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Research paper

Uranium, rare metals, and granulite-facies metamorphism

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ABSTRACT

During granulite-facies metamorphism of metasedimentary rocks by the infiltration of carbonic fluids, the disappearance of hydrated minerals leads to the liberation of aqueous fluids. These fluids are strongly enriched in F and Cl, and a series of Large-Ion-Lithophile (LIL) elements and rare metals, resulting in their depletion in granulites. To sum up the fate of these elements, we focus on three domains representing different crustal levels and showing distinct behaviours with respect to these elements. The Lapland metasedimentary granulites illustrate the behaviour of the LILE and rare metals during lower crustal metamorphism. There is no change in Ba, moderate loss in Rb, and extreme depletion in Cs, Li, and Sn. F and Cl contents are also very low compared to the protoliths or average upper continental crust. Biotite and amphibole breakdown leads to the incorporation of their partitioning into a fluid or a melt.

The Tranomaro metasomatized marbles recrystallizing under granulite-facies conditions represent a demonstrative example of fluid transfer from granulite-facies supracrustals to traps represented by regional scale skarns. Such fluids may be at the origin of the incompatible element enrichment detected in leucosomes of migmatites from St Malo in Brittany (France) and Black Hills in South Dakota. The northern French Massif Central provides us with an example of a potential association between incompatible element enrichment of granitic melts and granulite-facies metamorphism. U- and F-enriched fine-grained granites are emplaced along a crustal scale shear zone active during the emplacement within the St Sylvestre peraluminous leucogranitic complex. We propose that during granulite-facies metamorphism dominated by carbonic waves in a deep segment of the continental crust, these shear zones control: (i) the percolation of F-, LILE-, rare metal-rich fluids liberated primarily by the breakdown of biotite; (ii) the enhancement of partial melting by F-rich fluids at intermediate crustal levels with the generation of F-, LILE-, rare metal-rich granitic melts; (iii) their transfer through the crust with protracted fractionation facilitated by their low viscosity due to high F-Li contents; and finally (iv) their emplacement as rare metal intrusions at shallow crust levels.

1. Introduction

Granulite-facies rocks are a fundamental component of the continental crust, which encompass (1) dominantly mafic cumulates and gabbros in the lowermost crust, resulting from underplating by mantle magmas; they are mostly known from xenoliths in basalts; and (2) high-grade supracrustal rocks buried in the lower crust during orogenic processes. Regardless of their origin, they share three main characteristics: (1) they correspond to rocks (almost) free of OH-bearing silicates (micas and amphiboles); (2) they contain high-density, CO_2-rich, fluid inclusions; and (3) they are generally poor or depleted in large ion lithophile (LIL) elements. These three basic features led to two distinct models for the generation of granulite-facies rocks.

The first model relies on the pioneering work of J. Touret (1970, 1971) which showed that granulites are characterized by the presence of carbonic fluid inclusions. This, together with the observation of incipient charnockitization (Pichamuthu, 1960;

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Table 1
Trace element concentrations in Lapland granulites. Data from Hörmann et al. (1980) and Raith et al. (1982) for samples with the code letter R, and from Barbey and Cuney (1982) and this study (*) for samples with the code letter L.

(ppm)	K	Ba	Rb	Sr	Cs	Li	Sn	F(*)	Cl(*)	K/Rb	K/Ba	Rb/Sr	Rb/Cs	La/Th	Th/U	K/Th	K/U
Sillimanite-garnet gneiss																	
L176	35,184		91	279		5	0.1			387		0.33			14.5	3466	50,262
L188	31,200	949	113	156	0.69	7.7	0.1	760	117	276	32.9	0.72	164	4.6	13.7	3257	44,572
L313	21,824	918	82	167	0.50	9.5	0.7	610	76	266	23.8	0.49	164	2.9	13.7	1141	15,588
L371	28,960	1155	101	229	0.23	6	0.1	140	102	287	25.1	0.44	439	4.6	22.4	3236	72,400
L389	39,498	1201	136	255	0.29	4.8	0.25	150	170	290	32.9	0.53	469	3.1	12.2	2310	28,213
L530	27,632		111	176		8	0.1			249		0.63			32.9	1400	46,054
L555	29,707	843	101	171	0.49	4.8	0.4	170	111	294	35.2	0.59	206	3.0	23.0	1618	37,134
L558	27,217	1062	116	187	0.39	6	0.12	480	149	235	25.6	0.62	297	3.3	16.2	1523	24,743
L581	27,632	831	79	185	0.25	4.2	0.1	30	152	350	33.3	0.43	316	5.9	11.5	4010	46,054
L599	19,915	962	109	194	0.48	7.4	0.1	360	173	183	20.7	0.56	227	3.3	7.7	1298	9958
L959	30,537	867	118	147	0.36	6.5	0.2	740	71	259	35.2	0.80	328	3.3	34.4	1773	61,073
L963	37,507	1248	102	274	0.22	6.9	0.5	330	139	368	30.1	0.37	464	4.1	48.1	2597	125,023
R57II	16,845	632	65			20				259	26.7						
R59I	29,790	932	107	125		4				278	32.0	0.86					
R94I	22,571	1373	102	371		15				221	16.4	0.27					
Garnet gneiss																	
L308	26,886	1307	87	291	0.15	3.8	0.1	20	102	309	20.6	0.30	580	7.4	15.3	5870	89,618
L315	28,213		54	224		4.3	0.25			522		0.24			15.5	2273	35,267
L316	19,334	609	68	157	0.20	4.9	0.7	390	133	284	31.7	0.43	340	3.8	20.7	1868	38,669
L319	4647	195	16	135	0.18	4.6	0.75	270	112	290	23.8	0.12	89	17.4	2.8	4076	11,334
L360	25,392	1396	55	200	0.11	2.6	0.15	40	116	462	18.2	0.28	500	4.8	9.5	4439	42,320
L375	29,458	1025	85	209	0.13	4.6	0.4	330	141	347	28.7	0.41	654	6.5	68.4	4307	294,579
L515	26,139	845	98	343	0.27	12.5	0.15	650	118	267	30.9	0.29	363	4.3	15.3	3412	52,277
L516	28,628	874	106	154	0.19	8.4	0.1	270	99	270	32.8	0.69	558	4.7	12.5	3822	47,714
L517	15,102	513	41	336	0.12	5.6	0.1	20	124	368	29.4	0.12	342	13.4	16.3	4633	75,512
L523	32,279	1380	75	566	0.28	6.9	1	140	317	430	23.4	0.13	268	4.1	52.6	2044	107,597
L526	21,326	761	80	136	0.12	4.2	0.15	70	120	267	28.0	0.59	667	3.4	13.6	1957	26,657
L527	23,566	782	80	178	0.11	4.5	0.25	150		295	30.1	0.45	727	3.7	18.8	2512	47,133
L565	12,198	652	38	264	0.13	3.3	0.1	490	635	321	18.7	0.14	292	3.9	21.3	638	13,553
L580	13,941	723	83	336	0.59	11	2.3	130	136	168	19.3	0.25	141	3.0	26.2	591	15,490
L601	12,779	598	52	174	0.26	4	0.1	490	348	246	21.4	0.30	200	3.4	14.1	1135	15,974
L602	37,673	1003	80	289	0.28	4	0.1	300	720	471	37.6	0.28	286	3.7	27.4	2290	62,788
L604	18,339	537	51	199	0.11	2.8	0.1	70	124	360		0.26	464	3.3	17.2	1523	26,198
L684	13,111	443	55	335	0.54	10.2	0.3	950	240	238	29.6	0.16	102	3.9	9.0	1318	11,919
L838	27,798	818	88	163	0.19	3.3	0.12	20	140	316	34.0	0.54	463	8.0	11.1	6275	69,496
L969	27,134	958	83	216	0.15	7.8	0.6	30	73	327	28.3	0.38	553	3.2	49.1	1842	90,448
R57III	16,264	796	55	297		12				296	20.4	0.19					
R58II	9543	415	32	607		13				298	23.0	0.05					
R61I	11,451	260	23	27		2				498	44.0	0.85					
R69I	11,617	1399	51	353		13				228	8.3	0.14					
R70II	14,107	486	51	153		3				277	29.0	0.33					
R86I	7302	291	53	267		7				138	25.1	0.20					
R96I	12,862	398	35	366		5				367	32.3	0.10					
R102I	13,360	447	72	276		11				186	29.9	0.26					
R109II	9045	327	26	311		9				348		0.08					
R111I	7966	811	32	182		10				249	9.8	0.18					
R128I	10,373	496	49	272		10				212	20.9	0.18					
R150I	26,139	878	71	166		4				368	29.8	0.43					
RJ10II	8630	416	49	475		11				176	20.7	0.10					
RJ3I	2821	112	12	138		4				235	25.2	0.09					
RJ5II	10,787	337	40	119		4				270	32.0	0.34					
RJ7I	15,683	545	89	238		7				176	28.8	0.37					
Light garnet-alkali-feldspar gneiss																	
L370	32,030	1170	77	320	0.17	2.5	0.1	<20	170	416	27.4	0.24	453	12.5	10.0	16,015	160,151
L528	38,503	809	103	198	0.15	2.7	0.25	<20	178	374	47.6	0.52	687	1.7	10.0	9626	96,257
L529	43,150		123	270		3.5	0.32			351		0.46			10.0	21,575	215,748
L557	49,456	1404	128	226	0.15	5	0.12	50	139	386	35.2	0.57	853	4.5	16.1	5114	82,427
L862	37,922	332	65	94	0.04	1	0.25	<20	144	583	114.2	0.69	1625	2.0	8.2	9295	75,844
R76I	55,016		149	267		4				369		0.56					
R116I	30,205	1229	71	171		4				425	24.6	0.42					
R130I	33,026		46	50		2				718		0.92					
R143I	61,986	877	125	137		6				496	70.7	0.91					
R148I	43,730	1416	148	273		7				295	30.9	0.54					
R154I	24,894	540	39	95		6				638	46.1	0.41					
R156I	22,073	554	77	198		6				287	39.8	0.39					
Garnet-quartz gneiss																	
L567	12,447	509	40	145	0.11	3.5	0.1	490	80	311	24.5	0.28	364	3.6	13.4	1548	20,745
L577	5477	252	6	255	0.05	6	0.1	60	66	913	21.7	0.02	120	3.4	14.5	629	9128
L690	9128		35	79		3.1	0.2			261		0.44			13.8	367	5071
R69II	2738	147	9	77		4				304	18.6	0.12					
Calc-silicate rock																	
L583	913	42	5	188	0.20	2	2.4	180	825	183	21.7	0.03	25	2.2	3.2	93	299