2.76 0.58	106	+69.80/-19.34 2.31	154	+2.19/-0.84 0.39
Ru, ppb	69	+0.36/-0.22 0.054	—	+0.66/-0.39 —	—	+0.59/-0.26 —	—	+0.43/-0.25 —	—	+2.23/-1.13 —	—	+0.42/-0.20 —
Pd, ppb	89	+0.11/-0.036 0.51	—	— —	—	— —	—	— —	—	— —	—	— —
		+1.14/0.35	—	—	—	—	—	—	—	—	—	—

Table 2. (Contd.)

Component	n	I	n	II	n	III	n	IV	n	V	n	VI
Ag, ppb	1060	23.3 +7.6/-5.7	108	55.0 +38.3/-22.5	75	28.6 +12.7/-8.8	125	51.2 +53.1/-26.1	-	-	40	37.6 +10.3/-8.1
Cd, ppb	1794	126 +58/-40	599	132.1 +74.7/-47.7	92	482 +1340/-355	-	-	-	-	40	138 +24/-21
In, ppb	1392	77.3 +18.8/-15.1	565	99.1 +34.3/-25.5	23	72.8 +15.6/-12.9	-	-	23	96.7 +23.9/-19.2	42	74.7 +22.4/-17.2
Sn, ppm	2150	1.00 0.53/-0.35	937	1.63 +0.82/-0.54	69	0.63 +0.61/-0.31	30	1.48 +13.8/-1.34	37	2.67 +5.89/-1.84	81	0.92 +0.90/-0.46
Sb, ppm	1368	0.03 +0.05/-0.02	580	0.05 +0.03/-0.02	124	0.06 +0.11/-0.04	20	-	-	-	36	0.02 +0.01/-0.01
Te, ppm	75	0.003 +0.03/-0.001	-	-	-	-	-	-	-	-	-	-
I, ppb	41	16.2 +77.0/-13.4	20	56.8 +43.5/-24.6	-	-	-	-	-	-	94	16.0 +80.1/-13.4
Cs, ppm	3494	0.03 0.07/-0.02	1435	0.15 +0.27/-0.10	723	0.31 +0.54/-0.19	392	1.23 +2.69/-0.84	470	1.81 +7.77/-1.47	321	0.12 +1.06/-0.11
Ba, ppm	6285	20.1 +52.7/-14.5	6658	83.7 +190.2/-58.1	2025	165 +277/-103	1392	288 +418/-170	2304	458 +1676/-360	605	47.4 +107/-32.8
La, ppm	7175	3.75 +4.15/-1.97	6482	10.06 +17.06/-6.33	1980	4.82 +7.06/-2.86	1308	10.58 +12.1/-5.64	1972	30.21 +67.00/-20.82	560	4.32 +5.04/-2.32
Ce, ppm	7275	11.0 +9.9/-5.2	6563	25.6 +42.1/-15.9	1834	13.3 +18.6/-7.8	1310	24.8 +26.5/-12.8	1950	61.65 +107.8/-39.22	513	11.68 +12.18/-5.96
Pr, ppm	5093	1.60 +0.94/-0.59	4814	3.42 +3.06/-1.61	1084	1.52 +1.82/-0.83	976	3.30 +2.65/-1.47	839	5.55 +6.73/-3.04	379	1.65 +1.16/-0.68
Nd, ppm	7138	9.48 +5.93/-3.65	6255	17.6 +20.2/-9.4	1770	9.55 +10.05/-4.90	1229	15.0 +11.9/-6.6	1805	30.4 +34.9/-16.3	582	9.41 +5.64/-5.53
Sm, ppm	7312	3.15 +1.52/-1.03	6156	4.74 +3.64/-2.06	1769	2.39 +1.82/-1.03	1197	3.68 +2.39/-1.45	1814	6.85 +5.99/-3.20	600	2.86 +1.37/-0.93
Eu, ppm	6716	1.12 +0.38/-0.28	5718	1.40 +0.80/-0.51	1672	0.98 +0.72/-0.42	1166	1.18 +0.46/-0.33	1612	1.75 +1.28/-0.74	542	1.03 +0.41/-0.29
Gd, ppm	6183	4.13 +1.59/-1.15	5294	5.18 +3.05/-1.92	1395	3.00 +2.14/-1.25	1136	3.77 +1.93/-1.28	1624	6.07 +4.88/-2.70	506	3.68 +1.81/-1.21
Tb, ppm	4125	0.75 +0.24/-0.18	4403	0.86 +0.30/-0.22	953	0.50 +0.37/-0.21	472	0.66 +0.29/-0.20	686	0.92 +0.50/-0.33	365	0.73 +0.27/-0.20
Dy, ppm	6573	4.74 +1.73/-1.27	5998	4.82 +2.15/-1.49	1578	3.18 +1.63/-1.08	1139	3.57 +1.66/-1.13	1663	5.15 +2.67/-1.76	506	4.41 +2.00/-1.38
Ho, ppm	4913	1.02 +0.32/-0.24	4513	0.97 +0.32/-0.24	991	0.68 +0.39/-0.25	487	0.85 +0.25/-0.19	671	1.00 +0.50/-0.33	360	0.96 +0.40/-0.28
Er, ppm	6376	2.93	5407	2.46	1545	1.84	1075	2.01	1584	2.57	514	2.69

Table 2. (Contd.)

Component	<i>n</i>	I	<i>n</i>	II	<i>n</i>	III	<i>n</i>	IV	<i>n</i>	V	<i>n</i>	VI
Tm, ppm	3917	+1.02/-0.76 0.42	4125	+0.99/-0.71 0.34	881	+1.09/-0.68 0.27	367	+0.82/-0.58 0.31	576	+1.17/-0.81 0.34	341	+1.28/-0.87 0.40
Yb, ppm	6840	0.14/-0.10 2.81	6161	+0.13/-0.10 2.11	1695	+0.17/-0.10 1.80	1200	+0.15/-0.10 1.82	1751	+0.17/-0.11 2.04	594	+0.20/-0.13 2.44
Lu, ppm	5783	+1.04/-0.76 0.43	4713	+0.84/-0.60 0.31	1082	+0.93/-0.61 0.28	529	+0.81/-0.56 0.30	901	+0.92/-0.63 0.29	433	+1.36/-0.87 0.40
Hf, ppm	5555	+0.14/-0.11 2.26	4236	+0.13/-0.09 3.26	1376	+0.19/-0.11 1.32	945	+0.17/-0.11 2.13	1161	+0.16/-0.10 4.20	477	+0.19/-0.13 1.49
Ta, ppm	4900	+1.12/-0.75 0.31	3248	+2.09/-1.28 1.00	864	+0.97/-0.56 0.09	827	+1.11/-0.73 0.34	846	+3.10/-1.78 1.47	437	+0.92/-0.57 0.11
W, ppm	2197	+0.48/-0.19 0.05	998	+1.25/-0.56 0.21	210	+0.20/-0.06 0.12	138	+0.54/-0.21 0.22	39	+2.01/-0.85 0.90	92	+0.21/-0.07 0.06
Re, ppb	730	+0.14/-0.04 0.89	41	+0.18/-0.10 0.85	30	+0.24/-0.08 1.32	-	+0.23/-0.11 -	-	+1.11/-0.49 -	126	+0.06/-0.03 1.03
Os, ppb	56	+1.07/-0.48 0.005	-	+0.40/-0.27 -	-	+0.68/-0.45 -	-	-	-	-	-	+0.71/-0.42 -
Ir, ppb	87	+0.007/-0.003 0.022	-	-	-	-	-	-	21	5.20 +14.09/-3.80	-	-
Pt, ppb	272	+0.042/-0.015 0.67	32	+3.87/-2.04 4.30	-	-	61	26.3 +57.8/-18.1	-	-	24	2.75 +2.39/-1.28
Au, ppb	267	+2.10/-0.51 1.52	-	-	50	2.33 +1.75/-1.00	-	-	47	143 +250/-91	33	3.48 +2.34/-1.40
Tl, ppb	1876	+8.57/-1.29 12.7	729	28.1 -	89	44.1 +38.5/-20.6	-	-	21	73.5 +154/-49.7	56	52.2 +118.8/-36.2
Pb, ppm	5190	0.58 +11.7/-6.1	3716	1.04 +22.6/-12.5	1314	1.79 +2.04/-0.95	1155	3.94 +4.00/-1.98	858	3.33 +5.78/-2.11	504	0.96 +1.29/-0.55
Bi, ppm	1335	0.007 +0.005/-0.003	402	0.016 +0.011/-0.006	69	0.018 +0.016/-0.009	-	-	-	-	34	0.013 +0.005/0.004
Th, ppm	5798	0.34 +0.63/-0.22	3849	1.15 +2.02/-0.73	1637	0.60 +0.82/-0.35	1176	1.16 +1.10/-0.57	1208	2.61 +5.78/-1.80	523	0.49 +0.85/-0.31
U, ppm	5670	0.09 +0.15/-0.06	3981	0.42 +0.58/-0.24	1392	0.28 +0.43/-0.17	1083	0.67 +0.66/-0.33	1035	1.03 +2.43/-0.72	463	0.15 +0.29/-0.10
<i>T</i> , °C	2517	1240 +46/-45	3427	1200 +84/-79	1679	1175 +93/-86	1955	1190 +70/-66	4301	1220 +85/-79	34	1190 +65/-62
<i>P</i> , bar	1172	800 +1820/-560	1994	710 +2430/-550	588	1540 +3170/-1030	430	1740 +3510/-1160	582	1890 +4050/-1290	-	-

In Tables 2–5, *n* is the number of determinations. Concentrations of elements were calculated as geometric means for 95% confidence level, numerals beneath mean concentrations are the deviations (plus and minus, respectively, to the mean concentration).

Table 3. Mean concentrations of major components and volatile, ore, and trace elements in intermediate magmatic melts ($\text{SiO}_2 = 54\text{--}66$ wt %) in the dominant geodynamic environments (II–VI): data on mineral-hosted melt inclusions and quench glasses in volcanic rocks

Component	<i>n</i>	II	<i>n</i>	III	<i>n</i>	IV	<i>n</i>	V	<i>n</i>	VI
SiO ₂ , wt %	1844	61.04	11 357	60.10	2731	58.67	6228	58.96	422	57.68
		+3.79/–3.57		+4.35/–4.05		+5.23/–4.80		+2.83/–2.70		+4.23/–3.94
TiO ₂ , wt %	1830	0.90	11 239	0.99	2683	0.92	6149	0.55	392	0.85
		+0.79/–0.42		+0.72/–0.42		+0.70/–0.40		+0.35/–0.21		+0.41/–0.27
Al ₂ O ₃ , wt %	1825	16.76	11 213	15.20	2716	15.93	6202	18.19	393	15.41
		+3.06/–2.59		+1.80/–1.61		+2.10/–1.86		+2.80/–2.43		+3.42/–2.80
FeO, wt %	1826	4.93	11 216	6.98	2702	6.12	6190	3.41	393	7.69
		+4.41/–2.33		+3.61/–2.38		+4.44/–2.57		+1.81/–1.18		+4.52/–2.85
MnO, wt %	1704	0.19	10 734	0.15	2553	0.12	5782	0.14	389	0.15
		+0.15/–0.08		+0.10/–0.06		+0.12/–0.06		+0.13/–0.07		+0.09/–0.06
MgO, wt %	1834	0.82	11 303	2.01	2679	2.34	6143	0.73	407	2.21
		+1.31/–0.50		+1.67/–0.91		+2.72/–1.26		+0.96/–0.41		+1.99/–1.05
CaO, wt %	1821	1.95	11 299	5.44	2689	5.25	6184	2.44	393	6.44
		+2.59/–1.11		+2.74/–1.82		+4.18/–2.33		+1.85/–1.05		+2.40/–1.75
Na ₂ O, wt %	1822	6.04	11 207	3.85	2713	3.89	6196	4.26	393	2.96
		+2.84/–1.93		+1.43/–1.04		+1.11/–0.86		+1.96/–1.34		+1.57/–1.03
K ₂ O, wt %	1826	3.45	11 282	1.42	2712	1.65	6202	7.30	401	0.88
		+3.09/–1.63		+1.47/–0.72		+1.33/–0.74		+3.29/–2.27		+0.52/–0.33
P ₂ O ₅ , wt %	1596	0.20	9867	0.27	2424	0.27	4997	0.14	332	0.21
		+0.59/–0.15		+0.37/–0.16		+0.26/–0.13		+0.40/–0.10		+0.18/–0.10
H ₂ O, wt %	354	1.45	1236	1.42	720	1.60	908	1.68	128	1.51
		+1.43/–0.72		+1.55/–0.74		+2.68/–1.00		+2.36/–0.98		+0.45/–0.35
Cl, ppm	987	1680	8096	980	1289	950	3151	4280	158	2080
		+1830/–880		+930/–480		+1290/–550		+7760/–2760		+1630/–910
F, ppm	714	1390	4392	480	311	920	1054	3000	95	390
		+1790/–780		+990/–320		+3710/–740		+5180/–1900		+990/–280
S, ppm	511	300	7213	110	1047	300	1098	350	80	360
		+500/–190		+530/–90		+960/–230		+560/–210		+1610/–300
CO ₂ , ppm	134	170	403	90	170	460	209	460	26	20
		+810/–140		+320/–70		+1850/–370		+880/–300		+180/–20
Total		98.09		98.00		97.04		98.62		96.28
Li, ppm	425	18.62	1229	12.80	411	17.62	1359	32.20	88	8.74
		+12.56/–7.50		+16.59/–7.23		+15.55/–8.26		+23.74/–13.66		+5.77/–3.48
Be, ppm	93	3.45	335	0.71	158	1.31	90	6.88	80	0.85
		+0.99/–0.77		+0.51/–0.30		+0.79/–0.49		+11.54/–4.31		+0.52/–0.32
B, ppm	196	8.25	689	28.2	276	27.8	119	59.7	–	–
		+5.57/–3.33		+30.2/–14.6		+57.9/–18.8		+279.6/–49.2		–
Sc, ppm	420	7.36	1018	27.27	600	15.61	1405	4.69	95	30.98
		+6.58/–3.47		+15.46/–9.87		+9.83/–6.03		+2.76/–1.74		+12.27/–8.79
V, ppm	377	39.8	1251	192	590	154	1542	82.4	133	265
		+63.5/–24.5		+224/–103		+107/–63		+86.3/–42.1		+217/–119
Cr, ppm	117	19.3	941	40.6	472	44.7	210	94.7	136	16.0
		+258.6/–18.4		+387.4/–36.7		+131.3/–33.4		+1485.8/–89.0		+79.0/–13.3
Co, ppm	176	3.01	645	23.6	448	18.41	683	3.50	118	28.49
		+6.91/–2.10		+16.7/–9.8		+12.04/–7.28		+8.13/–2.45		+14.17/–9.46
Ni, ppm	82	34.5	813	17.8	458	26.8	176	81.6	115	11.9
		+565.0/–32.5		+57.7/–13.6		+47.0/–17.1		+1209/–76.4		+24.6/–8.0
Cu, ppm	83	25.0	860	99.2	406	84.6	117	30.7	159	85.8
		+82.9/–19.2		+116.0/–53.5		+320.4/–67.0		+154.7/–25.6		+167.7/–56.8
Zn, ppm	146	146.5	783	81.2	264	83.3	171	113.0	128	99.7

Table 3. (Contd.)

Component	<i>n</i>	II	<i>n</i>	III	<i>n</i>	IV	<i>n</i>	V	<i>n</i>	VI
Ga, ppm	129	+85.2/−53.9 27.9	338	+27.6/−20.6 49.3	92	+49.0/−30.9 45.2	90	+70.7/−43.5 28.2	52	+45.6/−31.3 20.5
Ge, ppm	42	+9.4/−7.0 1.92	54	+227.0/−40.5 1.72	—	+70.0/−27.4 —	—	+10.2/−7.5 —	—	+7.9/−5.7 —
As, ppm	—	+1.47/−0.83 —	659	+0.30/−0.25 2.77	—	— —	—	— —	34	1.83 +1.24/−0.74
Se, ppb	—	— —	36	+4.28/−1.68 324	—	— —	—	— —	—	— —
Br, ppb	—	— —	—	+1200/−255 —	44	5.75 +7.07/−3.17	—	— —	26	4.16 +3.98/−2.03
Rb, ppm	469	84.2 +105.4/−46.8	1541	22.2 +73.7/−17.1	936	48.7 +124.4/−35.0	1651	313 +140/−97	218	14.3 +11.5/−6.4
Sr, ppm	513	215 +708/−165	1637	229 +273/−125	939	479 +359/−205	1844	516 +818/−316	213	221 +238/−115
Y, ppm	481	38.6 +26.5/−15.7	1465	23.7 +22.1/−11.4	913	19.4 +14.4/−8.3	1648	27.1 +14.6/−9.5	218	24.0 +20.9/−11.2
Zr, ppm	519	602 +452/−258	1503	104 +189/−67	957	138 +107/−60	1755	290 +238/−131	115	78.4 +125.8/−48.3
Nb, ppm	527	120 +145/−66	1460	1.88 +3.91/−1.27	946	6.41 +9.30/−3.79	1650	45.7 +39.1/−21.1	235	1.46 +1.76/−0.80
Mo, ppm	66	3.47 +2.23/−1.36	442	0.92 +1.17/−0.52	112	1.84 +2.08/−0.98	92	3.74 +4.41/−2.03	34	0.46 +0.40/−0.21
Pd, ppb	—	— —	21	17.1 +5.5/−4.2	—	— —	—	— —	—	— —
Ag, ppb	—	— —	89	36.3 +55.9/−22.0	17	162 +2450/−152	—	— —	—	— —
Cd, ppb	26	193 +166/−89	99	416 +938/−278	—	— —	—	— —	—	— —
In, ppb	26	147 +28/−24	—	— —	—	— —	—	— —	21	93.1 +99.6/−48.1
Sn, ppm	39	5.16 +1.28/−1.03	187	1.32 +0.73/−0.47	36	9.80 +502.0/−9.61	23	27.7 +339.0/−25.57	35	0.74 +0.62/−0.34
Sb, ppm	29	0.15 +0.07/−0.05	241	0.38 +0.95/−0.27	—	— —	—	— —	—	— —
I, ppb	—	— —	—	— —	—	— —	—	— —	26	104 +240/−73
Cs, ppm	329	1.07 +1.16/−0.56	850	0.69 +0.90/−0.39	538	2.49 +5.01/−1.66	1523	15.56 +15.91/−7.87	154	0.64 +0.98/−0.39
Ba, ppm	663	721 +1113/−438	1666	371 +1045/−274	968	739 +529/−308	1886	780 +2853/−612	233	150 +205/−87
La, ppm	491	84.20 +64.46/−36.32	1442	6.00 +15.64/−4.33	823	17.20 +14.66/−7.91	1691	65.44 +39.17/−24.50	216	7.15 +7.27/−3.61
Ce, ppm	480	163.88 +87.32/−56.97	1499	20.66 +50.44/−14.66	842	36.96 +33.62/−17.61	1705	126.1 +78.3/−48.3	215	16.85 +15.52/−8.08
Pr, ppm	373	17.46 +6.16/−4.55	1229	1.86 +3.34/−1.20	299	3.88 +2.90/−1.66	1485	13.30 +6.54/−4.38	185	2.34 +1.84/−1.03
Nd, ppm	479	60.16 +21.45/−15.81	1387	14.29 +27.13/−9.36	747	19.32 +11.55/−7.23	1616	47.72 +22.94/−15.49	217	11.70 +10.41/−5.51
Sm, ppm	447	10.51 +5.42/−3.57	1395	2.80 +3.42/−1.54	682	4.23 +2.20/−1.45	1603	8.63 +3.89/−2.68	213	3.38 +2.73/−1.51
Eu, ppm	440	2.87	1360	1.13	689	1.11	1589	1.89	207	1.06

Table 3. (Contd.)

Component	<i>n</i>	II	<i>n</i>	III	<i>n</i>	IV	<i>n</i>	V	<i>n</i>	VI
Gd, ppm	467	+2.13/−1.22 8.46	1309	+0.85/−0.49 3.89	661	+0.38/−0.28 3.81	1548	+0.84/−0.58 6.56	188	+0.65/−0.40 3.61
Tb, ppm	358	+4.88/−3.09 1.18	891	+3.44/−1.83 0.59	248	+1.75/−1.20 0.69	1425	+2.74/−1.93 0.92	168	+2.48/−1.47 0.72
Dy, ppm	473	+0.60/−0.40 7.34	1368	+0.63/−0.30 3.80	651	+0.35/−0.23 3.10	1558	+0.28/−0.21 4.99	181	+0.45/−0.28 4.16
Ho, ppm	361	+4.48/−2.78 1.30	891	+2.86/−1.63 0.84	251	+1.72/−1.11 0.87	1456	+2.09/−1.47 0.97	155	+3.24/−1.82 0.91
Er, ppm	441	+0.53/−0.37 3.90	1318	+0.68/−0.38 2.19	611	+0.41/−0.28 1.55	1528	+0.37/−0.27 2.61	185	+0.54/−0.34 2.55
Tm, ppm	352	+2.62/−1.57 0.55	821	+1.48/−0.88 0.37	168	+0.91/−0.57 0.37	1266	+1.19/−0.82 0.40	123	+1.86/−1.08 0.57
Yb, ppm	489	+0.31/−0.20 3.47	1539	+0.36/−0.18 2.48	708	+0.22/−0.14 1.52	1588	+0.19/−0.13 2.35	197	+0.50/−0.27 2.53
Lu, ppm	416	+2.34/−1.40 0.57	1135	+1.44/−0.91 0.40	285	+0.99/−0.60 0.41	1412	+0.96/−0.68 0.38	184	+2.09/−1.15 0.49
Hf, ppm	410	+0.38/−0.23 12.02	1113	+0.32/−0.18 1.63	354	+0.34/−0.18 3.40	1471	+0.20/−0.13 5.73	185	+0.40/−0.22 1.82
Ta, ppm	381	+5.92/−3.97 8.71	1137	+1.92/−0.88 0.28	346	+2.74/−1.52 0.45	1532	+2.55/−1.76 2.01	151	+1.51/−0.82 0.09
W, ppm	70	+6.89/−3.85 0.88	356	+0.78/−0.21 0.88	59	+0.54/−0.24 0.27	26	+1.72/−0.93 5.21	44	+0.11/−0.05 0.10
Re, ppb	—	+0.36/−0.26 —	—	+1.61/−0.57 —	—	+0.27/−0.14 —	—	+40.95/−4.62 —	27	+0.12/−0.05 1.43
Au, ppb	—	— —	70	— 3.22	—	— —	—	— —	27	+0.67/−0.46 3.01
Tl, ppb	36	— 85.9	200	+3.44/−1.66 237	—	— —	—	— —	45	+6.13/−2.02 109.4
Pb, ppm	412	+32.1/−23.4 8.70	1213	+401/−149 5.28	518	— 10.60	1478	— 48.16	201	+94.9/−50.8 3.13
Bi, ppm	—	+9.46/−4.53 —	132	+11.45/−3.61 0.09	—	+12.36/−5.70 —	—	+19.76/−14.01 —	—	+3.02/−1.54 —
Th, ppm	425	— 10.94	1321	+0.26/−0.060 0.85	714	— 3.76	1597	— 24.51	206	— 0.97
U, ppm	414	+11.25/−5.55 2.95	1400	+4.15/−0.70 0.78	428	+5.29/−2.20 1.27	1572	+19.37/−10.82 7.51	196	+1.41/−0.57 0.47
<i>T</i> , °C	327	+2.68/−1.40 850	762	+1.97/−0.56 1150	321	+1.55/−0.70 1110	1362	+4.34/−2.75 950	—	+0.47/−0.24 —
<i>P</i> , bar	47	+88/−80 360	192	+120/−110 1010	96	+130/−115 900	102	+175/−150 1290	—	— —
		+700/−240		+1420/−590		+2850/−690		+6240/−1070		—

(4) The increase in the normalized concentrations of elements with an increase in their incompatibility generally replicates the distribution character of elements in the mean composition of the continental crust. At the same time, a simple model of the direct contamination of mantle melts (like the depletion of melts in environment I) with crustal material is unacceptable, because the mean concentrations of some incompatible elements in mafic melts are higher than in the continental crust. For example, the Ta and La

concentrations in the continental crust are 0.7 and 20 ppm, respectively (Rudnick and Gao, 2003), whereas those in the melts of environment V are 1.47 and 30.2 ppm, respectively. More promising models seem to be those involving the derivation and migration of small portions of highly enriched melts and/or fluids that modify the compositions of the mantle sources and/or mantle magmas.

(5) Melts related to the environments of continental margins (III and IV) are noted for significant vari-

Table 4. Mean concentrations of major components and volatile, ore, and trace elements in felsic magmatic melts ($\text{SiO}_2 > 66 \text{ wt } \%$) in the dominant geodynamic environments (II–VI): data on mineral-hosted melt inclusions and quench glasses in volcanic rocks

Component	<i>n</i>	II	<i>n</i>	III	<i>n</i>	IV	<i>n</i>	V	<i>n</i>	VI
SiO ₂ , wt %	1889	71.43	29199	73.13	10649	72.89	12927	73.99	261	68.42
		+2.10/–2.04		+3.07/–2.95		+3.19/–3.06		+2.73/–2.64		+2.48/–2.39
TiO ₂ , wt %	1880	0.29	28029	0.26	9878	0.18	10590	0.12	228	0.60
		+0.25/–0.13		+0.43/–0.16		+0.31/–0.11		+0.21/–0.08		+0.14/–0.11
Al ₂ O ₃ , wt %	1696	12.91	28272	12.88	10046	12.89	10852	12.11	228	13.59
		+1.84/–1.61		+1.55/–1.39		+1.60/–1.42		+1.54/–1.37		+1.37/–1.24
FeO, wt %	1705	3.07	28250	1.26	9969	1.12	10779	1.00	228	4.66
		+1.04/–0.78		+0.82/–0.49		+0.92/–0.51		+1.34/–0.57		+1.82/–1.31
MnO, wt %	1461	0.14	25816	0.06	8568	0.06	8776	0.05	227	0.11
		+0.13/–0.07		+0.11/–0.04		+0.10/–0.04		+0.16/–0.04		+0.10/–0.05
MgO, wt %	1643	0.13	27994	0.25	9547	0.17	9891	0.03	229	1.10
		+0.51/–0.10		+0.56/–0.17		+0.43/–0.12		+0.07/–0.02		+0.72/–0.43
CaO, wt %	1885	0.85	28300	1.12	10058	0.95	10684	0.51	228	3.48
		+1.07/–0.47		+0.75/–0.45		+0.97/–0.48		+0.38/–0.22		+1.37/–0.98
Na ₂ O, wt %	1692	4.86	28252	4.01	9893	3.69	10818	3.59	228	3.62
		+1.18/–0.95		+0.93/–0.75		+1.16/–0.88		+1.18/–0.89		+0.99/–0.78
K ₂ O, wt %	1696	3.74	28282	3.18	9951	3.82	10854	4.72	229	1.54
		+2.20/–1.38		+1.27/–0.91		+1.48/–1.06		+0.93/–0.77		+0.34/–0.28
P ₂ O ₅ , wt %	1416	0.03	18061	0.05	7535	0.04	2998	0.02	209	0.22
		+0.06/–0.02		+0.13/–0.04		+0.10/–0.03		+0.05/–0.02		+0.13/–0.08
H ₂ O, wt %	319	2.43	4055	2.36	2967	1.88	3426	2.62	56	1.35
		+2.75/–1.29		+3.18/–1.35		+2.32/–1.04		+2.55/–1.29		+0.62/–0.43
Cl, ppm	1095	1150	20017	1330	3612	1120	4392	1850	85	3760
		+1890/–720		+910/–540		+1420/–630		+2520/–1070		+4180/–1980
F, ppm	736	1480	12278	120	1622	600	3410	3160	30	630
		+3460/–1040		+1580/–110		+1990/–460		+7070/–2190		+360/–230
S, ppm	642	80	14791	60	2100	50	955	150	48	40
		+110/–50		+190/–40		+200/–40		+330/–100		+170/–30
CO ₂ , ppm	29	50	835	100	964	30	1364	150	–	–
		+130/–30		+220/–70		+190/–30		+420/–110		–
Total		99.22		98.72		97.94		99.30		99.13
Li, ppm	619	23.72	2918	35/97	1911	29.01	4905	55.36	–	–
		+17.50/–10.07		+38.87/–18.67		+39.71/–16.76		+6.43/–30.60		–
Be, ppm	114	2.99	792	1.63	644	2.20	1052	9.56	–	–
		+1.64/–1.06		+4.14/–1.17		+1.81/–0.99		+13.90/–5.67		–
B, ppm	303	19.67	2342	33.60	1561	46.18	2761	27.29	–	–
		+3.25/–2.79		+44.67/–19.18		+70.28/–27.87		+44.87/–16.97		–
Sc, ppm	420	8.63	2042	8.35	1031	4.56	2285	4.26	–	–
		+1.88/–1.54		+10.40/–4.63		+3.70/–2.04		+4.43/–2.17		–
V, ppm	376	17.0	1711	6.61	722	5.81	1798	1.42	35	48.4
		+22.1/–9.6		+20.71/–5.01		+16.82/–4.32		+4.45/–1.08		+73.8/–29.2
Cr, ppm	55	3.32	764	2.40	174	4.91	856	2.93	50	4.29
		+22.83/–2.90		+4.59/–1.58		+17.16/–3.81		+5.50/–1.91		+22.58/–3.60
Co, ppm	94	0.74	649	1.61	582	1.22	515	1.08	28	7.19
		+0.57/–0.32		+3.19/–1.07		+1.81/–0.73		+4.61/–0.87		+3.70/–2.44
Ni, ppm	21	1.60	608	1.32	148	4.56	864	1.72	–	–
		+8.71/–1.35		+1.91/–0.78		+9.09/–3.03		+3.61/–1.16		–
Cu, ppm	111	17.2	1509	6.44	1394	21.13	1520	4.48	101	24.9

Table 4. (Contd.)

Component	<i>n</i>	II	<i>n</i>	III	<i>n</i>	IV	<i>n</i>	V	<i>n</i>	VI
Zn, ppm	250	+10.8/-6.6 209.1	1478	+28.26/-5.24 36.04	1258	130.92/-18.20 40.52	3341	+16.41/-3.52 78.20	79	+53.9/-17.0 80.5
Ga, ppm	337	+79.7/-57.7 31.8	607	+39.75/-18.90 16.21	506	+35.31/-18.87 27.88	2845	+94.65/-42.82 25.38	—	+33.7/-23.7 —
Ge, ppm	21	+14.3/-9.8 4.06	73	+5.61/-4.16 2.53	38	+34.88/-15.50 1.71	104	+7.92/-6.03 2.00	—	— —
As, ppm	64	+2.45/-1.53 4.16	1248	+1.22/-0.82 6.84	428	+0.22/-0.20 130.6	392	+0.89/-0.62 6.40	46	— 3.45
Br, ppb	—	+1.58/-1.14 —	24	+11.76/-4.32 11.68	109	+2981/-125.1 2.43	—	+16.24/-4.59 —	—	+1.94/-1.24 —
Rb, ppm	648	— 102.7	3983	+3.31/-2.58 111	3044	+3.16/-1.37 131.8	6376	— 211.9	88	— 22.06
Sr, ppm	472	+34.3/-25.7 5.39	3951	+134/-61 81.8	2668	+153.0/-70.80 102.8	6101	+139.4/-84.1 4.89	87	+10.73/-7.22 264
Y, ppm	476	+42.03/-4.78 76.4	3924	+150.1/-52.9 24.58	2187	+317/-77.6 16.78	6180	+13.10/-3.56 57.60	87	+131/-88 28.45
Zr, ppm	477	+33.4/-23.2 917	3903	+21.23/-11.39 118.4	2400	+17.86/-8.65 122.9	6323	+90.32/-35.17 173.4	87	+13.77/-9.28 107.2
Nb, ppm	475	+1041/-488 139	3901	+104.9/-55.6 8.04	2271	+153.6/-68.3 10.73	6253	+292.6/-108.9 49.59	108	+63.5/-39.9 1.48
Mo, ppm	227	+184/-79 6.04	1265	+11.81/-4.78 1.88	877	+13.13/-5.91 3.00	2848	+84.76/-31.28 5.09	—	+0.78/-0.51 —
Ag, ppb	—	+1.26/-1.04 —	178	+1.94/-0.96 39.7	81	+5.67/-1.96 173.7	236	+3.47/-2.06 119.7	—	— —
Cd, ppb	—	— —	21	+40.6/-20.1 194.0	—	+1714/-157.7 —	57	+212.2/-76.5 135.5	—	— —
In, ppb	—	— —	—	+49.0/-39.1 —	—	— —	57	+30.2/-24.7 103.1	—	— —
Sn, ppm	208	— 9.27	404	— 3.06	726	— 9.83	1282	+29.1/-22.7 8.49	—	— —
Sb, ppm	74	+1.78/-1.49 0.48	396	+9.38/-2.31 3.21	388	+175.0/-9.31 29.62	295	+13.29/-5.18 0.56	—	— —
Cs, ppm	436	+0.20/-0.14 1.38	1925	+32.04/-2.92 3.91	1970	+1098/-28.84 5.40	3248	+0.47/-0.26 7.03	35	— 0.78
Ba, ppm	553	+0.57/-0.40 300	4013	+6.94/-2.50 602	2535	+14.92/-3.97 650	5784	+15.98/-4.88 78.3	109	+0.19/-0.15 330
La, ppm	452	+501/-188 95.09	3885	+687/-321 19.80	1813	+1363/-440 21.76	5226	+467.1/-67.1 64.44	88	+151/-103 10.50
Ce, ppm	465	+71.57/-40.83 201.11	3965	+14.75/-8.45 41.58	1881	+20.73/-10.62 41.03	5943	+77.49/-35.18 106.7	88	+6.64/-4.07 23.87
Pr, ppm	430	+171.1/-92.44 25.07	2579	+27.29/-16.48 4.57	892	+37.85/-19.69 4.48	4399	+154.2/-63.1 13.32	50	+14.02/-8.83 2.94
Nd, ppm	452	+15.79/-9.69 90.58	3124	+3.15/-1.87 18.17	1392	+3.39/-1.93 16.99	5088	+13.29/-6.65 46.46	88	+0.94/-0.71 15.40
Sm, ppm	635	+63.41/-37.30 19.00	3219	+14.41/-8.04 3.83	1475	+13.31/-7.46 3.38	4944	+67.53/-27.52 9.95	87	+7.78/-5.17 4.42
Eu, ppm	622	+6.78/-5.00 3.93	2702	+2.87/-1.64 0.68	1305	+2.59/-1.47 0.60	4498	+13.04/-5.64 0.65	82	+2.17/-1.45 1.14
Gd, ppm	445	+1.72/-1.20 15.11	2661	+0.75/-0.36 3.82	1184	+0.45/-0.26 3.08	4594	+1.22/-0.42 10.81	56	+0.26/-0.21 4.45

Table 4. (Contd.)

Component	<i>n</i>	II	<i>n</i>	III	<i>n</i>	IV	<i>n</i>	V	<i>n</i>	VI
Tb, ppm	426	+4.39/−3.40 2.41	1585	+3.32/−1.78 0.65	833	+2.48/−1.37 0.58	3676	+12.83/−5.87 1.48	50	+1.19/−0.94 0.74
Dy, ppm	452	+0.54/−0.44 14.26	2890	+0.49/−0.28 3.84	1192	+0.52/−0.27 3.07	4558	+1.17/−0.65 11.52	43	+0.21/−0.16 4.99
Ho, ppm	426	+4.39/−3.36 2.77	1615	+3.08/−1.71 0.89	795	+2.65/−1.42 0.68	3647	+14.31/−6.38 1.83	48	+1.16/−0.94 1.06
Er, ppm	443	+0.71/−0.57 7.78	2872	+0.73/−0.40 2.44	1160	+0.41/−0.26 1.85	4499	+1.61/−0.86 7.17	56	+0.24/−0.19 3.09
Tm, ppm	425	+2.28/−1.76 1.09	1552	+1.81/−1.04 0.44	728	+1.45/−0.81 0.31	3525	+7.67/−3.71 1.06	34	+0.94/−0.72 0.48
Yb, ppm	460	+0.32/−0.25 8.96	2937	+0.42/−0.22 2.78	1250	+0.22/−0.13 2.05	4804	+0.84/−0.47 6.45	85	+0.12/−0.10 3.23
Lu, ppm	421	+2.96/−2.08 1.05	1926	+2.05/−1.18 0.53	875	+1.64/−0.91 0.37	3698	+6.59/−3.26 1.03	84	+1.45/−1.00 0.53
Hf, ppm	620	+0.33/−0.25 23.5	2564	+0.42/−0.24 4.05	1090	+0.23/−0.14 3.67	4246	+0.88/−0.47 7.17	87	+0.31/−0.20 3.11
Ta, ppm	437	+12.3/−8.1 9.71	2736	+3.66/−1.92 0.77	1202	+2.28/−1.41 0.74	4406	+5.98/−3.26 3.60	61	+1.58/−1.05 0.10
W, ppm	53	+5.42/−3.48 1.97	807	+1.01/−0.44 1.95	430	+0.93/−0.41 23.00	1525	+3.81/−1.85 3.65	—	+0.04/−0.03 —
Re, ppb	—	+1.61/−0.89 —	—	+4.63/−1.37 —	29	+98.77/−18.66 147.8	—	+4.42/−2.00 —	31	— 1.09
Au, ppb	—	—	—	—	38	+113.0/−64.0 68.43	42	— 2.20	29	+0.93/−0.50 1.32
Tl, ppb	—	—	97	— 418	169	+273.8/−54.74 648	269	+10.36/−1.81 2665	—	+1.21/−0.63 —
Pb, ppm	623	— 9.91	2926	+788/−273 15.12	1862	+288/−199 18.81	5248	+2094/−1173 35.99	109	— 5.58
Bi, ppm	—	+3.39/−2.53 —	324	+9.13/−5.69 1.90	368	+12.94/−7.67 4.48	608	+17.41/−11.73 0.70	—	+1.96/−1.45 —
Th, ppm	648	— 16.04	3304	+5.69/−1.42 10.73	1994	+22.52/−3.74 12.22	5805	+0.88/−0.39 25.36	108	— 1.07
U, ppm	636	+6.38/−4.56 4.68	3267	+14.09/−6.09 2.62	1951	+14.91/−6.71 4.08	5637	+16.56/−10.02 7.59	108	+0.63/−0.39 0.75
<i>T</i> , °C	284	+2.09/−1.44 850	1396	+2.65/−1.32 850	1192	+4.05/−2.03 830	3338	+4.05/−2.64 790	20	+0.33/−0.23 955
<i>P</i> , bar	46	+54/−50 475	892	+90/−80 1170	727	+120/−105 940	479	+80/−70 1550	20	+60/−55 2270
		+340/−200		+1220/−600		+2960/−710		+900/−570		+3140/−1320

ations in the left-hand parts of the patterns, a phenomenon commonly described with reference to geochemical anomalies. A shining example of such anomalies is the widely known negative Ta–Nb anomaly. The nature of this anomaly is still uncertain. A strong decrease in Nb and Ta concentrations in melts could not result from the mixing of magmas from different sources, because the concentration levels of these elements are very low (particularly in melts of environment III, in which Ta and Nb concentrations are lower than in the mafic magmas of mid-oceanic

ridges). Both Nb and Ta were likely retained in the residue in the course of melting. These elements are selectively concentrated in, for example, rutile, but mafic melts in equilibrium with rutile would have been notably enriched in Ti, which is not the case.

(6) Another interesting feature of the mafic melts of environments III and IV is their positive Pb anomaly (high Ce/Pb = 7.41 and 6.29, respectively). The origin of this anomaly is also disputable. Both elements are strongly incompatible when silicate minerals crystallize from melts. The fractionation of Ce and

Table 5. Ratios of elements in mafic magmatic melts ($\text{SiO}_2 = 40\text{--}54$ wt %) in the dominant geodynamic environments (I–VI): data on mineral-hosted melt inclusions and quench glasses in volcanic rocks

Year	<i>n</i>	I	<i>n</i>	II	<i>n</i>	III	<i>n</i>	IV	<i>n</i>	V	<i>n</i>	VI
H₂O/Ce												
2010	649	190	204	130	300	1310	124	950	152	70	63	880
		+80/–50		+130/–60		+3040/–910		+4100/–770		+520/–60		+1000/–470
2022	2522	210	3250	180	739	1460	743	820	714	70	217	550
		+90/–60		+300/–110		+3800/–1050		+1890/–570		+230/–50		+1070/–370
Ce/Pb												
2010	421	23.1	378	25.6	251	6.2	172	7.4	116	32.3	69	14.9
		+8.4/–6.2		+16.8/–10.1		+3.8/–2.3		+6.1/–3.3		+15.5/–7.1		+9.9/–6.0
2022	4833	24.6	3506	28.3	1284	4.8	11244	5.9	839	14.7	463	13.8
		+7.7/–5.9		+10.9/–7.9		+4.1/–2.2		+6.0/–3.0		+22.6/–8.9		+13.6/–6.8
K₂O/H₂O												
2010	1177	0.6	1194	1.0	872	0.4	429	0.7	553	1.9	196	0.3
		+0.4/–0.2		+1.5/–0.6		+0.7/–0.2		+1.9/–0.5		+4.2/–1.3		+0.2/–0.10
2022	3756	0.6	5232	1.0	2651	0.4	1795	0.5	1921	2.0	421	0.3
		+0.4/–0.2		+2.1/–0.7		+0.8/–0.3		+0.7/–0.3		+4.9/–1.4		+0.2/–0.1
K₂O/Cl												
2010	1288	11.7	1855	22.6	1459	7.9	1068	14.5	1219	14.7	142	3.2
		+18.4/–7.1		+26.7/–12.2		+8.3/–4.1		+13.4/–7.0		+24.0/–9.1		+2.3/–1.3
2022	5593	14.3	8364	24.2	5350	7.1	4159	12.6	4578	19.4	478	5.5
		+19.9/–8.3		+27.4/–12.9		+9.4/–4.0		+15.4/–6.9		+30.6/–11.8		+7.6/–3.2
La/Yb												
2010	1028	1.2	1044	2.7	526	2.4	211	6.1	236	13.9	123	1.6
		+1.1/–0.6		+5.1/–1.8		+2.4/–1.2		+10.0/–3.8		+36.0/–10.0		+1.5/–0.8
2022	6754	1.2	6148	3.6	1678	2.1	1200	5.2	1701	12.3	537	1.5
		+1.0/–0.5		+5.7/–2.2		+2.5/–1.1		+5.6/–2.7		+26.6/–8.4		+1.3/–0.7
Nb/U												
2010	477	42.7	446	50.7	391	5.4	164	12.8	222	25.4	76	2.3
		+10.7/–8.5		+14.0/–11.0		+3.1/–2.0		+18.0/–7.5		+49.6/–16.8		+1.4/–0.9
2022	5186	45.1	3728	45.8	1343	6.3	1068	8.0	1003	33.5	451	15.7
		+11.7/–9.3		+13.2/–10.3		+8.0/–3.5		+13.5/–5.0		+40.8/–18.4		+46.1/–11.7
Nb/Yb												
2010	733	1.1	835	6.0	494	0.9	208	3.7	257	11.6	78	0.4
		+2.2/–0.7		+8.8/–3.6		+0.6/–0.4		+5.2/–2.2		+36.5/–8.8		+0.2/–0.2
2022	5980	1.1	5891	4.2	1636	0.8	1186	1.9	1701	10.0	525	0.7
		+2.0/–0.7		+6.8/–2.6		+0.9/–0.4		+2.8/–1.1		+27.3/–7.3		+0.9/–0.4
Zr/Nb												
2010	892	24.2	897	8.8	616	38.1	235	17.9	313	6.4	132	47.1
		+38.3/–14.8		+6.6/–3.8		+20.2/–13.2		+20.3/–9.5		+8.9/–3.7		+58.4/–26.1
2022	6171	23.0	6119	9.8	1867	34.5	1314	21.7	1996	6.5	545	34.8
		+36.0/–14		+7.2/–4.1		+32.2/–16.7		+21.5/–10.8		+7.9/–3.6		+41.6/–19.0
Th/Ta												
2010	503	1.0	343	1.0	100	6.6	129	2.8	170	1.4	64	3.9
		+0.3/–0.2		+0.4/–0.3		+12.6/–4.3		+5.9/–1.9		+1.0/–0.6		+16.4/–3.1
2022	4814	1.0	2606	1.1	861	4.8	801	5.3	786	1.8	407	2.1

Table 5. (Contd.)

Year	<i>n</i>	I	<i>n</i>	II	<i>n</i>	III	<i>n</i>	IV	<i>n</i>	V	<i>n</i>	VI
		+0.3/−0.2		+0.3/−0.2		+9.4/−3.2		+7.6/−3.1		+1.9/−0.9		+3.8/−1.3
Th/Yb												
2010	632	0.1 +0.2/−0.1	464	0.6 +0.9/−0.4	421	0.3 +0.4/−0.2	167	0.7 +1.2/−0.4	255	1.5 +4.0/−1.1	41	0.1 +0.6/−0.1
2022	5299	0.1 +0.2/−0.1	3200	0.6 +1.0/−0.4	1432	0.3 +0.6/−0.2	1097	0.7 +0.6/−0.3	1093	1.5 +2.8/−1.0	484	0.2 +0.4/−0.1
Th/U												
2010	578	2.7 +0.8/−0.6	463	3.5 +1.4/−1.0	343	1.7 +1.0/−0.6	171	2.5 +1.2/−0.8	248	3.4 +1.4/−1.0	48	2.6 +0.8/−0.6
2022	5546	3.0 +0.8/−0.6	3289	3.3 +0.8/−0.7	1371	2.2 +1.6/−0.9	1076	2.6 +1.2/−0.8	1023	3.8 +1.6/−1.1	433	2.9 +1.2/−0.8
Ba/Rb												
2010	636	11.1 +2.9/−2.3	629	11.4 +5.2/−3.6	184	13.5 +8.8/−5.3	190	28.0 +28.6/−24.2	194	11.1 +8.7/−4.9	165	10.5 +6.2/−3.9
2022	5298	11.0 +2.7/−2.2	4874	11.5 +4.5/−3.2	1247	12.8 +13.1/−6.5	1137	22.8 +21.6/−11.1	1343	12.8 +9.9/−5.6	578	9.6 +3.9/−2.8
P₂O₅/F												
2010	309	7.6 +5.0/−3.0	1000	5.3 +3.8/−2.2	527	4.0 +4.2/−2.0	95	4.2 +5.0/−2.3	412	2.6 +8.4/−2.0	—	—
2022	2314	7.6 +3.4/−2.3	4544	4.8 +4.2/−2.2	1713	4.9 +7.2/−2.9	1240	6.1 +6.7/−3.2	1971	3.3 +9.1/−2.4	159	9.4 +9.9/−4.8
TiO₂/Dy												
2010	1030	2800 +840/−650	929	4100 +1900/−1300	494	2900 +750/−600	196	3400 +1000/−790	239	3300 +2700/−1500	99	2700 +490/−420
2022	6029	2800 +610/−500	5734	4190 +1850/−1280	1542	2720 +950/−700	1091	3300 +1180/−870	1387	3910 +2770/−1620	460	2720 +630/−510

Pb can be driven by sulfides, because Pb is a typical chalcophile element (Hart and Gaetani, 2006). However, sulfides are quite commonly found in mafic magmas in all environments, whereas a Pb anomaly is obvious in the melts only of two of them. Another possible enrichment mechanism of magmas (or their sources) in Pb relative Ce is material transfer with aqueous fluids derived at the degassing of a subducted slab (Ayers, 1998). Note that a Pb anomaly is also typical of intermediate and felsic melts, and the Pb anomaly of the latter is pronounced even better than their Nb anomaly.

Table 5 lists some average ratios of components in mafic magmas from various environments. Obviously, the number of analyses for the elements has significantly increased over the past 12 years. This information quantitatively appends the conclusions that can be derived from the analysis of the multielemental patterns. Many of the variation ranges significantly overlap and very little change from one environment to another, for example, those of the Th/U, P₂O₅/F, and

TiO₂/Dy ratios. These ratios are insusceptible to geodynamic environments, and the insignificant variations in these ratios were likely caused by local processes. The rest of the ratios are distributed more contrastingly, but none of them can be used to reasonably determine the affiliation of a composition with any of the six environments. Moreover, some parameters make it possible to combine some environments into larger groups within which differences are insignificant. For example, environments of platform boundaries (III and IV) notably differ from environments related to mantle plumes in Ce/Pb, Nb/U, Zr/Nb, and Th/Ta ratio. Some parameters of environment I are closely similar to those of “plume” environments (for example, the Th/Ta ratio), whereas other parameters make this environment similar to environments III and IV (for example, the Zr/Nb ratio). Environment I principally differs from all other environments in the La/Yb and Th/Yb ratios (these ratios can be employed as indicators of the depleted mantle). It is worth mentioning that this depletion is not associated

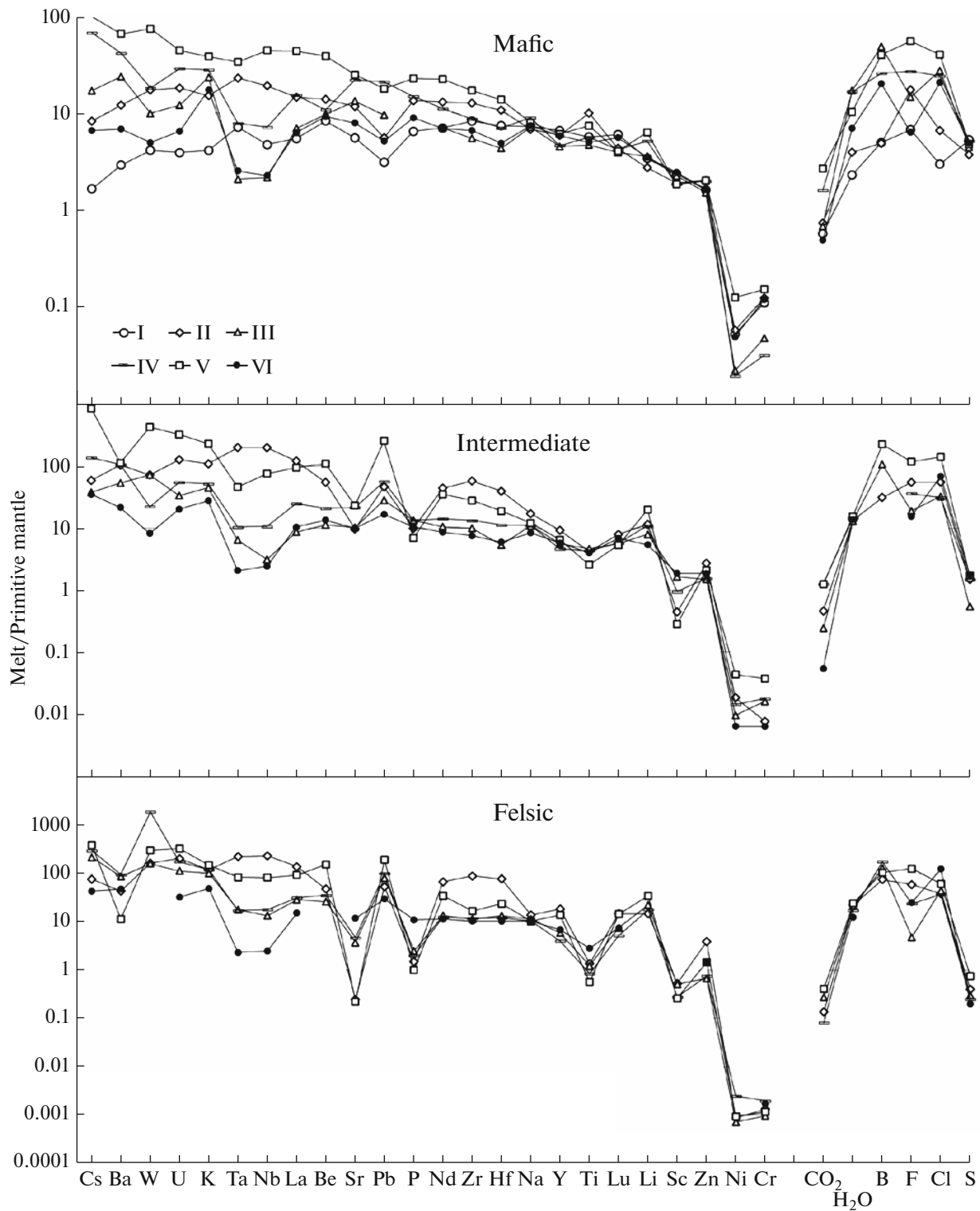


Fig. 3. Primitive mantle-normalized (Sun and McDonough, 1989) trace-element and REE patterns of mafic, intermediate, and felsic melts in (I) mid-oceanic ridges, (II) oceanic islands, (III) island arcs, (IV) active continental margins, (V) continental rifts and continental hotspot areas, and (VI) backarc spreading areas.

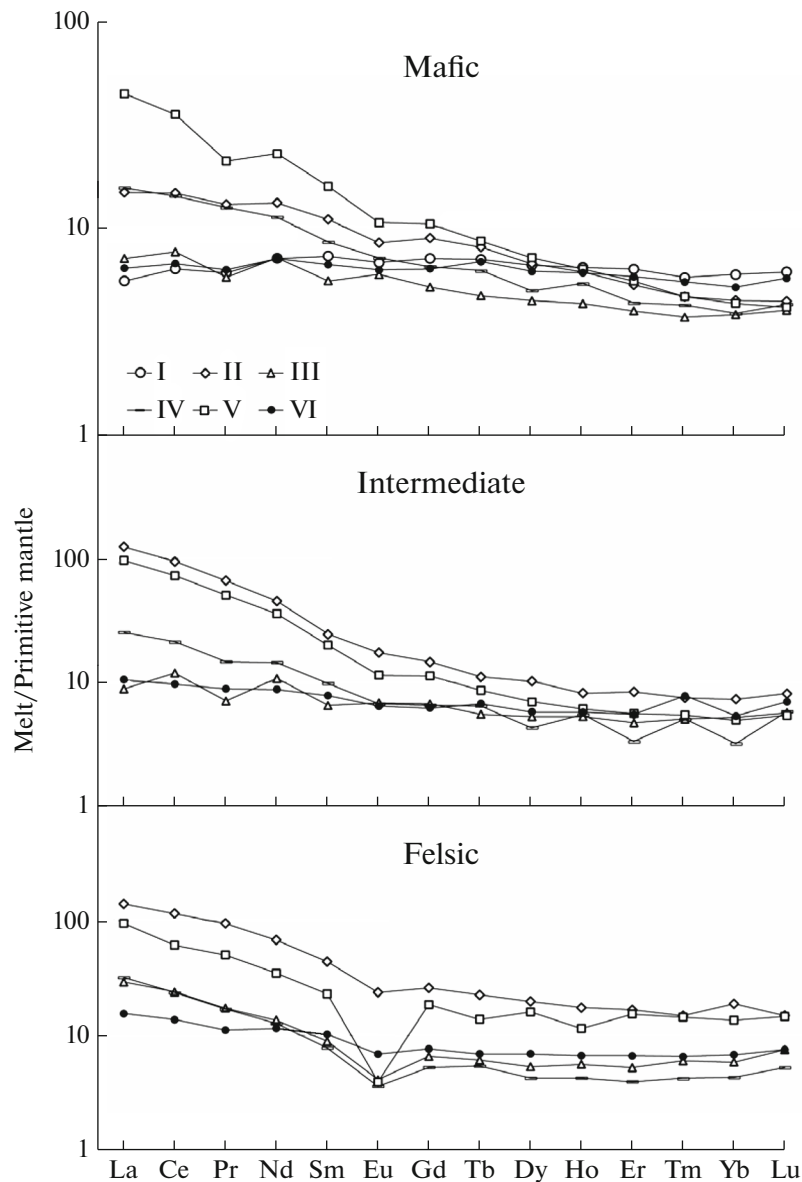


Fig. 4. Primitive mantle-normalized (Sun and McDonough, 1989) REE patterns of mafic, intermediate, and felsic melts in (I) mid-oceanic ridges, (II) island arcs, (III) oceanic islands, (IV) active continental margins, (V) continental rifts and continental hotspot areas, and (VI) backarc spreading areas.

with any significant changes in the ratios of incompatible elements: for example, the H_2O/Ce and Ce/Pb ratios in environments I and II are similar but principally differ from those in III + IV. Quantitative interpretations of these differences is a challenging task, because they may be related to the redistribution of components with the involvement of melts and fluids that had been derived under different thermodynamic parameters. Some of the differences may have likely been inherited during various evolutionary stages of geospheres. In this context, it would be interesting to trace the changes in the ratios of elements in similar melts with time, but such data on ancient complexes are still very sparse.

CONCLUSIONS

(1) Our database has been remarkably extended and now includes more than 2600000 determinations of 75 elements in mineral-hosted melt inclusions and in quench glasses in volcanic rocks. These data were generalized, and mean concentrations of major components and volatile, ore, and trace elements in magmatic melts were calculated for all of the dominant Earth's geodynamic environments.

(2) Our newly acquired data confirm that, from the viewpoint of geochemical specifics, all melts data on which are available from the current version of the database definitely belong to any of the following six

types, which correspond to the previously distinguished geodynamic environments: (I) environments of the spreading of oceanic plates (mid-oceanic ridges), (II) environments with mantle plumes at oceanic plates (oceanic islands and lava plateaus), (III and IV) environments related to subduction processes (III is arc magmatic zone on the oceanic crust, and IV is magmatic zones in active continental margins in which magma-generating processes involve the continental crust), (V) continental rifts and areas with continental hotspots, and (VI) environments of backarc spreading (Naumov et al., 2010).

(3) The distribution of SiO₂ concentrations in natural magmatic melts is bimodal in all of the geodynamic environments: one of the maxima occurs at SiO₂ = 50–52 wt %, and the other at 72–76 wt %. The smallest number of analyses corresponds to SiO₂ concentrations of 62–66%.

(4) The primitive mantle-normalized multielemental patterns for the mean compositions of mafic, intermediate, and felsic rocks in environments I–VI show inherent features of melt compositions in each of the environments.

(5) Generalized and averaged data on the composition of mineral-hosted melt inclusions and glasses in rocks were used to calculate the average ratios of incompatible trace and volatile components (e.g., H₂O/Ce, K₂O/Cl, Nb/U, Ba/Rb, and Ce/Pb) in the magmatic melts of each of the environments. The variations in these ratios were calculated, and it is demonstrated that ratios of incompatible elements are mostly statistically significantly different in the different environments. The differences are particularly significant in the different environments, and these differences are the largest between the ratios of elements of different incompatibility (for example, Nb/Yb) and some volatiles (for example, K₂O/H₂O).

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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