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A Geochemical Survey of Granitic Rocks in the Bergell Alps[1] [2]

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Abstract

We present 107 new chemical analyses of major elements for Tertiary mobilized rocks of the Bergell complex and associated rocks. The chemical pattern, best illustrated in ternary diagrams (Fig. 4) and multivariate discriminant analyses (Figs. 5 and 6), shows distinctly separate populations for Bergell granite (granite-granodiorite composition) and Bergell tonalite. Among potential source rocks, Gruf migmatites occupy a similar field as Bergell granite; Hercynic granites of the Pennine nappes are enriched in SiO_2 and K_2O. The composition of tonalite lies between these granitic rocks and amphibolites. There is no clear regional zonation but compositional gradients exist directly along contacts between tonalite and granite. In the vicinity of the amphibolite-tonalite contact in the E-corner of the massif, both rocks have a similar composition.

Chemical data are consistent with a model of mobilization at deeper crustal levels and mixing and homogenization during emplacement (H.-R. Wenk, 1973) rather than magmatic differentiation of a homogeneous melt (Richardson et al., 1976). In particular, Bergell granite may be derived from Gruf migmatites without chemical exchange and Bergell tonalite may be derived from a mixture of amphibolites and gneisses which still surround the northern part of the massiv in direct extension of the tonalite sequence.

Comparison of modal and normative An content illustrates a pattern typical of metamorphic plagioclase (E. Wenk, 1948) with discontinuities in An-content. Favored composition ranges are An 0–4, 24–32, 36–40 and 46–48 (Fig. 9).

CONTENT

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[1]) Dedicated to Prof. E. Wenk, Basel, on occasion of his 70th. birthday.
[2]) Part VII of "Geological observations in the Bergell Alps".
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1. INTRODUCTION

Most petrologic studies of the Bergell Alps have emphasized volumewise rare mafic, ultramafic, carbonate and pelitic rocks. Apart from the pioneering work of DRESCHER (1940), leuco- and mesocratic gneisses, which constitute the bulk volume, have been neglected. In this study, we attempt to correct this omission by contributing chemical data concerning these rocks whose origin has been a center of discussion for over 125 years (STUDER, 1851). Adding 107 new chemical analyses to the 60 available in the literature (WEBER, 1957; WEIBEL, 1960; MOTICSKA, 1970; RICHARDSON et al., 1976) allows us to have some confidence in the *statistical* significance of the data and to attempt explaining them with a plausible model. Our aim is to try to decide between two main hypotheses that Tertiary granitic rocks of the Bergell Alps are (i) the result of *differentiation from a homogeneous magma* or (ii) of anatexis, mobilization and *remelting of different preexisting crustal rocks with only moderate mixing and differentiation.*

Hitherto, models for the origin of Bergell igneous rocks have generally been based on structural observations and not on geophysical or geochemical evidence (CORNELIUS, 1913; STAUB, 1924; DRESCHER and STORZ, 1926; GYR, 1967; CRESPI and SCHIAVINATO, 1966; H.-R. WENK, 1973). Also in this presentation of chemical data of major elements, we fail to arrive at an unequivocal interpretation and expect that our conclusions will have to be revised, particularly if discordant U/Pb age data on zircons become available and tell us more about the premagmatic history of the material.

We collected different plutonic rocks of the Begell complex and compared them with potential source rocks of the surrounding Pennine nappes. Sample localities are indicated on the tectonic map in Fig. 1, and a brief petrographic summary is given in Table 1. We will first review some regional structural relationships, then present analyses using various graphical and analytical representations for geochemical data.

2. STRUCTURAL RELATIONSHIPS

The structure of the Bergell complex has been described elsewhere (see H.-R. WENK, 1973, also, for further references). A tectonic sketch (Fig. 1)

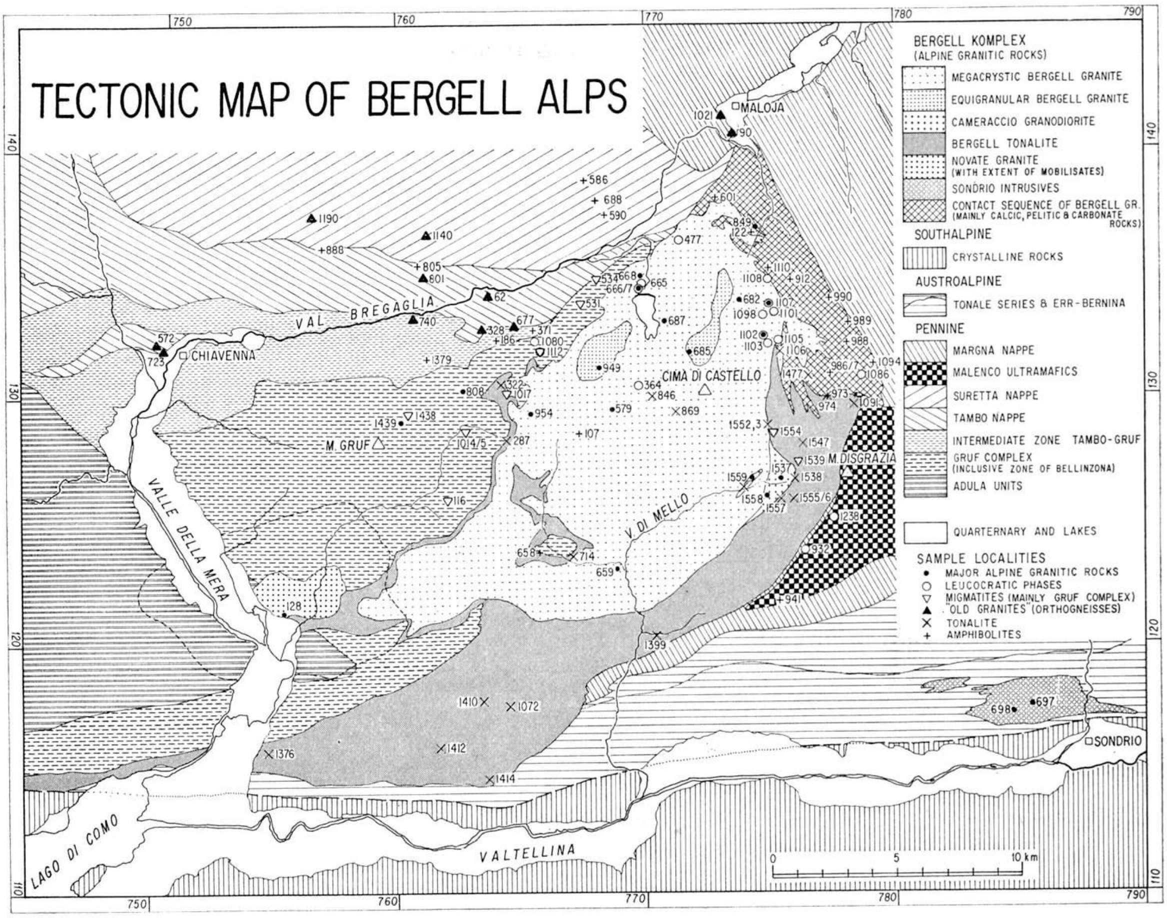

Fig. 1. Tectonic sketch of the Bergell Alps. Sample localities are indicated.

provides a summary. The young Alpine granitic rocks, which are the central subject of this paper, lie in most places conformably in the stack of higher Pennine nappes. In tectonic level, the Bergell granite, which overlies the Gruf complex to the south, corresponds to the Tambo nappe which overlies it to the north of the large anticlinal structure. Emplacement of this granite nappe took place in a solid or semisolid state as is evidenced by the deformation microstructure, particularly of quartz, but the material was more ductile and at higher temperature in the southwestern part which shows extensive plastic deformation than in the northeastern region where deformation was brittle and parts of the original igneous contact are well preserved. The strainfield in which the granite was deformed is the same as that which controlled the last intensive deformation of the country rocks as borne out by the pattern of planar and linear structures. Lineations, fold axes and foliations in the granitic rocks are generally parallel to those of the country rocks, but particularly in tonalite, there are exceptions to the general gentle E dip of fold axes. Lineations in the tonalite bend around the Bergell granite in the NE and plunge steeply northwards with typical *whirlpool structures* in Val Preda

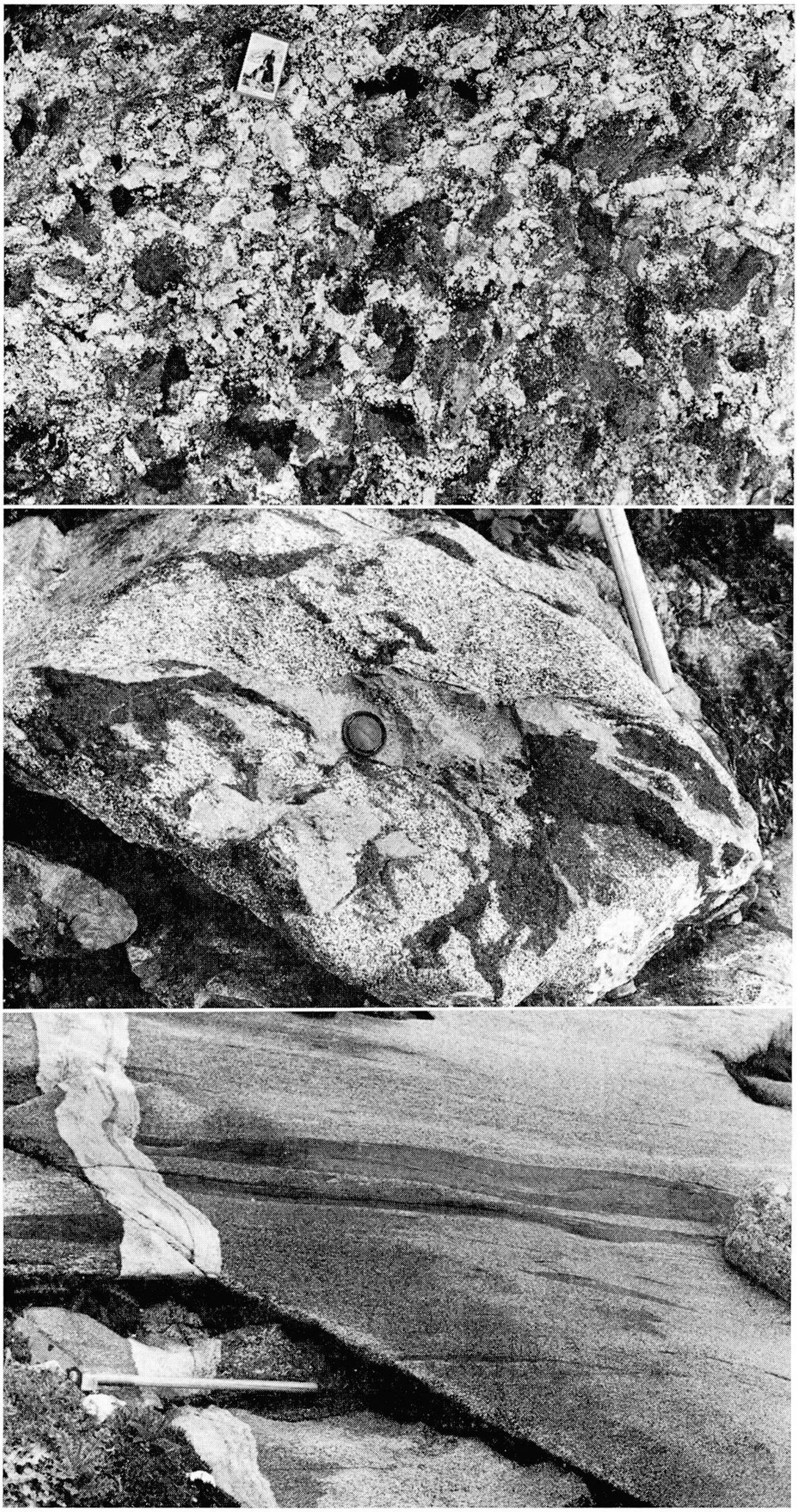

Fig. 2.

a) Interaction of mobile granitic phases with amphibolites near Cap. Del Grande. Notice the large alkalifeldspar and hornblende porphyroblasts.

b) Transition zone between tonalite and amphibolite at Alpe Sissone (light mobile phase corresponds to sample 973, fine grained matrix to 974).

c) Tonalite (1091) in Val Sissone. Notice elongated dark inclusions of amphibolite composition and cross cutting zoned pegmatite vein.

Table 1. *Description of analyzed specimens* (symbols in parentheses indicate small amounts, exclamation mark indicates abundance)

¹) Samples deposited in collection of Bern University, not available.
²) c = calcite, d = diopside, e = enstatite, g = garnet, h = hematite, t = tourmaline. Various opaques, monazite and zircon are not listed.
* Intermediate rock types. Special symbols in graphical representations.
+ Special rock types. Not used in statistical calculations and graphical representation.

Sci	Locality	Coordinates	Quartz (m mylonitic, u undulatory, i igneous)	Feldspars: plagioclase An Ab Or (* partially altered, M megacryst, i intergrowth, po porphyroblast, Z zoned)	Feldspars: alkali fs An Ab Or	Feldspars (m microcline, p perthite, my myrmekite)	Sheet silicates: B (Biotite, color: b(rown), r(ed), g(reen), h(alo))	M (Muscovite)	C (Chlorite int. col.: bl(ue), b(rown), p(urple), g(rey))	H = hornblende, A = actinolite	Epidote (Z zoisite, C clinozoisite, E epidote, A allanite)	apatite	sphene	Other accessories²)	Remarks
Alpine granites and granodiorites															
Megacrystic Bergell granite															
579	Sciora Dadent	768.65/129.54	u	28 71 1	0 9 91	M p my	bg, h		b		A	×	×		
659	San Martino	768.8/123.2	u	28–31		M p my	bg		b	H	A	×		c	
667	Albigna, dam	769.875/134.35	m	25–27 bent		M p	bg		b		A	×	×		
667a	Albigna, dam	769.875/134.35	m	25–27		M p	bg		b		A	×	×		
668¹)	Albigna, dam	770.0/135.5													
682	Forno-Casnile	773.875/134.00	u	27–29		M p my	bg, h		b	H	A	×	×	h	
687	Cap. Albigna	770.8/133.2	m	23 76 1	5 23 72	M p my	bg, h	×	p (needles)			×		h	
849	Forno-Plan Canin	774.66/136.97	m	23 76 1 *	1 10 89	p	rb	×	bl			×		h	strongly altered
954	P. Badile	765.47/129.36	u	30 68 2	1 12 87	M p	bg		bl		A	×	×		
1102a	Mte. Rosso	774.77/132.57	(u)	27–28 Z		M p my	g			H	A	×			
1107a	Cap. Forno	775.05/133.85	u	30 Z		M p my	b		p		A C	×			
1552*	Torrone-Sissone	775.95/126.2	u	29–31		M p my	b		b	H	A!	×			contact w. tonalite
Equigranular Bergell granite															
685¹)	Cantone-Albigna	771.625/131.95													
949	Fort Sciora	768.17/131.35	m	30 68 2 bent	1 12 87	m p	b h	×	bl	H	A	×			strongly deformed
Cameraccio granodiorite															
1537	A. Cameraccio	775.7/126.95	u	25–30 Z* w. replacements		M m my!	b		b	H	E	×	×	h	
1558	A. Pioda	775.15/126.3	u	28–31		m p my	b		b	H	E	×	×		mylonitic
1559	Cas. Pioda	774.05/126.25	u	24–27		M p my	gb		bl-p	H	A, E	×	×		
Megacrystic granite in Gruf complex															
808*	Boch. Tegiola	762.65/130.50	m	21–38 79–61 1 Z	0 12 88	M m p my	rb h		bl		A	×			mylonitic texture
1439*	Cma. Codera	760.25/129.25	rexl	24–39 75–61 1 Z	0 12 88	M m p my	b	×	p		A, E	×			rexl. mylonite
Novate granite															
128	Novate	754.4/121.5	u	18 81 1	0 8 92	my	rb h	×	g			×			cataclastic
Sondrio intrusives															
697+	Ligari-Triangia	785.4/117.6	i (u)	15–38 Z! *		m	rb	×	p-bl		A	×			
698+	Ligari-Triangia	784.7/117.3	i (u)	30–56 Z! osc. *			b		p	H	A, E	×			exc. igneous text.
Microgranite															
477	Vallun d. Largh	771.4/136.45	u, rexl	21–31 77–67 2 Z *	0 8 92	m	bg h	×	bl			×		c, h	in Bergell granite
1080	Laret-Bondasca	765.56/132.37	(u), large	22–39 67–60·1 Z *	0 6 94	my	bg	×	bl		E	×		c	in Gruf migmatite
1086	V. Sissone	778.7/131.0	u	13–16 86–83·1 *	0 6 94	m my	b h	×	bl		C	×		c, h, t	in amphibolite
1098	Cap. Forno	774.69/133.58	u	17–39 82–60·1 Z! *	0 8 92	m p my	b	×	bl		C	×			contact w. calcsilicates
1101	Cap. Forno	775.18/133.50	u, rexl	19–26 80–72·1 Z! *	0 5 95	m my	bg h	×	bl		E	×			
1107b	Cap. Forno	775.05/133.85	u	18–26 Z **		m p my	bg h	×	bl		A, E	×		h	in Bergell granite
1108	P. dei Rossi	775.1/135.1	u	16–20 *		m my	bg	×	b+needles					g	in amphibolite
Aplite dikes															
665	Albigna, dam	769.8/134.225	rexl	23–30 Z *		m my	b	×	bl			×			cataclastic
666	Albigna, dam	769.875/134.35		20–30 Z *		m my	b	×	bl		A	×		c, g	
932	Preda Rossa	776.4/123.85	u	4 96 0 Z *	0 10 90	m p	(bg)	×						g	cataclastic dike in ultramafic
1102b	Mte. Rosso	774.77/132.57	graphic	×		m p	(b)		(p)						in granite
1103	Mte. Rosso	774.98/132.18	u	10–13		m	(b)	(×)	(bl-p)			×			
1105¹)	Mte. Rosso	775.32/132.29													
1107c	Cap. Forno	775.05/133.85	u	24–27		m	(b)	×	p			×	×		
1112b	Lera-Bondasca	765.85/131.9	u	24–38 Z, *		my	b	×	p		E	×			catacl.-mylon. in Gruf migmatite
Pegmatite dikes															
364	Vadrec Albigna	769.65/130.6	graphic	10 90 0	0 8 92 + 2 97 1	p			(p)					g	
1112c	Lera-Bondasca	765.85/131.9	m	10 bent and broken		p my		×						g	
1112d	Lera-Bondasca	765.85/131.9	catacl.	10		m		×						g	fine grained
1238	Disgrazia	777.50/125.2	catacl.	9 90 1	0 5 95		(b)	×	(p)						in ultramafic
Gruf migmatites and related rocks															
116	Averta-Codera	762.05/126.05	rexl	24–27		p my	gb		bl		A	×			fine grained
531	N Borgonovo	767.49/134.075	m, rexl	24 75 1 2 phases	0 10 90	m p	gb				E	×		h	mesocratic
531b¹)	N Borgonovo	767.49/134.075													leucocratic
534	V. Torta	768.125/134.85	m, rexl	23–27		(m) p	gb		g		A	×			
1017	Trubinasca	764.25/130.22	m, rexl	26–27 *		M m my	b	(×)	g						augengneiss
1112a	Lera-Bondasca	765.85/131.9	catacl.	25		p! my	gb	(×)			A	×			
1438	Cma. Codera	760.5/129.4	catacl.	22 77 1	1 6 93	p!! my	gb				C	×			
1539	Cme. Chiareggio	776.05/127.6	u	27–29		M m p	b	(×)		H	A-E	×	×		inclusion in tonalite
1554	Torrone-Sissone	775.22/128.55	u	28		M p my	b					×			inclusion in tonalite
"Sivigia diorite"															
1014+	A. Sivigia	762.63/128.72	rexl	40–47 60–53 0 M					b	H				e	transformed from 1015
1015+	A. Sivigia	762.63/128.72	(u)	37–47 63–53 0 M			b (h)				A			c, e, h	ultramafic breccia
Old granitic rocks (augengneisses of higher Pennine nappes)															
Tambo nappe															
62	Promontogno	763.74/134.32	rexl	0 99 1	0 6 94	M m	(b,h)	×			C	×		h	
328	Marlun-Bondasca	763.5/133.0	rexl	× *		M m my	gb	×				×			fine folding
572	Pianazzola	750.35/132.55	rexl, porph	21 78 1	1 10 90 +4 95 1	M m p my	r, h!	×			E-C	×			
677	Mungac-Bondasca	764.70/132.9	m, rexl	26 73 1	0 8 92	M m p my	rb	(×)				×			
723	Chiavenna	750.7/132.1	rexl, porph	×		M m p	rb,h!	×				×			
740¹)	Castasegna	760.615/133.4													
801	Soglio	761.01/135.07	rexl	0 99 1	1 6 93	M m	(gb)	×	g-bl			×			folded
Suretta nappe															
1140	Cambun-Soglio	761.3/136.9	rexl	0.5 99 0.5	1 3 96	m p	g	×	g-bl		E	×	×	g	
1190	Passo Lago	756.65/137.6		6											
Margna nappe															
90	Maloja	773.45/140.72	mosaic	1 99 0		m p		×				×	×	h	
1021	Maloja	773.2/141.4	mosaic	1 99 0		p		×			E, C	×		c	
Tonalite															
Central Area															
287	P. Porcellizzo	763.95/128.75	(u)	38–48		p my	bg		b	H	E-C	×	×		
714	Bagni Masino	764.2/130.75	u	46 53 1	0 3 97		bg		bl g	H	A-E	×	×	c	mosaic texture
1072	Baita Colino	764.49/118.18	subgrains	35–*50* 64–*50*·*1*–*0* av. 47 52 1			bg			H	E-C	×	×		
1106	Mte. Rosso	775.30/132.17	u	35–53 64–47 1–9* av. 44 55 1	0 7 93	my	bg		p	H	E	×	×		
1376	Nuova Olonio	754.7/116.0	subgrains	38–44 61–55 1	0 6 94		bg			H	E	×	×		gneissose
1399	Filorera	770.3/120.5	rexl	41 58 1 broken	0 8 92	my	bg		bl g	H	E		×		mylonitic
1410	Pso. Colino	763.35/117.9	u	38–39	×		b		g	H	E-C	×	×	h	mosaic texture
1412	Malvedello	761.6/116.15	rexl	35–48 65–52 0 av. 45 55 0	0 3 97		b			H	E	×	×		mosaic texture
1414	Poira	763.7/114.75	u, rexl	34–54 65–45 1 (+23 76 1)* broken	0 9 91	my	rb		g	H	C	×	×	h	
1538	A. Cameraccio	775.92/127.2	u	38–41 + 45–61 Z		my	bg		p	H	E	×	×		
1547	Cme. Chiareggio	776.45/128.05	u	33–40		my	b			H	A-E	×	×	h	contact w. calcsilicates
Contact with amphibolites															
322*	Trubinasca	764.2/130.75		38–45 M			g			H	E	×	×	c, d	
973*	A. Sissone	777.22/130.12		86·14·0+30·68·2			bg		b	H	E	×	×		
1091*	V. Sissone	778.46/129.79	u	36–49 Z! * osc.			bg		gr	H	C	×	×		igneous texture
1555*	A. Pioda	775.95/126.2	(u)	36–48 Z *		my	b		b	H	E	×	×		dark inclusions in 1556
1556*	A. Pioda	775.95/126.2	u	41–48 Z, broken		my	bg		bp	H	E	×	×	h	
Inclusions in granite and granite contact															
846*	Vadrec Albigna	770.25/130.2	on cracks	28–52 72–48 0 Z		p	bg			H	A	×	×	c	
689*	Pso. Zocca-Castello	771.26/129.62	u	27–50 72–49 1 Z	0 7 93	my	bg		g	H		×	×		H in clusters
1553*	Torrone-Sissone	775.02/129.05	u	31–45 Z		p my	bg		p	H	A	×	×	h	
1557*	A. Pioda	775.75/126.05	u	30–31 *		M m my	bg		p	H	A-E	×	×		
1560*	Bta. Remoluzzo	773.85/126.0	u	31–38 Z *		p my	rb			H	A-E	×	×		mylonitic
Dike															
1477*	Cma. Vazzeda	776.6/130.9	incl.	46–72 53–28 1–0 Z! osc. *			b			H	E	×	×	h	"lamprophyre" in marbles
Amphibolites															
107*	Pso. Bondo	767.3/128.5	×	30–41 Z	×		bg		b	H		×	×	d	inclusions in Bergell granite
122	Forno-Plan Canin	774.42/136.63		33 po			g	(×)	g	H		×	×	c	porphyroblastic
186	Gerp-Bondasca	764.0/132.3		30 70 0 +14 86 0 i					g (radial)	H			×	c	hornblendite
371	Trienza-Bondasca	765.4/132.75	(×)	(21) 27–29			(bg)		b	H			×	c	mosaic, kinks
586	V. Furcela	767.45/139.2		0 po					b	H	E-C		×	c	folded
590	V. Furcela	768.34/137.74	m, rexl	0				×	b		C			c, d	
601	Lavinair Crusc	772.87/138.10	×	27+48–53 * patchy, i						H	E	×	×	c, d, h	
658	Bagni Masino	765.75/123.865	(×)	46 54 0+15 84 1 i					b	H	E	×	×	d, h	exc. mosaic text.
688*	Nambrun-Roticcio	768.0/138.0		0 po				×	b	A	Z	×	×		folded
805	Soglio	760.87/135.36	×	2 98 0			b			H	E	×	×		foliated
888	Pso. Turbine	757.14/136.24	×	0					b	H	C		×	h	hornblendite
912	Mte. Forno	775.76/134.80	×	47 52 0 + 20 79 1 i				(×)	bl	H		×	×		
941	Sasso Arso	775.3/121.96		(*)			g		bl	A	E	×	×		
974	A. Sissone	777.22/130.12	(×)	65–77 35–23 0 i						H	E	×	×	h	mosaic texture
986	Cap. Grande	777.42/131.16		45 55 0 M						H		×		h	strongly foliated
987	Cap. Grande	777.42/131.16	(×)	49–56 po						H	E	×		h	rexl.
988	A. Vazzeda	778.12/132.36		18–22 82–71 0 po i						H		×	×		
989	V. Bona	778.36/133.02		23–34 77–66 0 po * i						H	E	×		c, h	fine grained
990	Pso. Muretto	777.53/134.25		× po			b			H	C	×	×		
1094	Pian di Lupo	779.21/132.63		38 62 0 + 48 52 0 po i						H-A					fibrous
1110	P. dei Rossi	775.12/135.25	(×)	32–42 67–57 1				(×)	b	H		×	×	c, h	mosaic texture
1379	Lizöl	761.2/131.65		47–53–0 + 83 17 0						H			×	h	

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Table 2. *Chemical analyses (weight percent oxides) and norm calculations (hornblende-biotite norm) of Bergell rocks*

Sci	Locality	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	H_2O	Qtz	Cor	Or	Ab	An	Hbl	Bi	Py	Mt	Tn	Ap	Femic
Alpine granites and granodiorites																									
Megacrystic Bergell granite																									
579	Sciora	69.0	0.31	16.5	0.9	2.1	0.05	0.9	2.25	3.1	4.3	0.16	0.35	28.5	3.8	23.9	25.4	9.2	0	7.0	0	1.0	0.7	0.3	9
659	S. Martino	65.6	0.4	16.0	0.85	2.5	0.07	1.9	3.9	3.8	4.2	0.30	0.3	19.2	0	20.2	31.5	14.3	0	11.6	0.7	0.9	0.8	0.6	15
667	Albigna	70.1	0.3	15.1	0.9	1.5	0.06	1.2	2.3	3.5	4.4	0.21	0.2	26.9	1.4	24.6	28.8	9.1	0	6.9	0	0.9	0.6	0.4	9
667a	Albigna	70.1	0.4	15.0	0.7	1.75	0.06	1.2	2.5	3.5	4.0	0.23	0.2	28.2	1.6	21.6	29.2	9.6	0	7.6	0	0.7	0.8	0.5	10
668	Albigna	67.5	0.4	16.5	0.4	2.4	0.05	1.3	2.7	3.9	4.2	0.24	0.2	22.3	1.9	21.5	32.4	10.5	0	9.5	0	0.4	0.8	0.5	11
682	Casnile	69.1	0.4	15.1	0.8	1.95	0.06	1.4	2.9	3.5	4.0	0.28	0.3	26.5	1.0	20.9	29.1	11.3	0	8.7	0	0.8	0.8	0.6	11
687	Albigna	71.8	0.25	14.8	0.3	1.55	0.05	0.9	2.3	3.5	3.9	0.20	0.3	30.3	1.6	21.6	29.2	9.3	0	6.4	0	0.4	0.5	0.4	8
849	Plan Canin	68.0	0.22	17.9	1.1	0.7	0.03	0.5	1.4	3.55	5.45	0.08	0.6	22.4	4.5	34.3	28.6	5.7	0	2.4	0	1.2	0.5	0.2	4
954	Badile	66.2	0.45	15.9	1.1	2.45	0.09	1.6	3.4	3.9	4.2	0.27	0.2	19.8	0	21.1	32.5	13.5	0	10.2	0	1.2	0.9	0.6	13
1102a	Rosso	64.6	0.5	16.2	1.15	2.9	0.08	2.1	4.2	3.9	4.0	0.30	0.1	17.9	0	18.0	32.4	14.9	0	12.8	0.9	1.2	1.0	0.6	17
1107a	Forno	67.7	0.4	16.0	0.65	2.75	0.08	1.8	3.5	4.0	3.0	0.27	0	24.6	1.1	12.1	34.0	14.2	0	11.9	0	0.7	0.8	0.6	14
*1552	Torrone	63.0	0.58	17.4	1.3	2.7	0.08	2.3	3.7	3.25	4.65	0.51	0.2	18.9	2.5	22.2	26.3	13.1	0	13.1	0	1.4	1.2	1.1	17
Equigranular Bergell granite																									
685	Cantone	73.6	0.2	14.4	0.3	1.1	0.04	0.65	1.85	3.3	4.2	0.16	0.2	32.8	1.9	24.8	27.2	7.5	0	4.5	0	0.3	0.4	0.3	6
949	Ft. Sciora	69.0	0.26	17.4	1.2	1.25	0.04	0.6	1.85	3.4	4.7	0.09	0.25	25.9	4.3	28.4	27.7	7.7	0	3.8	0	1.3	0.5	0.2	6
Cameraccio granodiorite																									
1537	Cameraccio	68.0	0.36	16.1	0.8	1.85	0.06	1.45	3.1	3.65	3.9	0.18	0.35	24.3	1.2	20.2	30.5	13.1	0	8.6	0	0.8	0.8	0.4	11
1558	A. Pioda	66.0	0.37	17.3	1.15	1.7	0.06	1.45	3.0	3.5	4.0	0.23	1.1	23.3	3.1	21.3	29.2	12.3	0	8.0	0	1.2	0.8	0.5	10
1559	Cas. Pioda	66.0	0.37	16.7	0.9	1.6	0.06	1.4	2.95	3.5	4.0	0.19	2.25	23.6	2.4	21.7	29.5	12.4	0	7.9	0	1.0	0.8	0.4	10
Megacrystic granite in Gruf migmatites																									
* 808	Tegiola	69.0	0.28	17.35	1.15	1.3	0.04	0.7	1.95	3.65	3.9	0.11	0.15	27.3	4.6	22.9	30.5	8.1	0	4.3	0	1.2	0.6	0.2	6
1439	Codera	68.6	0.37	15.9	1.25	1.9	0.05	0.8	2.45	3.6	3.6	0.13	1.2	27.7	2.7	20.2	30.6	10.2	0	5.9	0	1.3	0.8	0.3	8
Novate granite																									
128	Novate	73.3	0.09	13.7	0.4	0.5	0.03	1.45	1.95	4.0	3.75	0.05	0.3	29.8	0	20.7	33.8	8.4	0	6.1	0.3	0.4	0.2	0.1	7
Sondrio intrusives																									
* 697	Triangia	72.2	0.2	15.5	0.3	1.5	0.07	0.7	3.0	3.0	2.8	0.16	0.4	36.1	3.0	15.0	25.6	13.4	0	5.6	0	0.3	0.4	0.3	7
* 698	Triangia	62.2	0.55	17.5	1.25	3.9	0.14	2.65	6.55	2.6	1.6	0.22	0.5	26.3	0.9	0	22.8	29.7	0	17.0	0.2	1.3	1.2	0.5	20
Microgranite																									
477	V. Largh	72.3	0.22	15.2	1.1	0.8	0.03	0.4	1.65	3.15	4.0	0.08	0.7	33.7	3.5	25.2	26.3	7.1	0	2.2	0	1.2	0.5	0.2	4
1080	Laret	69.7	0.35	15.6	0.2	2.1	0.03	0.8	2.4	3.8	4.0	0.18	0.8	26.2	1.7	21.8	31.9	9.6	0	7.2	0	0.2	0.7	0.4	9
1086	Sissone	73.7	0	14.7	0.1	0.8	0.03	0.15	1.1	4.7	3.9	0.07	0.6	27.3	1.0	24.1	39.9	5.0	0	2.2	0	0.1	0	0.1	2
1098	Forno	71.9	0.2	14.9	0.2	1.6	0.05	0.8	1.6	4.2	4.0	0.13	0.3	27.2	1.4	22.3	35.3	6.4	0	6.2	0	0.2	0.4	0.3	7
1101	Forno	70.5	0.21	16.05	0.7	1.15	0.04	0.45	1.95	3.8	4.65	0.07	0.45	25.0	1.8	28.2	31.3	8.5	0	3.5	0	0.7	0.4	0.1	5
1107b	Forno	72.9	0.2	14.7	0.4	1.1	0.04	0.7	1.0	3.9	4.9	0	0.1	27.4	1.6	29.1	32.0	4.3	0	4.6	0	0.4	0.4	0	5
1108	Rossi	75.5	0	13.9	0.2	0.8	0.03	0.9	0.1	4.7	3.7	0	0	31.3	2.2	21.0	39.8	0.5	0	4.8	0	0.2	0	0	5
Aplite dikes																									
665	Albigna	73.9	0.2	14.2	0.25	1.25	0.05	0.6	1.5	3.5	3.9	0.14	0.4	33.8	2.3	22.7	29.3	5.9	0	4.7	0	0.3	0.4	0.3	6
666	Albigna	74.1	0.25	14.2	0.3	1.4	0.05	0.4	1.35	3.3	3.9	0.15	0.5	35.6	3.1	23.1	27.6	4.9	0	4.3	0	0.3	0.5	0.3	5
932	Pr. Rossa	73.7	0.20	16.05	0.3	0.2	0.11	0.13	0.2	3.8	5.05	0.09	0.2	29.9	4.7	32.5	31.0	0	0	0.7	0	0.3	0.2	0.2	2
1102b	Rosso	77.0	0	12.9	0.2	0.45	0	0.2	0.9	3.7	4.5	0	0	34.0	0.3	28.6	30.6	4.5	0	1.5	0	0.2	0	0	2
1103	Rosso	75.3	0	13.6	0	0.45	0	0.1	0.8	3.3	6.2	0	0	28.7	0	39.8	25.8	4.0	0	1.3	0	0	0	0	1
1105	Rosso	70.5	0.16	16.15	0.75	0.9	0.03	0.3	1.25	3.75	5.25	0.06	0.5	24.5	2.6	33.0	30.6	5.3	0	2.4	0	0.8	0.3	0.1	4
1107c	Forno	76.3	0	13.3	0	0.35	0	0.2	0.2	3.7	5.8	0	0	30.0	0.6	37.0	29.6	1.0	0	1.5	0	0	0	0	2
1112b	Lera	72.8	0.1	15.2	0.35	1.2	0	1.0	1.4	4.0	3.9	0.12	0.1	29.7	2.5	21.7	33.4	5.8	0	5.8	0	0.4	0.2	0.3	7
Pegmatite dikes																									
364	Albigna	75.0	0.02	13.65	0.3	0.3	0.02	0.2	1.25	3.95	4.85	0.05	0.2	29.0	0	31.1	32.6	5.2	0	1.1	0.2	0.3	0	0.1	2
1112c	Lera	76.0	0	14.1	0.25	0.3	0	0.5	0.1	5.4	2.7	0.16	0.2	31.7	2.5	16.2	46.7	0	0	2.2	0	0.3	0	0.2	3
1112d	Lera	75.9	0	14.0	0.3	0.5	0.25	0.2	0	4.6	3.6	0.18	0.2	33.0	2.8	22.3	39.2	0	0	2.0	0	0.3	0	0	2
1238	Disgrazia	80.0	0.02	11.8	0.2	0.35	0.03	0.15	0.85	3.7	1.35	0.07	0.9	49.5	3.3	8.3	33.4	3.8	0	1.2	0	0.2	0	0.2	2
Gruf migmatites and related rocks																									
116	Codera	69.0	0.55	15.2	1.5	2.15	0.06	0.9	3.15	3.4	3.55	0.18	0.4	28.0	1.3	19.3	28.7	12.7	0	6.6	0	1.6	1.2	0.4	10
531	Borgonovo	67.7	0.26	17.4	1.2	1.4	0.05	0.85	2.25	3.8	4.5	0.11	0.3	22.4	3.1	26.2	31.4	9.6	0	5.0	0	1.3	0.5	0.2	7
531b	Borgonovo	65.0	0.51	18.6	1.45	3.0	0.06	1.2	3.6	3.5	2.25	0.18	0.4	27.5	5.5	8.9	30.4	15.1	0	9.5	0	1.5	1.1	0.4	12
534	Torta	64.2	0.7	17.0	0.6	4.45	0.11	1.5	3.7	3.9	2.7	0.35	0.4	23.3	2.9	8.7	33.7	13.8	0	14.6	0	0.6	1.5	0.7	17
1017	Trubinasca	69.9	0.55	14.2	0.6	2.7	0.05	0.9	2.0	3.5	4.5	0.19	0.7	27.4	1.2	24.4	29.0	6.9	0	8.6	0	0.6	1.2	0.4	11
1112a	Lera	71.1	0.35	14.6	0.5	2.0	0.07	1.0	1.8	3.6	4.4	0.22	0.2	28.4	1.8	24.2	29.8	6.3	0	7.6	0	0.5	0.7	0.5	9
1438	Gruf	67.0	0.35	15.2	1.2	2.5	0.07	1.6	3.15	3.3	3.8	0.11	1.7	25.7	0.7	18.9	27.8	14.0	0	10.3	0	1.3	0.7	0.2	13
1539	Cameraccio	69.0	0.48	15.5	1.1	2.1	1.05	1.0	2.8	3.6	3.3	0.29	0.6	28.6	2.4	15.8	30.4	10.4	0	9.3	0	1.2	1.0	0.6	12
1554	Torrone	67.0	0.49	17.2	0.95	2.45	0.08	1.2	2.8	3.8	2.85	0.22	0.85	27.2	4.3	13.2	32.7	10.9	0	8.9	0	1.0	1.0	0.5	11
Sivigia diorite																									
–1014	Sivigia	59.5	0.3	20.2	0.4	2.25	0.06	3.20	7.3	4.7	1.5	0.14	0.3	11.1	0	0	40.6	29.2	0.6	15.4	1.7	0.4	0.6	0.3	19
–1015	Sivigia	54.6	0.55	14.4	0.85	9.25	0.21	11.00	3.6	2.4	1.7	0.12	1.2	9.6	3.3	0	20.5	15.2	0	17.7	31.3	0.9	1.2	0.3	51
Old granitic rocks																									
Tambo nappe																									
62	Promontogno	73.3	0.16	14.6	1.15	0.65	0.04	0.3	0.95	3.15	4.85	0.24	0.4	33.2	3.6	31.2	25.6	2.6	0	1.5	0	1.2	0.3	0.5	4
328	Marlun	76.8	0	11.9	0.35	1.2	0.07	0.4	0.4	1.9	5.9	0.14	0.7	40.9	2.3	37.2	13.7	1.1	0	3.9	0	0.4	0	0.3	5
572	Pianazzola	70.7	0.33	16.35	0.95	2.05	0.03	0.6	1.2	3.2	4.05	0.11	0.25	32.5	5.8	23.2	26.5	4.1	0	5.7	0	1.0	0.7	0.2	8
677	Bondasca	71.7	0.5	14.3	0.4	2.45	0.04	0.9	1.85	2.8	4.7	0.25	0.2	32.5	2.8	25.9	22.4	5.9	0	8.2	0	0.4	1.1	0.5	10
723	Chiavenna	73.9	0.4	13.5	0.15	2.25	0.05	0.7	1.1	2.5	4.9	0.21	0.1	37.1	3.5	27.9	19.7	2.8	0	7.3	0	0.2	0.9	0.4	9
740	Castasegna	73.6	0.35	13.8	0.5	1.85	0.06	0.6	1.45	2.7	4.6	0.20	0.2	35.9	3.0	26.9	21.7	4.8	0	5.8	0	0.5	0.7	0.4	8
801	Soglio	68.7	0.20	17.85	1.1	1.2	0.04	0.75	1.0	3.35	5.05	0.23	0.35	26.7	6.5	30.4	27.0	2.8	0	4.3	0	1.2	0.4	0.5	6
Suretta nappe																									
1140	Cambun	72.7	0.15	15.65	1.2	0.9	0.03	0.4	0.45	3.0	4.45	0.17	0.65	35.8	6.3	28.1	24.6	0.6	0	2.3	0	1.3	0.3	0.4	4
1190	Passo Lago	72.6	0.06	13.8	1.2	0.6	0.02	0.2	1.85	3.05	4.8	0.21	1.35	31.6	0.9	31.5	25.0	7.8	0	0.9	0	1.3	0.1	0.5	3
Margna nappe																									
90	Maloja	71.3	0.23	15.1	1.35	1.2	0.04	0.6	1.25	3.65	4.05	0.16	0.85	30.7	3.5	24.6	30.7	4.4	0	3.6	0	1.4	0.5	0.3	6
1021	Maloja	68.0	0.32	17.6	1.1	2.0	0.06	0.8	1.85	3.65	3.7	0.16	0.6	27.5	5.5	20.4	30.7	7.1	0	6.3	0	1.2	0.7	0.3	8
Tonalite																									
Central area																									
287	Porcellizzo	59.2	0.82	16.1	2.6	3.5	0.10	3.75	6.0	3.3	2.3	0.28	1.7	19.3	0	3.3	28.8	22.9	0	19.3	1.1	2.8	1.8	0.6	26
714	Bagni	53.5	0.85	18.6	2.1	5.8	0.17	4.4	8.6	3.5	2.0	0.35	0.2	7.1	0	0	30.1	29.1	6.5	20.8	1.6	2.2	1.8	0.7	34
1072	Colino	56.3	0.67	18.7	3.1	3.05	0.09	5.25	5.45	3.2	1.6	0.17	2.3	17.3	3.4	0	28.2	24.1	0	17.0	4.8	3.3	1.4	0.4	27
1106	Rosso	58.0	0.79	18.1	2.5	3.45	0.11	3.35	6.4	3.2	2.85	0.29	1.0	15.3	0	7.8	27.2	26.9	0	17.6	0.2	2.6	1.7	0.6	23
1376	N. Olonia	58.6	0.54	17.1	2.7	4.25	0.11	2.5	6.8	3.0	2.6	0.28	1.2	17.9	0	7.3	25.9	26.2	0	16.1	1.9	2.9	1.2	0.6	23
1399	Filorera	57.6	0.74	17.9	3.1	4.4	0.14	2.7	6.1	2.95	2.4	0.30	1.3	18.7	1.1	5.5	25.6	26.5	0	16.9	0	3.3	1.6	0.6	22
1410	Colino	58.0	0.62	17.95	2.85	4.6	0.12	2.8	6.9	2.95	1.6	0.16	1.3	19.5	0	0	26.1	31.8	0	17.1	0.6	3.1	1.3	0.3	22
1412	Malvedello	57.6	0.66	17.5	3.5	3.8	0.12	3.45	6.6	3.05	1.8	0.16	1.4	18.9	0	0.7	26.9	29.5	0	18.0	0.3	3.8	1.4	0.3	24
1414	Poira	62.0	0.55	17.6	2.2	3.5	0.10	2.0	5.15	2.75	2.7	0.14	1.3	24.2	2.0	9.8	23.5	23.3	0	13.1	0	2.4	1.2	0.3	17
1538	Cameraccio	57.5	0.95	18.6	2.1	4.2	0.14	3.3	5.3	3.5	2.1	0.87	1.2	19.7	4.7	1.7	30.6	17.6	0	19.5	0	2.2	2.0	1.9	26
1547	Pso. Mello	59.0	0.67	18.3	2.0	4.0	0.12	3.4	6.05	3.55	2.0	0.10	0.7	17.3	0.4	1.0	30.8	27.3	0	19.3	0	2.1	1.4	0.2	23
Contact with amphibolites																									
* 322	Trubinasca	48.7	1.00	17.7	2.5	7.7	0.21	6.0	9.4	3.4	2.5	0.53	0.2	0	0	0	28.4	25.6	11.4	26.0	2.6	2.6	2.1	1.1	46
* 973	Sissone	45.0	1.10	19.6	4.75	7.2	0.16	6.1	12.9	1.8	0.6	0.19	0.5	0	0,	0	12.1	44.4	24.2	6.4	5.1	5.1	2.3	0.4	43
*1091	Sissone	50.0	0.85	16.8	2.6	6.25	0.19	7.4	11.3	2.3	1.1	0.11	1.2	0.5	0	0	20.1	32.6	30.3	11.6	0	2.7	1.8	0.2	47
*1555	A. Pioda	52.2	1.08	17.2	2.75	5.95	0.21	6.2	8.2	3.15	1.55	0.08	1.15	5.1	0	0	27.6	28.6	12.4	16.3	4.5	2.9	2.3	0.2	39
*1556	A. Pioda	55.8	0.82	18.7	2.4	4.45	0.14	3.65	6.15	3.25	2.3	0.14	2.0	15.1	1.2	2.1	28.3	27.4	0	21.2	0	2.6	1.8	0.3	26
Inclusions in granite and granite contact																									
* 846	Albigna	55.2	0.85	14.0	1.4	4.4	0.18	7.6	7.4	2.6	5.3	0.59	0.5	9.5	0	11.8	19.8	10.8	0	35.9	7.6	1.5	1.8	1.2	48
* 869	Castello	57.2	0.75	14.7	1.3	4.1	0.14	6.4	7.1	3.4	3.6	0.58	0.6	12.7	0	3.9	28.1	14.2	0	31.0	5.8	1.4	1.6	1.2	41
*1553	Torrone	61.5	0.65	17.8	1.7	3.45	0.11	2.7	4.95	3.75	2.7	0.08	0.55	18.1	0.8	7.8	32.1	21.9	0	15.8	0	1.8	1.4	0.2	19
*1557	A. Pioda	61.5	0.69	18.8	1.8	2.85	0.08	2.3	4.4	3.6	3.05	0.22	1.0	19.2	3.3	11.9	30.6	18.1	0	12.9	0	1.9	1.5	0.5	17
*1560	Remoluzzo	61.8	0.74	17.3	1.8	3.1	0.10	2.4	4.6	3.2	3.1	0.81	0.8	22.9	3.6	11.7	27.2	15.2	0	14.0	0	1.9	1.6	1.7	19
Dikes																									
*1477	Vazzeda	51.6	0.97	19.9	2.05	6.8	0.15	3.75	7.35	2.5	2.55	0.52	1.5	13.1	2.4	0.2	21.3	30.5	0	27.0	0	2.2	2.1	1.1	32
Amphibolites																									
* 107	Pso. Bondo	46.0	1.4	14.1	2.15	4.65	0.12	10.75	11.25	2.1	3.85	1.12	2.35	1.1	0	0	16.5	17.8	8.4	40.3	8.2	2.3	2.9	2.4	64
122	Plan Canin	47.8	1.75	16.05	3.55	5.9	0.15	8.2	10.65	2.65	0.55	0.23	2.65	0	0	0	20.9	31.0	23.6	5.9	10.5	3.8	3.7	0.5	48
186	Gerp	42.1	1.6	14.3	3.75	8.5	0.23	13.5	12.3	1.8	0.3	0.04	1.5	0	0	0	3.1	30.2	40.4	3.1	0	3.9	3.4	0.1	66
371	Trienza	44.0	4.1	13.3	2.4	12.35	0.22	7.25	11.4	2.3	0.4	0.10	1.8	0	0	0	12.5	25.9	28.2	4.4	12.5	2.6	9.0	0.2	61
586	Furcela	51.2	1.3	14.6	4.6	5.05	0.15	6.75	8.1	4.0	0.35	0.14	3.5	0.9	0	0	37.0	21.6	21.6	3.8	7.1	5.0	2.8	0.3	41
590[1]	Furcela	46.6	1.55	13.9	2.45	5.8	0.16	6.65	12.1	3.25	0.12	0.18	3.6	0	0	0	23.1	24.7	41.9	1.3	2.4	2.8	3.5	0.4	52
601	Lavinair	53.0	1.05	14.6	0.15	7.05	0.09	6.2	12.7	2.35	0.4	0.19	1.95	2.1	0	0	21.4	28.9	38.4	4.3	2.1	0.2	2.3	0.4	48
658	Bagni	52.1	1.4	16.5	2.6	6.3	0.16	6.4	11.2	2.7	0.4	0.21	0.2	2.0	0	0	24.1	31.9	26.5	4.2	5.2	2.7	2.9	0.4	42
* 688	Furcela	51.0	1.35	15.1	2.5	5.6	0.14	10.0	5.9	4.25	0.15	0.17	4.1	0	0	0	37.8	22.0	2.9	1.6	22.5	2.7	2.9	0.4	40
805	Soglio	51.5	1.9	16.0	2.95	7.25	0.15	5.8	7.4	3.6	0.85	0.18	2.2	3.5	0	0	32.7	25.7	6.1	9.1	15.3	3.2	4.1	0.4	38
888	Turbine	46.5	1.85	14.6	4.65	8.55	0.26	7.7	10.2	2.4	0.55	0.26	2.6	0	0	0	19.1	28.5	24.0	5.9	12.8	5.0	4.0	0.6	52
912	Forno	47.9	1.8	16.2	2.5	9.1	0.22	5.4	13.1	3.0	0.6	0.24	0.1	0	0	0	19.0	29.3	36.3	6.3	2.1	2.6	3.8	0.5	52
941	Pr. Rossa	43.1	2.25	19.1	2.9	7.4	0.14	7.1	14.4	2.9	0.3	0.45	0.2	0	0	0	5.3	38.1	35.9	3.1	0	3.0	4.7	0.9	51
974	Sissone	46.0	1.6	14.4	5.0	9.05	0.26	8.4	12.6	1.6	0.3	0.23	0.5	0	0	0	9.6	32.0	38.1	3.2	7.8	5.4	3.4	0.5	58
986	Grande	50.4	0.9	17.6	2.3	5.4	0.15	8.0	11.1	3.6	0.1	0.18	0	0	0	0	24.2	31.2	30.0	1.0	9.0	2.4	1.9	0.4	45
987	Grande	48.0	1.05	19.5	2.9	3.95	0.10	6.6	12.75	2.9	0.12	0.13	1.95	0	0	0	20.3	40.3	29.9	1.3	2.7	3.1	2.2	0.3	39
988	Vazzeda	52.4	1.1	15.9	1.4	6.6	0.14	7.7	9.7	4.5	0.2	0.16	0	0	0	0	31.0	22.3	32.3	2.0	8.4	1.4	2.3	0.3	47
989	V. Bona	50.4	1.15	17.4	2.65	5.7	0.18	6.7	10.7	4.1	0.3	0.24	0.5	0	0	0	28.9	28.0	30.3	3.1	4.1	2.8	2.4	0.5	43
990	Muretto	51.0	1.4	16.4	2.5	5.05	0.12	7.3	9.35	4.2	0.2	0.33	1.8	0	0	0	33.0	25.5	22.2	2.1	10.9	2.6	2.9	0.7	41
1094	Pian Lupo	50.0	1.0	18.3	0.95	6.25	0.16	7.8	10.2	3.6	0.1	0.06	1.6	0	0	0	25.6	33.4	21.2	1.0	11.9	1.0	2.1	0.1	41
1110	P. d. Rossi	48.2	1.85	14.3	2.75	7.1	0.16	7.3	10.6	5.9	0.3	0.21	1.3	0	0	0	23.5	11.6	43.1	3.1	2.4	2.9	3.8	0.4	56
1379	Lizöl	55.0	1.27	16.8	4.45	3.85	0.12	4.25	9.95	2.75	0.2	0.12	1.2	11.7	0	0	25.2	33.8	17.3	2.1	2.0	4.8	2.7	0.3	29

[1]) Contains 3.45% CO_2.

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Rossa and W of Cevo. In the southern massive tonalite complex fold axes plunge *westward*. The linear texture of tonalite given by the orientation of hornblende prisms, is very pronounced (Moticska, 1970).

It is puzzling that Bergell granite is surrounded on all sides by *calcic* rocks (H.-R. Wenk, 1973). Apart from local exceptions, they constitute the contact. These calcic rocks are rich in hornblende and form amphibolites to the north and east. To the south, they appear as an alkalifeldspar bearing hornblende-biotite-andesine-gneiss which has been called "*serizzo*" by Italian geologists and "*tonalite*" by Swiss. It was assumed to be an igneous rock formed by magmatic differentiation during Alpine plutonism in the Bergell area (Staub, 1924; Gyr, 1967; Condcliffe and Mottana, 1976). Therefore, megacrystic Bergell granite ("Ghiandone") and Bergell tonalite ("Serizzo") have been given similar colors on geological maps and were classified together despite their very different chemical and mineralogical composition and despite their different geographical distribution. We will use the term "tonalite" in this paper to describe the mobilized hornblende-biotite-gneisses without attaching to it any genetic significance.

As can be seen in Fig. 1, the hornblende-bearing rocks extend as a tectonically thinned band of mixed tonalite and amphibolite in the north. Along the eastern granite contact (Forno–Rossi–Murtaira) they form a thick sequence of amphibolites, penetrated by dikes of aplite and microgranite. Farther south at Alpe Sissone, fine-grained amphibolites change into coarse hornblende gneiss of gabbroic character over a distance of a few hundred meters. Some outcrops near Cap. del Grande (777.30/131.15) and above A. Sissone (777.4/130.2) are spectacular and display hornblende crystals up to 5 cm in size (Fig. 2a). Veins of mobilized calcic material become frequent farther SW (Fig. 2b), and this rock of igneous character composes in a massive sequence the whole southern part of the contact with Bergell granite. In most of this "tonalite", we observe many inclusions of dark, hornblende-rich material which – in the field – are easiest interpreted as restites, i.e. undigested relicts (Fig. 2c). Other restites occur in the tonalite far from any contact and include olivine-enstatite ultramafic rocks (Pso. di Mello, V. Codera-Porcellizzo), calcite marbles (Val Sissone-Cameraccio, V. Codera, Vicosoprano, including spinel-phlogopite-forsterite-pargasite-calcite marbles at Pso. di Mello and the rhodonite bearing calcsilicate rocks at Bagni Masino), cordierite and andalusite bearing pelitic schists (e.g. cordierite-spinel-phlogopite-anthophyllite schists at Pso. di Mello and corundum-margarite-phlogopite-clinozoisite fels at V. Preda Rossa) and biotite-alkalifeldspar gneisses (A. Cameraccio, V. dei Ratti). In the mountains between V. dei Ratti and Valtellina, tonalite is most extensive and homogeneous. It extends as a narrow tail as far west as Bellinzona (Weber, 1957). Thus, structurally, tonalite and amphibolite appear closely related and can be regarded as a three-dimensional fairly complete envelope of the Bergell granite as documented by the granite border, by windows in the granite displaying the base (Bagni Masino, V. Ferro, Albigna, A. Pioda) and by inclusion zones in the roof (Cma. di Castello, Pso. Bondo, Sciora Dadent).

The granite-tonalite contact is best accessible in Val Masino. A transition zone about 500 m wide, in which the hornblende content increases and the content of alkalifeldspar megacrysts gradually decreases, is well exposed in quarries between Cataeggio and San Martino. The rocks in this zone are heterogeneous with hornblende-rich xenoliths floating in a granite matrix. Many xenoliths occur as swarms and resemble a breccia which marks the contact. This heterogeneity in the well-foliated southern flank of the granite, which is expressed as alternating bands of granite and tonalite, could be the result of isoclinal folding which is very common in the surrounding rocks.

3. THE SAMPLES
GEOGRAPHIC DISTRIBUTION AND PETROGRAPHIC DESCRIPTION

Table 1 contains a listing of all samples for which chemical analyses are given in Table 2. Sample numbers refer to the Sci collection of H.R.W. Sample localities are defined by the local name and coordinates of the Swiss National map. They are also marked on the map in Fig. 1. A brief petrographic description is added for each specimen. It includes An content of plagioclase which has been determined either with the universal stage microscope using the zone method (An is given in the list), or with microprobe (An Ab Or are calculated from analyses of Ca, Na, K).

The rocks are divided into groups according to tectonic setting and petrographic composition and in the graphical representations different symbols are assigned to each. In addition to 107 new analyses, we included in all graphical representations and calculations, but not in Tables 1 and 2 and Fig. 1, 60 analyses available in the literature. There are special cases such as inclusions, rocks from direct contact and mobilisates within a rock which are difficult to classify. While many are of particular petrologic interest and will be discussed in some detail, they are only representative of very small volumes. They are marked with asterisks in Tables 1 and 2.

Bergell granite is either megacrystic or equigranular. Large alkalifeldspars with an Ab content of 7–12% are perthitic and appear microscopically as orthoclase. They generally contain more or less euhedral and oriented plagioclase inclusions. X-ray powder investigations of triclinicities shows a large spread with no regular pattern (Gyr, 1967; Wenk, 1967). Almost all granite samples show frequent myrmekitic texture. Alkali-feldspar associated with myrmekite and large megacrysts have a similar chemical composition. Plagioclase is generally homogeneous, An contents range from 20 to 38% and average to 25, Or content is about 1.5% and constant throughout the massif. Plagioclase occurs as rather large euhedral crystals and as small inclusions in alkali-feldspar, both have the same composition. Rarely, except in the NE corner of the field of occurrence, it shows either normal or oscillatory zoning.

The main femic mineral is a greenish-brown biotite with lamellar alteration to chlorite (clinochlore with brown interference colors). Subordinate phases are hornblende and muscovite. Magnetite, apatite and allanite are common accessories, other opaques (hematite, ilmenite), zircon and monazite are more rare, the latter producing pleochroic halos in biotite.

Textures are typical of intense deformation (compare Figs. 11 and 12 in Wenk, 1973). Many large feldspar crystals are broken and bent. Quartz is either strongly undulatory or mylonitic with fine-grained recrystallization. Mylonitic and cataclastic texture is particularly pronounced in inclusions of megacrystic granite in the Gruf complex (808, 19439) which are also characterized by strong zoning of plagioclase.

For a detailed discussion of the quartz-feldspar reactions and intergrowths we refer to the exellent papers of Drescher (1940, 1948, 1969).

Cameraccio granite is a homogeneous granitic rock from the border between megacrystic Bergell granite and tonalite and is similar to the equigranular variety of Bergell granite. These two rocks may actually represent the same unit although the contact between Bergell granite and Cameraccio granite is usually sharp with occasional cross cutting relations, while the contact between megacrystic and equigranular Bergell granite is gradual.

Sondrio igneous rocks can immediately be recognized in thin sections by their typical igneous appearance with strongly zoned, euhedral plagioclase and interstitial quartz. There is lack of significant deformation in these rocks which occur very close to the young Insubric fault. In contrast to Bergell granites the Sondrio igneous rocks are definitely postkinematic.

Microgranites are associated with the central granite body and occur as large dikes or lenses both in granite and country rocks. In contrast to Bergell granite microcline (Ab 5–10) is the dominant alkalifeldspar, plagioclase (An 15–30) is zoned and usually altered with large muscovite flakes in the core region, myrmekite is common. Quartz is deformed and undulatory, in some samples we observe recrystallization. Brownish-green biotite shows frequently halos around tiny inclusions. Muscovite is the dominant mica. Chlorite has characteristically blue interference colors. Epidote minerals are present in most thin sections but generally no allanite.

Microgranites associated with Bergell granite resemble in the field *Novate-granite* (Piccoli, 1962) which forms a stock of penetrating dikes and migmatites and is situated to the West and tectonically below the Bergell granite. Strong cataclastic deformation with bent plagioclase and broken quartz, lack of zoning and alteration in plagioclase and predominance of biotite over muscovite distinguish it from Bergell microgranites.

Aplites differ from microgranites particularly by finer grain size and a clear excess of light mica. Plagioclase is less altered but more intensively deformed with quartz extremely fine grained and strung out into highly flattened grains.

Pegmatites with graphic texture of alkalifeldspar and coarse perthite exsolution contain garnet, tourmaline, beryl and sporadically dumortierite, cosalite and some rare phosphate minerals (MAURIZIO and LAREIDA, 1975). They are often zoned with micaceous and quartzofeldspathic layers (e.g. Fig. 2c). An of plagioclase is 10–15%. We notice to our surprise that also these leucocratic rocks, which were formed last, are deformed.

The relative age sequence of leucocratic rocks is microgranite-aplite-pegmatite. Occasionally aplites crosscut pegmatites. Occurrence of abyssal rocks is not restricted to Bergell granite but extends across the contact into Gruf migmatites, amphibolites and also into ultramafic rocks belonging to the Disgrazia complex. We notice that in this latter case plagioclase is albite (An 5).

Migmatites form a rather heterogeneous group of isoclinically folded alkalifeldspar-biotite gneisses. Microscopically they resemble Bergell granite but mylonitization is usually more advanced. Most of the analyzed samples are from the extensive Gruf complex but we added gneiss inclusions in tonalite of unknown tectonic origin (1539, 1554) to this group. Also enclosed are two analyses of "Sivigia diorite" (WENK, 1973; compare his Fig. 5b, c), a megacrystic labradorite-hornblende-hypersthene rock (1014) transformed from a brecciated ultramafic sequence (1015) which has become well-known for metasomatic transformations with spherical zoning (ARTUS, 1959).

Old granites occur as extensive sequences of augengneisses in the upper Pennine nappes. They recrystallized from Prealpine granites (at least in the Tambo nappe they are of Hercynic age, GULSON, 1973) during Alpine regional metamorphism and most major minerals – with exception perhaps of the large microcline "augen"-megacrysts reflect the metamorphic conditions. They are greenschist facies in Margna, Suretta, and part of Tambo nappe and grade into amphibolite facies with closer proximity to Gruf migmatites and Bergell granite contact. Plagioclase is generally albite except for some high grade samples of the same sequence in Val Bondasca (328, 677). As anorthite content increases, red-brown biotite becomes more common. In Margna augengneisses from Maloja Pass only muscovite is present. We notice that the fabrics of these "old" rocks show fewer features of plastic deformation than both Bergell granite and Gruf migmatites. Recrystallization occurred at a late stage with quartz attaining preferred orientation in a perfect mosaic pattern and barely undulatory.

Bergell tonalites are strongly lineated hornblende-biotite gneisses, epidote, chlorite, sphene and often alkali-feldspar bearing. Plagioclase ranges in composition from An 28 (rims of zoned crystals which occur as tonalite inclusions in Bergell granite, 846, 869) to An 85 (contact with amphibolites, 973) but most compositions center around An 45–50. Apart from some unusual samples, normal and more rarely oscillatory zoning is not very pronounced. It extends from An 35–55 with both calcic core and sodic rim being quite homogeneous. Alkalifeldspar is very pure – more so than in granite – and generally recognized by myrmekitic texture. Quartz is present in most tonalite, often undulatory or recrystallized. There is a striking abundance of epidote. Occasionally, diopside coexists with hornblende, which may be partially actinolitic. Textures vary widely with an igneous resemblance in some samples but more often the fabric is recrystallized to a metamorphic mosaic texture. Deformation is indicated by fragments of broken plagioclase crystals.

Amphibolites have been collected in many different tectonic units. Some carry biotite and chlorite, quartz is usually subordinate or missing, and some high-grade samples contain diopside. In low grade rocks of "amphibolite" composition, hornblende is substituted by actinolite. Plagioclase composition varies from albite to bytownite, depending on metamorphic grade. Also, textures are very different from sample to sample, as is indicated in table 2. Poikiloblastic and porphyroblastic textures are generally typical for the border zones, while in the central part of high-grade metamorphism, lepidoblastic fabrics dominate.

4. CHEMICAL ANALYSES

4.1. Experimental procedure

Rock analyses were done at ETH by B. Ayranci and R. Heusser. Modified rapid methods were combined with atomic absorption analyses. The accuracy for SiO_2 is about ± 0.3–0.5% of the total amount present and for other components when present with more than 1% about ± 0.1–0.2%. We notice an excellent agreement between two independent analyses of the same rock (667 and 667a), indicating that the sampling of about 1 kg of material was adequate even for coarse megacrystic granites. Also we have done a few determinations on rocks from the same outcrops for which Richardson et al. (1976) have supplied data and agreement is very satisfactory (e.g. our 1376 and their PS 5, 659-PS 14, 667-PS 11, 1072-PS 38, 1414-VA 9) which makes us confident that different sampling procedures and different analytical methods applied at different laboratories yield comparable results.

4.2. Norm calculation

It is customary to recalculate weight percent oxides to a norm and we used the CIPW norm (Johanssen, 1931), modified for hornblende-biotite, following the procedure and applying computer programs by Hutchinson (1975). In the norm calculations we corrected Or-values to contain 10% Ab. The results of these calculations for most phases are listed in Table 2. From *normative* values we calculated Q-P-A, An-Ab-Or and A-C-F ternary diagrams (Fig. 5) which can be compared with *modal* diagrams (e.g. Streckeisen, 1967, 1976). While we corrected for alkali-feldspar composition we did not adjust for variations in hornblende composition assuming that they are minor (E. Wenk et al., 1974), and did not consider the presence of chlorite, muscovite and epidote which exist in significant quantities in some of the rocks.

5. STATISTICAL ANALYSIS

Chemical analyses can be represented in various ways. Variation diagrams (Fig. 3) illustrate the relationship between a single chemical variable and silica. They display a continuous distribution of data points. Ternary diagrams (Fig. 4) allow representation of three components. In some diagrams, we notice a clustering of points, defining groups. A more systematic way to explore differences between groups is to derive analytically those linear functions of all variables which minimize the dispersion within each group of rocks and maximize the differences between groups. This can be done by applying discriminant function analysis, a multivariate classification procedure which has been mainly developed for social sciences (Cooley and Lohnes, 1971), but has also been applied to geological problems (Griffiths, 1966, Isphording et al., 1976). A very lucid discussion of the theory of discriminant function analysis is presented by Davis (1973).

The discriminant function is a linear combination of the original variables in which each term is multiplied by a coefficient which can be related to the weighting of the original variable in the calculation of the discriminant score. The derived functions enable the determination of group similarities and differences, often reducing a multivariable problem for which we have little feeling to a one or two dimensional problem. The coefficients of the discriminant function are obtained by maximizing the ratio of the squared differences between the group centroids and the pooled within group variance. The transformation thus segregates the groups while reducing the area in discriminant space covered by each group. Large standardized coefficients indicate that the corresponding variables are most significant for the separation of groups.

Table 3. *Average composition of the most important rock groups (weight percent oxides) calculated mean and standard deviation (in parentheses)*

	Number	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O
Bergell granite	39	68.0	0.35	16.2	0.8	1.8	0.06	1.3	3.0	3.8	4.0
		(2.8)	(0.13)	(1.2)	(0.4)	(0.7)	(0.04)	(0.6)	(0.9)	(0.4)	(0.6)
	31*	67.6	0.36	16.2	0.8	1.9	0.06	1.3	3.1	3.7	4.1
		(2.5)	(0.11)	(1.1)	(0.3)	(0.6)	(0.04)	(0.5)	(0.9)	(0.4)	(0.5)
Gruf migmatites	12	67.6	0.51	16.1	1.0	2.5	0.16	1.2	3.0	3.5	3.6
		(2.0)	(0.15)	(1.3)	(0.3)	(0.7)	(0.28)	(0.3)	(0.9)	(0.3)	(0.7)
Old granites	11	72.1	0.25	15.0	0.9	1.5	0.04	0.6	1.2	3.0	4.7
		(2.5)	(0.14)	(1.8)	(0.4)	(0.7)	(0.05)	(0.2)	(0.5)	(0.5)	(0.6)
Tonalite	43	56.6	0.86	17.7	2.5	4.3	0.12	3.9	7.1	3.1	2.3
		(4.2)	(0.43)	(1.1)	(0.9)	(1.3)	(0.06)	(1.6)	(1.7)	(0.5)	(0.8)
	27*	56.9	0.87	17.8	2.6	4.2	0.11	3.6	7.0	3.1	2.1
		(2.2)	(0.53)	(0.7)	(0.8)	(0.9)	(0.05)	0.9	(1.0)	(0.5)	(0.5)
Amphibolites	24	48.4	1.58	15.9	3.0	6.7	0.18	7.3	11.2	3.2	0.7
		(3.3)	(0.64)	(1.6)	(1.2)	(1.9)	(0.06)	(1.8)	(1.9)	(1.0)	(0.9)
	22*	48.6	1.58	15.9	3.0	6.7	0.19	7.1	11.3	3.3	0.4
		(3.4)	(0.67)	(1.7)	(1.2)	(1.9)	(0.06)	(1.7)	(1.9)	(1.0)	(0.4)

* Omitting samples from contact and inclusions marked with asterisk (*) in Tables 1 and 2.

Table 4. *Coefficients for multivariate discriminant functions*

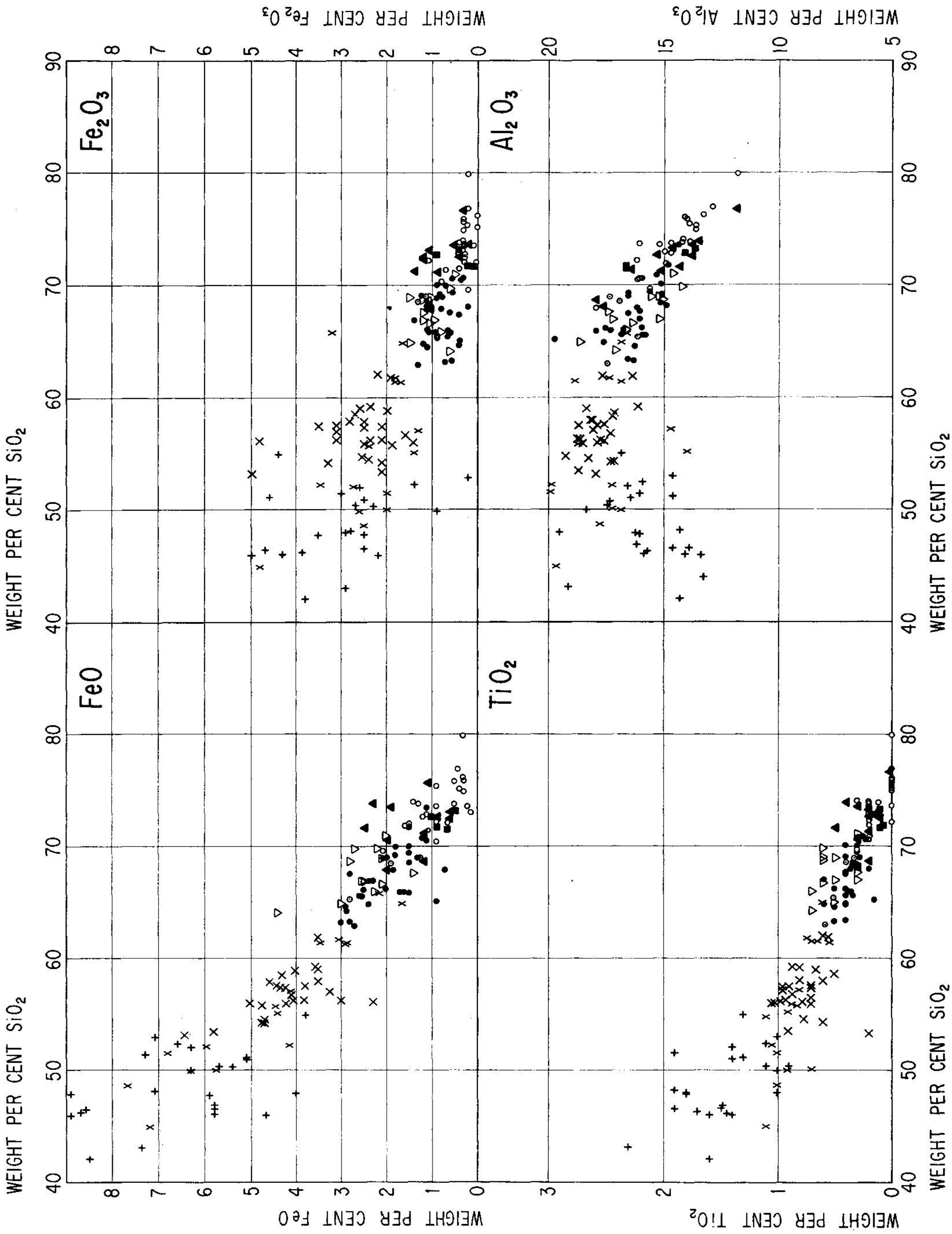
Variable j	Coefficient c_j Function 1	Function 2
SiO_2	0.88	3.57
TiO_2	−0.34	0.52
Al_2O_3	0.28	−0.32
Fe_2O_3	−0.22	−0.14
FeO	0.30	0.54
MnO	0.10	0.00
MgO	−0.56	1.61
CaO	−0.94	1.72
Na_2O	−0.22	0.70
K_2O	0.99	0.30
P_2O_5	−0.10	−0.21
H_2O	−0.17	−0.14
Eigenvalue	10.33	0.72
% trace	90.5	6.3

Discriminant function: $D_i = \sum_j c_j Z_{ij}$

(Z_{ij} = variable in standard normal form)

*c_j is the standardized discriminant function coefficient.

We divided all analyses into five groups (Table 3) omitting leucocratic hypabyssal rocks and Novate granite for which only a few analyses were available. Since there are five groups up to four functions may be derived from the data. The first function (see Table 4) shown as abscissa in Fig. 5 accounts for over 90% of the total variation and most heavily weighs K_2O, CaO, MgO and SiO_2. It clearly separates granitic rocks, including tonalites



Fe_2O_3
Al_2O_3
FeO
TiO_2
WEIGHT PER CENT Fe_2O_3
WEIGHT PER CENT Al_2O_3
WEIGHT PER CENT FeO
WEIGHT PER CENT TiO_2
WEIGHT PER CENT SiO_2

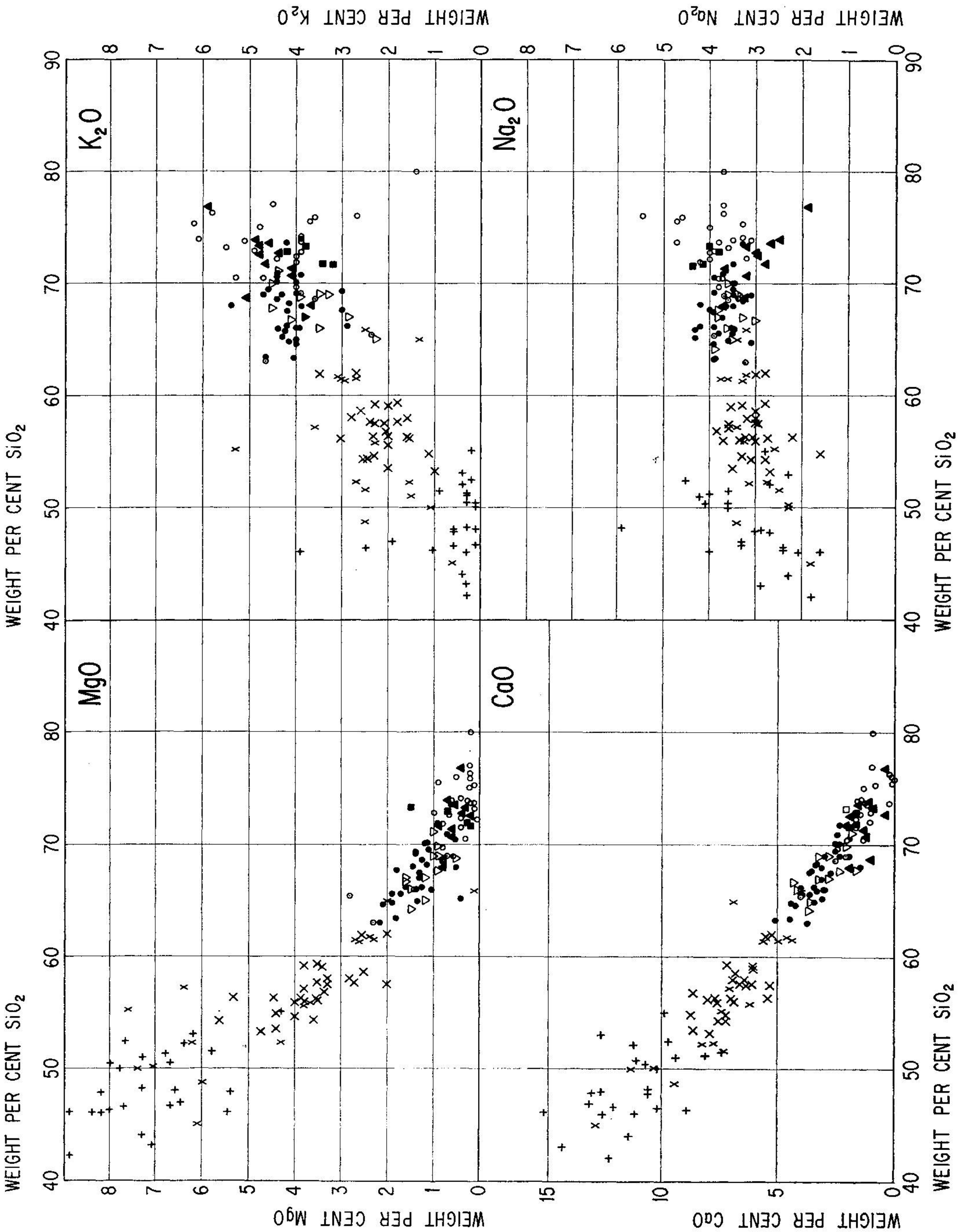


Fig. 3. Variation diagrams of oxides as a function of SiO_2-content (in weight percent). For symbols see Fig. 4.

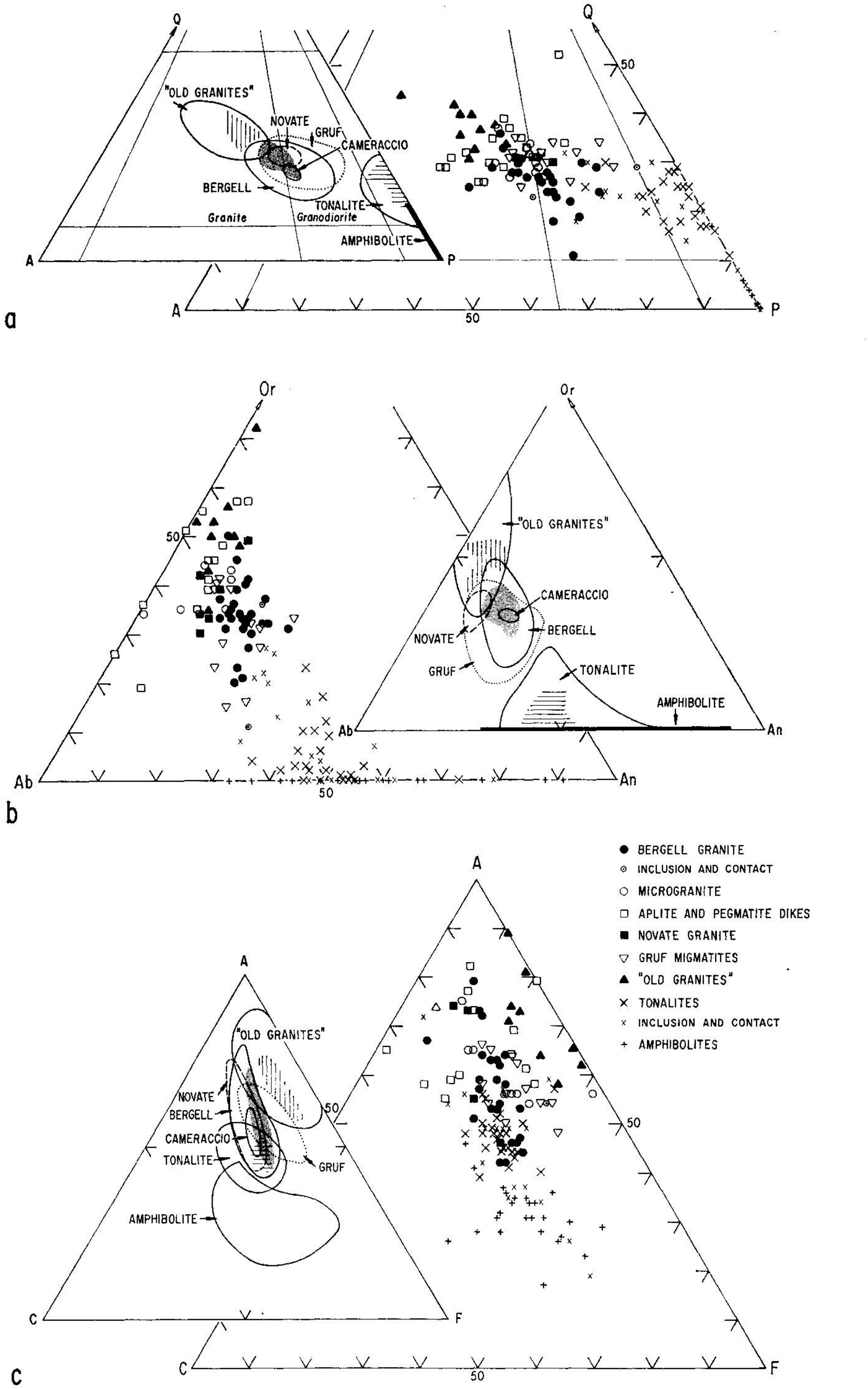


Fig. 4. Ternary diagrams calculated from normative values. 103 new analyses (excluding 697, 698, 1014, 1015) and 50 analyses available in the literature are represented. a) Q-P-A, b) Or-Ab-An, c) A-C-F. Inserted smaller triangles show groups.

Table 5. *Pairwise discriminant function analysis (compare Fig. 6)*

Variable j	Old granites-Gruf C_j*)	% added	Bergell-Gruf C_j	% added	Bergell-granites C_j	Old granites % added	Amphibolite-tonalite All variables C_j	% added	Amphibolite-tonalite w/o K_2O, Na_2O C_j	% added	Bergell-tonalite C_j	% added
SiO_2	23.19	470.65	1.25	−8.03	−0.69	−24.56	1.31	−65.29	0.80	−64.01	2.08	145.0
TiO_2	6.98	−8.42	6.56	19.57	−13.80	11.83	3.17	13.98	2.44	17.17	−1.49	4.68
Al_2O_3	26.95	−136.37	0.94	−1.71	−1.38	14.50	−0.20	2.22	−0.27	4.79	1.63	−15.29
Fe_2O_3	8.07	−6.0	4.04	18.95	3.12	2.68	1.20	3.54	0.51	2.44	0.08	−0.81
FeO	25.85	−116.87	3.56	42.38	8.56	−24.46	1.25	18.58	0.60	14.24	1.79	−27.10
MnO	−3.66	2.11	4.47	8.44	−46.13	8.46	−9.29	−3.54	−4.67	−2.84	14.89	−5.56
MgO	−0.77	2.00	−2.77	4.78	−4.58	26.50	2.25	46.77	1.46	46.50	1.11	−18.18
CaO	17.52	−136.24	0.42	0.04	−5.80	85.78	2.51	62.91	1.93	76.90	1.35	−34.48
Na_2O	16.40	−39.10	1.51	−5.82	0.29	−1.84	3.62	2.48	–	–	1.82	7.71
K_2O	19.26	89.45	−0.39	2.90	−1.15	−6.06	−1.46	14.14	–	–	3.96	43.03
P_2O_5	26.57	−3.62	10.90	16.95	15.56	7.70	1.67	−0.37	−0.42	0.15	−1.04	0.91
H_2O	31.68	−17.58	2.02	1.56	0.79	−0.54	2.44	4.59	1.55	4.66	−0.03	0.10
Calculated F value	5.05		3.35		6.41		17.47		13.58		24.00	
Test F value	(0.01, 12, 10) = 4.71		(0.01, 12, 38) = 2.69		(0.01, 12, 37) = 2.70		(0.01, 12, 54) = 2.53		(0.01, 10, 56) = 2.66		(0.01, 12, 69) = 2.45	
D_1 Centers and	2304		122.6		−70.3		134.8		77.1		199.2	
D_0 midpoint of	2293		119.8		−76.1		126.6		72.0		191.0	
D_2 groups.	2282		116.9		−81.9		118.4		66.9		182.9	
Mahalanobis D^2	22.19		5.64		11.63		16.38		10.24		16.33	

– Null hypothesis for all analyses is $D_1 = D_2$ (mean discriminant score for Group 1 is equal to the mean of Group 2, i.e., all samples are from the same group).

– Test F value (a, b, c) is calculated for the 100(1−a)% confidence level for a distribution with b and c degrees of freedom (b is the number of variables and c+b+1 is the number of samples).

*) Coefficients C_j are *not* standardized.

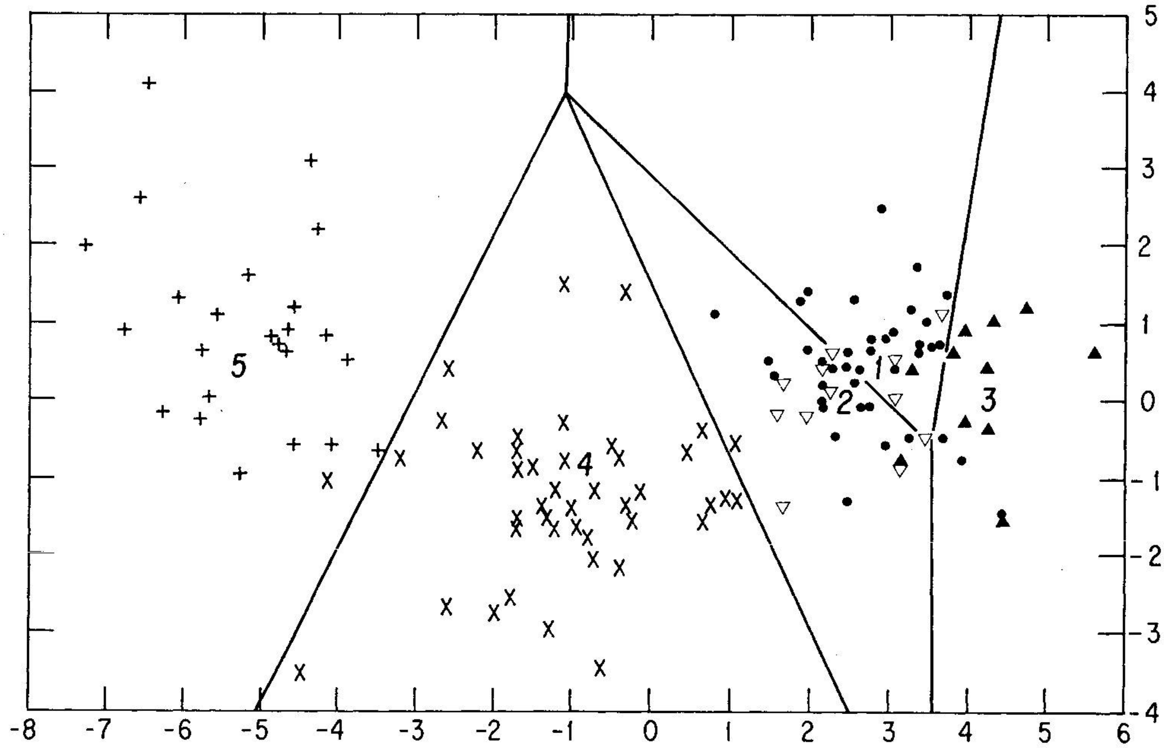


Fig. 5. Plot of discriminant scores. Numbers represent group centroids and refer to Bergell Granite (1), Gruf migmatites (2), old granites (3), tonalite (4), and amphibolites (5). Coefficients for the two functions are given in Table 4 (function 1: abscissa, function 2: ordinate). Territorial separation is indicated.

from amphibolites. The second function which accounts for over 6% of the total variation weighs SiO_2, CaO, TiO_2 and MgO heavily. This function shown as ordinate in Fig. 5 distinguishes siliceous from the more basic rocks, although the separation is less obvious than for the first function. The heavy weight of TiO_2 indicates that some of the groups have a higher proportion of Ti minerals present. The other functions account for less than 3% of the variation and were not considered further. A combination of the two functions shows a clear segregation into clusters with sharp boundaries between all groups except Bergell granite, old granites, and Gruf migmatites (Fig. 5). Most significant is the large separation of tonalite and Bergell granite which do not even occupy adjacent fields.

Differences between two groups can be examined further by pairwise discriminant functions as shown for granitic rocks in Fig. 6a (see Table 5 for accompanying statistics). All groups were found to be statistically distinct i.e. they have calculated F values greater than the test value. The Null Hypothesis, which states that the centroids of two groups are the same ($D_1 = D_2$), was rejected in all cases, although there was a significant number of misclassified samples in the Gruf-Bergell comparison. The best discriminating variables

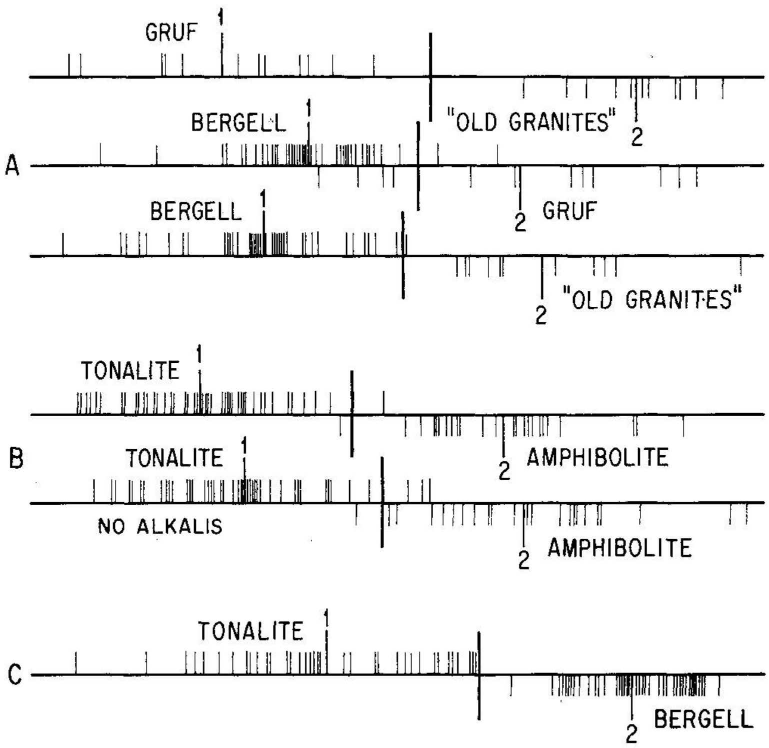


Fig. 6. Plot of pairwise discriminant scores for granitic rocks (a), for calcic rocks both with and without consideration of alkalis (b) and for Bergell granite and tonalite (c). Numbers refer to group centroids and dotted lines refer to the midpoint of the group centroids. Compare Table 5 for scale.

are those whose relative contribution (% added in Table 5) to the spread of the groups is large and greater than zero. Those variables with a negative percent added act to merge the two groups. Another index of the effectiveness of the discriminant function is the Mahalonobis D^2 value which is defined as the difference between the midpoint of the group centroids and each centroid. The Gruf-Bergell comparison has the smallest D^2 value of the pairwise analyses of the granites. Bergell granite and the Gruf migmatites appear to be most similar. In a second analysis we compared tonalites and amphibolites (Fig. 6b), first considering all elements. D^2 is large and the F statistic is significant (Table 5) indicating that the groups are different. The efficiency of the function defined as the number correctly classified over the total number of samples is 97%. Key discriminators are MgO and CaO with the alkalis contributing slightly to the separation of the groups. In order to decide whether alkali metasomatism is responsible for the group separation alkalis were removed from the analysis. This reduces the D^2 value but it is still significant. Major discriminators are still MgO and CaO while silica contributes negatively to the separation. A comparison of tonalites and Bergell granite demonstrates that these two rock types are more significantly separated than any of the other groups (Fig. 6c) with SiO_2 and K_2O being the most distinguishing elements.

Statistical analysis has thus borne out many aspects of the chemical variations in these rocks that are not obvious in conventional representations.

6. GRANITIC ROCKS

Prealpine granites in the upper Pennine nappes are generally rich in K, poor in Ca, Mg, Fe. SiO_2 ranges from 68 to 77% and averages to 72. All these rocks plot in the field of normal granites in the normative Q-P-A diagram in Fig. 4a (using STRECKEISEN's, 1967, 1976 nomenclature).

In *migmatites* of the lower Pennine nappes, particularly the Gruf complex, the chemical composition is more variable, they are richer in Ca and Fe-Mg and correspondingly lower in Si and plot in the field of granite-granodiorite. We think that they represent reworked and partially remobilized crystalline basement. Their distribution coincides with the zone of highest grade metamorphism in the Central Alps.

Most important in this study, are *Tertiary granitic rocks.* As pointed out first by WEIBEL (1960), megacrystic "Bergell granite" is not a true granite but occupies a broad field ranging from granite to granodiorite which is distinctly different from old granites (Fig. 4a). There is minor variation in composition and we could not decipher any regional variation in major element concentrations. Local heterogeneity may have been caused by partial differentiation from a homogeneous magma. This is indicated by an excellent correlations of SiO_2 and CaO (Fig. 3) for samples of Bergell granite which is much higher than the general correlations among all granitic rocks. But we expect that chemical heterogeneities of the original material contributed to the geographically irregular scatter of compositions. No intrusive relations are observed in the field between megacrystic types of different compositions. There is no chemical difference between the equigranular variety (949, 685) which composes the central part of the body and the megacrystic type. Cameraccio granodiorite (1537, 1558, 1559) is a chemically very homogeneous equigranular variety and plots in the center of the field for Bergell granite. Dikes and small masses of megacrystic granite within Gruf migmatites (808, 1439) are similar and represent either extensions of Bergell granite itself or evidence for in situ formation of granite from migmatites. We notice that there is a striking similarity between Gruf migmatites and Bergell granite which is confirmed by the statistical analysis (Fig. 5) and suggests a genetic relationship. Near the NE contact of the massif a true granite (Plan Canin type, 849) occurs with high K_2O.

Leucocratic rocks, which crosscut Bergell granite and country rocks near the contact, occur as small stocks and dikes and are volumewise of minor importance. Their SiO_2-rich chemical composition marks them as late crystallisates, rich in water (plagioclase in micrograrnites is strongly altered to muscovite) and may be partly of hydrothermal origin.

Novate granite resembles Bergell granite in composition but the few analyzed samples show a considerable spread with a rather good linear correlation in the A-C-F diagram which is different from other granitic rocks. We regard this as evidence for contamination of this granite with country rocks, which agrees with field relations showing numerous inclusions (PICCOLI, 1962) and discordant U-Pb ages of zircons (GULSON and KROGH, 1973).

7. TONALITES AND AMPHIBOLITES

Along contacts with amphibolite, tonalites appear as a mobile intrusion (Fig. 2b) and it is easy to distinguish the two rocks. When field observations are not available the division is best done on the basis of microscopic evidence:

— Tonalites: coarse-grained biotite-hornblende gneisses, rich in sphene and epidote, often quartz, and alkalifeldspar bearing (myrmekite), occasionally with zoned plagioclase.
— Amphibolites: fibrous to massive rocks, textures ranging from poikiloblastic (with large plagioclase porphyroblasts) to recrystallized homeoblastic, low in biotite and quartz, generally without alkalifeldspar.

The average composition of tonalite is intermediate between that of Bergell granite and amphibolite (Table 3) and statistical analysis shows that it is more closely related to the latter (Fig. 6b, c). The interaction between tonalite and two adjacent rocks can be implied from pairwise discriminant function analysis (Table 4) which shows that ferromagnesian elements distinguish it from amphibolite while SiO_2 tends to diminish the separation. SiO_2 and K_2O distinguish it from Bergell granite (high percent added values). We may interpret the former feature to indicate partial melting, minor differentiation

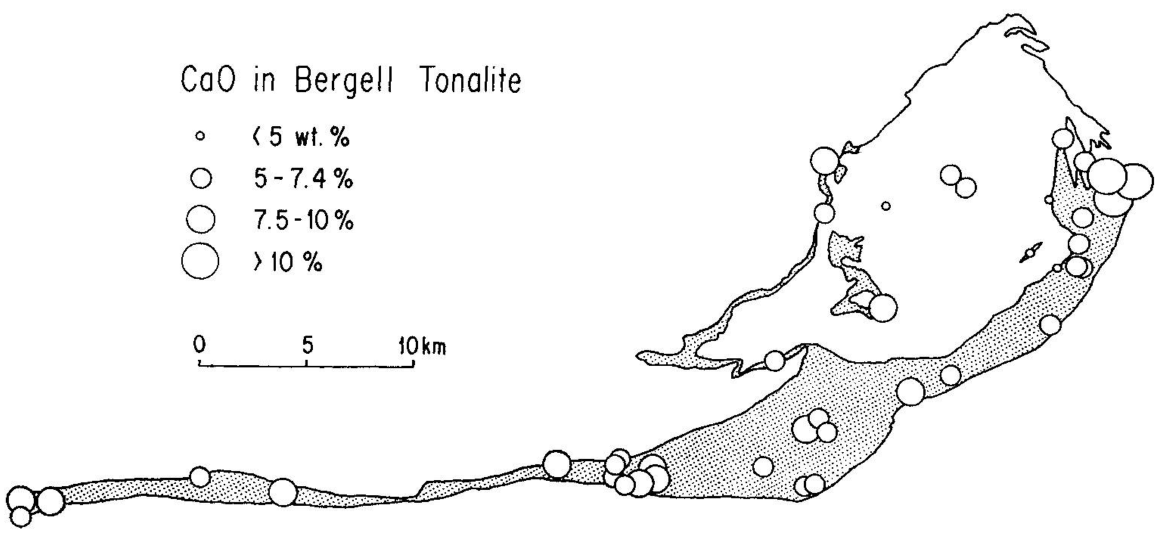


Fig. 7. Regional variation of CaO (weight percent) in Bergell tonalite. Notice high values in the vicinity of amphibolite and low values at contacts with Bergell granite.

and metasomatism leading to a concentration of femic components during the mobilization of amphibolite. The latter could be due to exchange of leucocratic material, e.g. by intrusion of pegmatitic dikes, between granite and tonalite.

There is no clear regional zonation but a tendency for a melanocratic type rich in CaO near contacts with amphibolite and in the southwestern extension (Fig. 7). Tonalites from the central portion of the massif are similar suggesting that this massif has been thoroughly homogenized before its emplacement. Inclusions of tonalite in Bergell granite are exceptionally rich in K_2O and MgO (107, 846, 869).

The average composition (Table 3) of 22 Bergell amphibolites from a wide range of metamorphic grade and tectonic settings is similar to that of amphibolites in the Ticino region farther west (E. WENK et al., 1974), and seems to be representative of Alpine amphibolites in the Pennine realm. We cannot decipher any regular pattern regarding the variation in chemical components except for the water content which is higher in low grade samples.

Of particular interest in this study of chemical variations are suites of samples from the *contact between tonalite and amphibolite*. 974 (amphibolite)

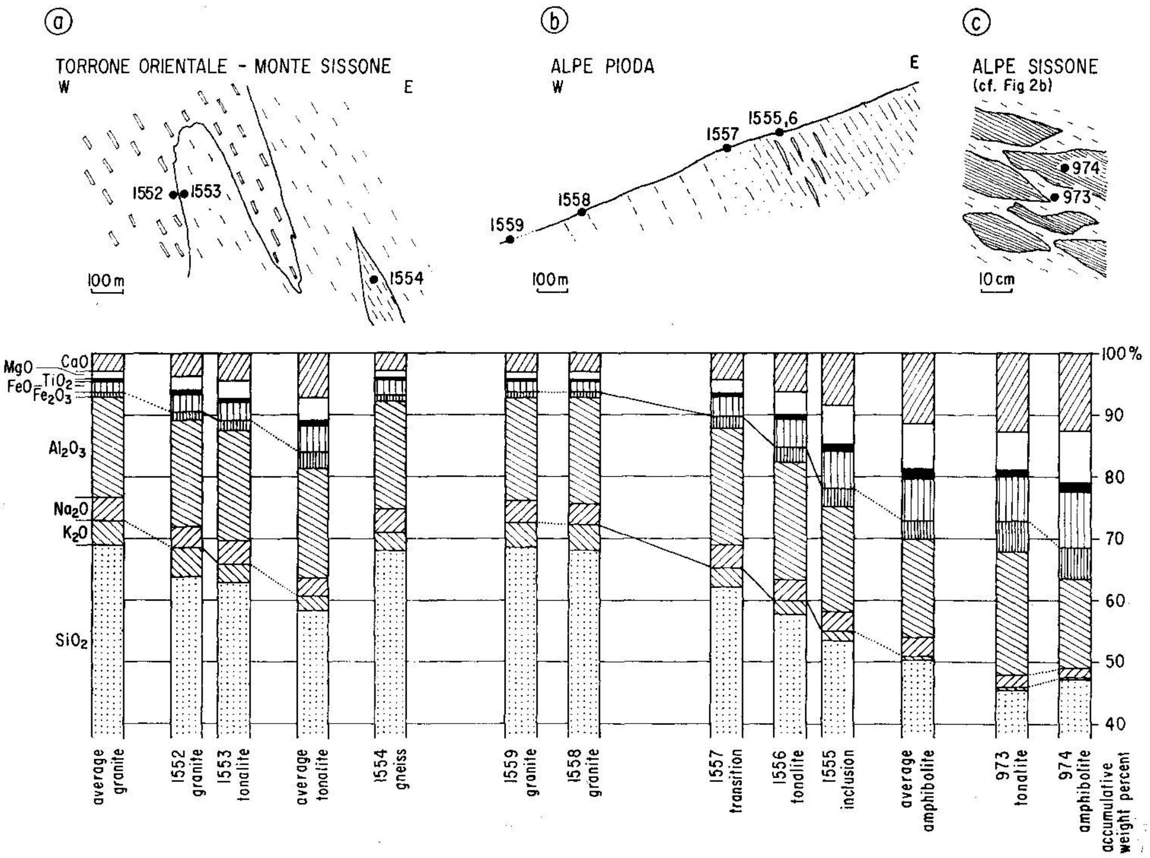


Fig. 8. Three cross sections through tonalite contact and variation in chemical composition illustrated with accumulative diagrams of weight percent oxides.

and 973 (tonalite) are such a pair from Val Sissone (Fig. 2b and Fig. 8c), in the border zone of mobilization. 1091 is another tonalite from the Sissone contact region. The two rock types in this area have similar chemical composition despite mineralogical differences (more plagioclase and biotite in tonalite) which indicates that mobilization of amphibolite can take place in situ and at least initially without addition of material.

At the *contact between tonalite and granite* in upper Val di Mello (Fig. 8a), both megacrystic Bergell Granite (1552) and tonalite (1553) show intermediate compositions with respect to all elements. Ca, Mg, Fe, Ti migrate into granite, Si, K into tonalite. Al and Na remain constant.

The same is true for the *contact between Cameraccio granite and tonalite* (Fig. 8b [1555–1559]). Here the transition is gradual over 1 km and in the field often difficult to assess. The chemical analyses show again a clear pattern with an exchange of Mg, Fe, Ca and Si, K. Tonalite in this area shows about two volume percent of calcic inclusions (1555) which appear in the field as thin parallel bands. Their composition resembles amphibolites and they may constitute restites of a large amphibolite body reworked "lit par lit".

It seems that these processes contributed to the formation of Bergell tonalite: a) *Mobilization* by partial melting of amphibolites (obvious in Val Sissone along the northeastern contact). b) *Mixing* of amphibolite material with aplite and pegmatite dikes and especially with pelitic and leucocratic gneisses changed the chemical composition, and c) *Diffusional processes* reduced the compositional gradient between tonalite and Bergell granite, particularly the addition fo volatile elements such as K and Si to tonalite which have resulted in crystallization of quartz, alkalifeldspar and biotite. Metamorphic recrystallization of these rocks may have altered original igneous fabrics considerably.

We can demonstrate a chemical interaction between granite and tonalite but we maintain that it is secondary and that these two rocks never formed a homogeneous magma. This follows from field evidence with lack of large-scale intrusive relationships between the magma types, the clear compositional separation emerging in ternary diagrams (Fig. 4) and particularly in the statistical analysis. It is further corroborated by the large content of Al_2O_3 and the presence of epidote which is unusual for igneous rocks. Most igneous structures between tonalite and granite are generally not preserved and it is doubtful that both rocks were in contact as liquid magmas. We think that the compositional gradient formed at a late stage of igneous activity or is due to metasomatism. The separation into silica-rich and silica-poor rocks is less evident in two component variation diagrams (Fig. 3), where we find similar trends as observed by LARSON (1948) in plutonic rocks from the Baja California batholith. The good correlation of salic and ferric elements is rather striking. But as illustrated in Fig. 3, it is true for all analyzed rocks, even genetically unrelated ones. It is no proof that associated rock types are related through differentiation since any mixing model produces a similar pattern.

8. PLAGIOCLASE COMPOSITION

Of all the main minerals present in the rocks which we studied in this project, plagioclase shows by far the largest compositional variations ranging from pure albite to calcic bytownite. Alkalifeldspar in all rocks has a rather constant composition $Or_{90}Ab_{10}$, hornblende (E. WENK et al., 1974) and biotite (E. WENK et al., 1963) show little variation. Therefore the material provides an opportunity to study the relationship between normative plagioclase composition (computed with the hornblende norm) which ranges more or less continuously from An 0 to 90 and the measured values. In Fig. 9a we observe a pattern typical of metamorphic plagioclase with a discontinuous distribution, i.e. the measured An-content of plagioclase is not simply proportional to normative An content even in rocks of similar metamorphic grade. A similar pattern was first described by E.WENK (1948) who contrasted metamorphic with volcanic plagioclases. The latter follow closely BOWEN's (1913) melting curve (also shown on Fig. 9a). Only a few calcic cores are close to this curve and therefore consistent with a crystallization in equilibrium from a melt, while many are even below the 45° line and thus more sodic than the norm

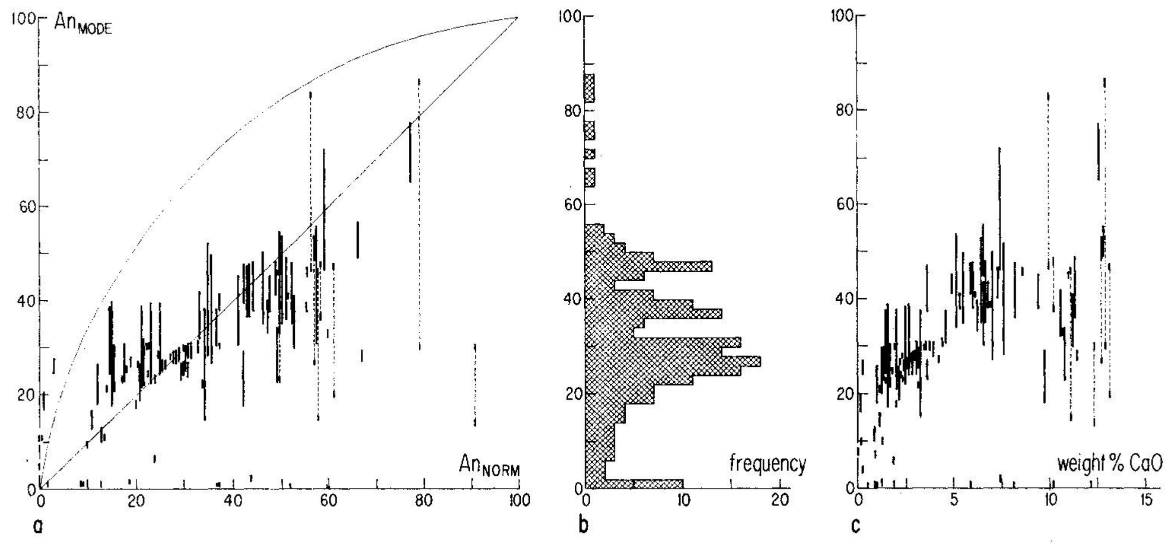


Fig. 9. Composition of plagioclase in analyzed samples.

a) Modal (measured) An content versus normative An (calculated with hornblende norm). Melting curve (from BOWEN, 1913) is indicated.

b) Histogram of modal An in 2% intervals. In order to reduce overweighing, zoned specimens are only counted in the 3% of maximum and minimum An content which are generally volume wise most important. Sampling is insignificant above 60%.

c) Modal An-content versus Ca (weight percent) illustrating a rather good correlation (in contrast to this it is random for Na_2O).

value suggests. It should be emphasized that some displacements are due to lower metamorphic grade (e.g. albite amphibolites) but we attribute them mostly to subsolidus phase relations. Samples 186, 812, 973, 974 are all from high grade rocks and contain oligoclase.

Fig. 9b is a histogram constructed for 2% intervals of An-contents which documents the stepwise An-distribution even more clearly. Frequency maxima occur at 0, 24–32, 36–40 and 46–48% An. This distribution compares well with a study of Alpine amphibolites (E. Wenk and Keller, 1969), but is different from medium amphibolite facies banded gneisses in which E. Wenk and H.-R. Wenk (1977) have described An 18–25, 28–35, 60–67 and 85–95 as

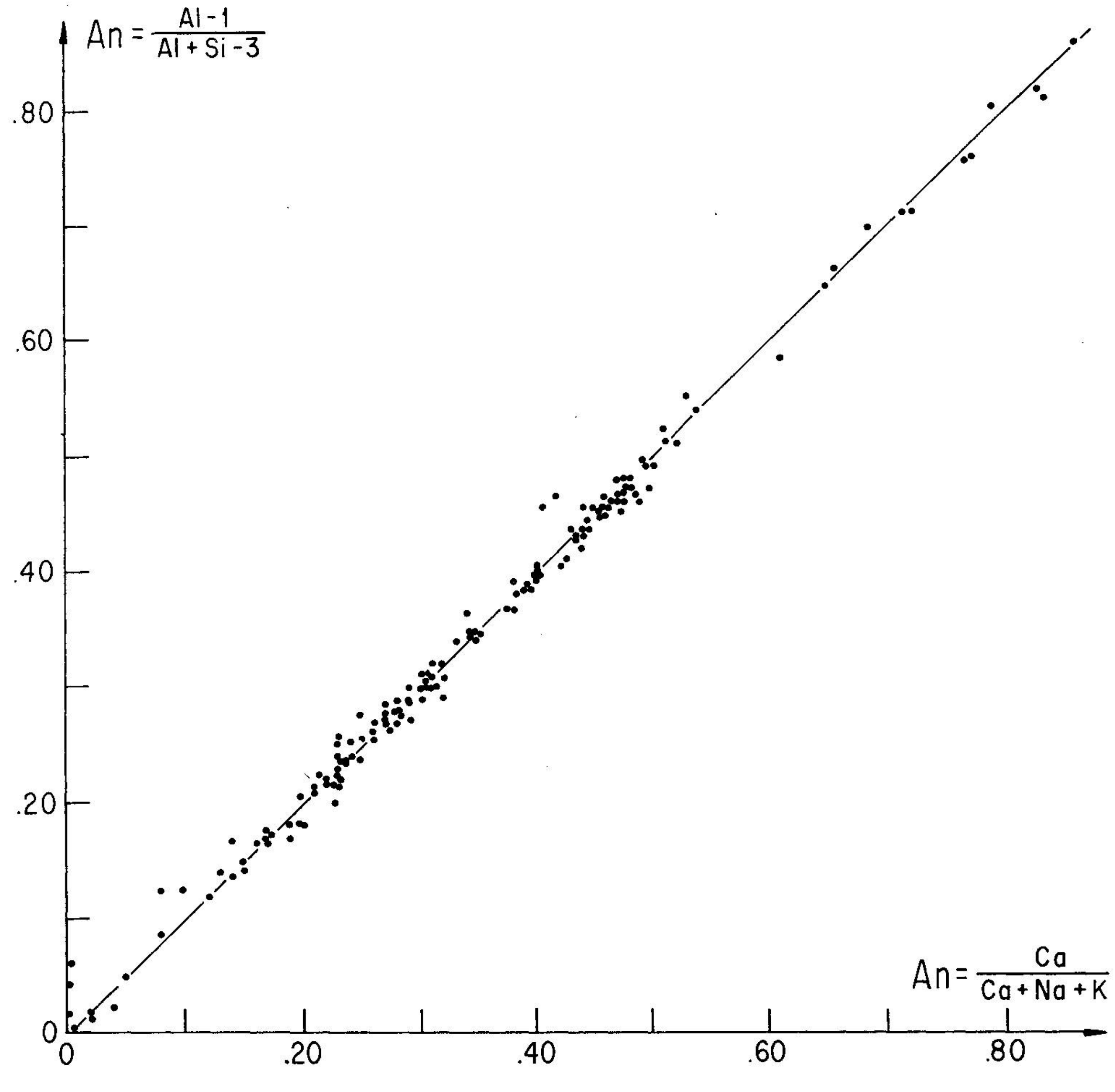


Fig. 10. Microprobe analyses of plagioclase. An is calculated both from Si, Al and Na, Ca, K. Each point represents an average of 2–20 point analyses on the same crystal. Notice the good correlation indicating reliable analyses and stoichiometry of the samples.

favored compositions. The correlation of plagioclase composition with CaO content of the bulk rocks is rather good (Fig. 9c) while it is poor with Na_2O. Since Na_2O and Al_2O_3 are similar in all rocks and most rocks contain excess quartz, the bulk CaO content is most directly responsible for the compositional variation of plagioclase.

Fig. 10 shows a plot of all microprobe analyses comparing the An content calculated as Ca/(Ca + Na + K) with (Al-1)/(Al + Si-3). The excellent linear correlation indicates that both the analyses are reliable and also that all plagioclases are nearly stoichiometric.

Since our microprobe analyses of Bergell granites contain data about the distribution of Ba, Sr, Na and Ca in alkalifeldspar-plagioclase pairs we were testing the applicability of BARTH's (1956) geothermometer, which has recently been modified for nonideality of the alkalifeldspar solid solution (STORMER, 1975). The results are not very consistent and suggest especially for Ca and Na unreasonably low temperatures. We attribute this to nonequilibrium of the two feldspars and think that alkalifeldspar megacrysts either were altered considerably by ionic exchange during subsequent metamorphism or that they represent porphyroblasts which grew is a quasisolid rock by replacement (DRESCHER-KADEN, 1946; compare also the discussion by WILDE, 1971). They are characteristically very pure (An is less than 0.6%, generally around 0.1% and Ab is rather constant at 10–15%). Distribution of trace elements shows significant variations but there are experimental limitations in accurately analyzing these very small concentrations (Ba in plagioclase is almost absent, in alkalifeldspar it reaches 0.02 formula units, Sr in both feldspars is up to 0.004).

9. DISCUSSION AND CONCLUSIONS

In a QPA diagram Bergell granite plots in the granite-granodiorite field, tonalite in the quartzdiorite field, the latter is with 20–45% femic components often gabbroic in character. Judging from representations such as in Figs. 4, 5, 6, and from average compositions in Table 3, we have *two separate* populations and do not agree with RICHARDSON et al. (1976) who proposed a continuous range of compositions between Bergell granite and tonalite. These two rock rypes have a different origin i.e. they are derived from different parent material.

The melting experiments of CONDLIFFE and MOTTANA (1975, 1976) add constraints but clearly their conditions do not correspond to those during the formation of Bergell granite. In Bergell granite (Ghiandone), they found at 1 kb a crystallization sequence plagioclase-biotite-quartz-alkalifeldspar indicating that the megacrysts, so typical of Bergell granite, cannot be considered phenocrysts (GANSSER and GYR, 1964). At 2 kb biotite and hornblende are the first minerals to crystallize at 850–950° C, becoming slightly more stable as pressure increases. If Bergell granitic rocks behave similarly to standard granodiorites and tonalites then PIWINSKII's (1973a, b) melting curves can be applied and a solidus temperature of 670° C for Bergell granite and 700–730° C for tonalite can be estimated for the pressure range of 3–8 kb which is most likely from petrologic evidence. Piwinskii demonstrated that at higher pressures crystallization of quartz preceded plagioclase, contrary to textural observations.

It is uncertain whether complete melting has occurred, particularly of hornblende, and textural evidence is often difficult to assess because both mafic and sialic minerals recrystallized to considerable extent at subsolidus conditions giving rise to metamorphic textures. Temperatures of 1000° C were reached in some metamorphic assemblages presently underneath the granite (Val Codera, H.-R. WENK et al., 1974), which may be close to the source region. Experimental determinations of the H_2O content of melts forming from metamorphic rocks containing mica and hornblende indicate that under these conditions partial or even complete melting will occur (e.g. PIWINSKII and WYLLIE, 1970)

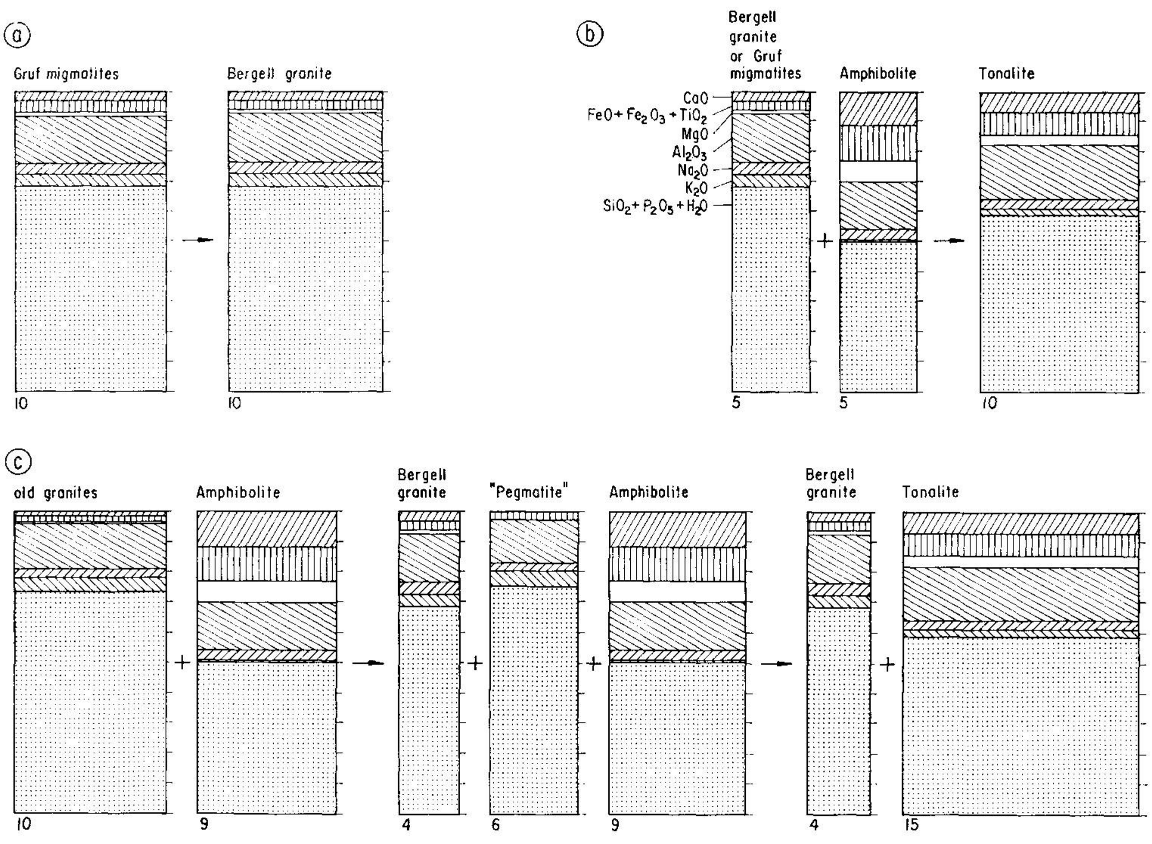


Fig. 11. Three mixing models of major elements illustrating possible origin of Bergell granite and tonalite. Calculated from average rock compositions (Table 3).

even though anatectic granites are generally water undersaturated. Rejuvenation must have been very intensive, leaving only few remnants of old material. U/Pb ages of zircon both of granites and tonalite give nearly concordant Tertiary ages (Gulson and Krogh, 1973). As pointed out by Condliffe and Mottana (1975), the high solidus temperature at low pressure precludes melting of amphibolite by intrusion of a granitic magma at the present tectonic levels. But in the Bergell Alps, tonalites are in fact restricted to deeper units while granites are in contact with amphibolites along the high NE corner of the massif. Melting experiments are consistent with a model which assumes *melting* at considerable depth (20–30 km) but *crystallization* above 15 km.

Intermediate rock types demonstrate movements of material. We find a compositional gradient along the granite-tonalite contact and tonalites depleted in SiO_2 and K_2O in the vicinity of amphibolites (Fig. 8). The banded tonalites (Fig. 2c) which are common in the whole southern area, suggest that leucocratic material has been added. In Fig. 11 we summarize some models for the origin of Bergell granite and tonalite based on average major element composition (Table 3). Clearly, there are other possibilities. Gruf migmatites and Bergell granite have a very similar chemical composition. Thus (Fig. 11a) Bergell granite could have formed directly from Gruf material – deep seated crystalline basement – by anatexis without any chemical exchange. In fact dikes and small stocks of Bergell-type granite in migmatites (808, 1439) may be such in situ mobilisates.

If amphibolites and leucocratic material are mixed and homogenized in equal portions a rock of tonalite composition results (Fig. 11b) – particularly if some pelitic material, which is common in the Forno-Vazzeda amphibolites, is incorporated. Such a mechanism is not unlikely since many migmatites are associated with amphibolites (Bagni Masino, Trubinasca, Forno) and large inclusions of gneisses are still present in tonalite (V. di Mello, V. dei Ratti).

A more complicated scheme is illustrated in Fig. 11c. It takes account of the similarity in tectonic position of Tambo augengneisses resting on Gruf migmatites in northern Val Bondasca and Bergell granite resting on Gruf migmatites in southern Vàl Bondasca. Hercynic Tambo granites may have been mobilized and differentiated into a granodioritic magma and leucocratic phases which penetrated amphibolites in the Forno region (compare Fig. 21 in Wenk, 1969) and added up to 20% granitic material. Mobilization and homogenization produced tonalites. These are clearly limiting cases. There is evidence for each of the three models: In situ mobilization (a), in situ homogenization (b) and a rather complex history requiring transport of material through diffusion and intruding dikes (c), and the actual processes involved a combination of all these three mechanisms. In all models large amounts of granitic material are consumed to form tonalite. Presently tonalite accounts for 100 km^2 of surface outcrops, Bergell granite for 150 km^2. But in Oligocene-Miocene pebbles in the Southalpine Molasse which originates mainly from the presently eroded western part of the Bergell complex, tonalite is much more abundant. We estimate that originally there may have been twice as much tonalite as Bergell granite.

Thus we believe that remelting of granitic and calcic rocks was responsible for the formation of magmas and the variety of Tertiary igneous rocks in the Bergell Alps. But anatexis did not occur in situ such as described by MEHNERT (1968) for the Black Forest batholith which shows a homogeneous central part grading into migmatites and metagraywackes at the external boundary. In the Bergell melting took place at deep crustal levels and was followed by intensive differential movements both in liquid and solid state. Also in contrast to Black Forest or to the classical Caledonian granites recently studied by BROWN (1967), parent rocks of Bergell granite were of a composition which did not require alkali metasomatism. K is excessive in all potential source rocks and Na is practically constant in all rocks which we analyzed. The transformation of amphibolites into tonalites needs addition of SiO_2 and K_2O which we view rather as a mixing process involving gneiss layers in amphibolites and assimilation of leucocratic dikes emanating from the Bergell granite than metasomatism though the latter has contributed to reduce compositional gradients between the two magmas.

Isotope studies are not conclusive at present but we expect that they will give the final answer about the origin of Bergell granite. The initial Sr 87/Sr 86 ratio has been used to trace the early history of granitic rocks. PIDGEON and COMPSTON (1965) interpreted a matching initial Sr 87/Sr 86 ratio in granite and country rocks from New South Wales as evidence for in situ mobilization. GULSON (1973) derived low initial ratios of 0.705 for Tambo granites, Gruf migmatites and Bergell granite, thus both rock types can be possible parents. Unfortunately the resolution in GULSON and KROGH's (1973) U/Pb determinations was not good enough to establish through a series of discordant ages the origin of the source material.

Even though we do not have a definite proof we tend to adopt the conclusions of CARMICHAEL et al. (1974) p. 593 in their discussion of the granite problem stating that "today there is not much support for once popular genetic models that derive great volumes of granitic magma by fractionization of parental basaltic liquids, nor for others that postulate metasomatic granitization on a large scale without participation of granite melts." The best compromise between the extreme views of magmatists and metasomatists, most recently brought forward by RICHARDSON et al. (1976) and DRESCHER-KADEN (1969) seems to be to rely on processes of local remelting and anatexis with moderate chemical exchange, homogenization and only very subordinate differentiation, a mechanism which has been proposed previously by E. WENK

(1962a) and CRESPI and SCHIAVINATO (1966), and for which we have added quantitative evidence.

In conclusion we touch briefly some of the geological implications of such a model. There is considerable evidence to suggest that all calcic rocks which surround the Bergell granite may originally represent volcanic deposits. The composition of amphibolites corresponds to tholeitic basalts, either of an island arc or oceanic type. Pillow structures (MONTRASIO, 1973) and Mn mineralization in amphibolites (FERRARIO and MONTRASIO, 1976) and tonalite (rhodonite at Casera Sceroia/Bagni Masino, Sci. 522) favor an oceanic source. Associated ultramafic sequences (Chiavenna, Poschiavo-Val Malenco) are probably also altered and metamorphosed relics of oceanic crust. These volcanic deposits and granitic units of continental origin were subducted during shortening of the crust and a southern continental segment overrode the northern part (compare the imaginative drawing Fig. 17 in H.-R. WENK, 1973). At deep tectonic levels anatexis and complete remelting took place. Remelting of granitic rocks produced a Bergell granite magma, whereas remelting of amphibolites and gneisses with K_2O and SiO_2 addition through leucocratic dikes produced a tonalite magma. Mobilization of amphibolite only occurred in the deeper southern portions while in the higher northeastern contact zone melting conditions were only reached for rocks of granitic composition. Loss in strength of "subducted" material resulted in an upward intrusion of a large bubble shaped mass such as suggested by GROUT (1945) and emplacement in the northward moving upper Pennine units. Due to rapid tectonic movements, magmas never reached equilibrium and were not able to differentiate appreciably. They cooled quickly and solidified leaving imprints of plastic deformation. Thrust movements outlasted the igneous activity and the accompanying metamorphic recrystallization.

The time relation of igneous activity, deformation and metamorphism is complicated. Explorers of the Central Alps have classified *separate* episodes for different localities, such as nappe emplacement, regional metamorphism and Bergell intrusion. We see the evolution rather as a *simultaneous* interaction of many forces, with variable duration and intensity which have to be evaluated for each particular time and place (Fig. 12). In our model tectonic movements, igneous activity and regional metamorphism are organically related. A correspondence between granitic intrusions in the Bergell and the regional metamorphism in the Lepontine Alps was first suggested by E. WENK (1962). Recent geological investigations add constraints, particularly on relative time relationships.

Tectonic movements on a large scale initiated subduction at continental margins and melting at deep levels; some magmas intruded overlying sequences and cooled rapidly at a high level (Adamello, Sondrio, see BORSI et al., 1966 for ages), others became involved in deformation within the crust, crystal-

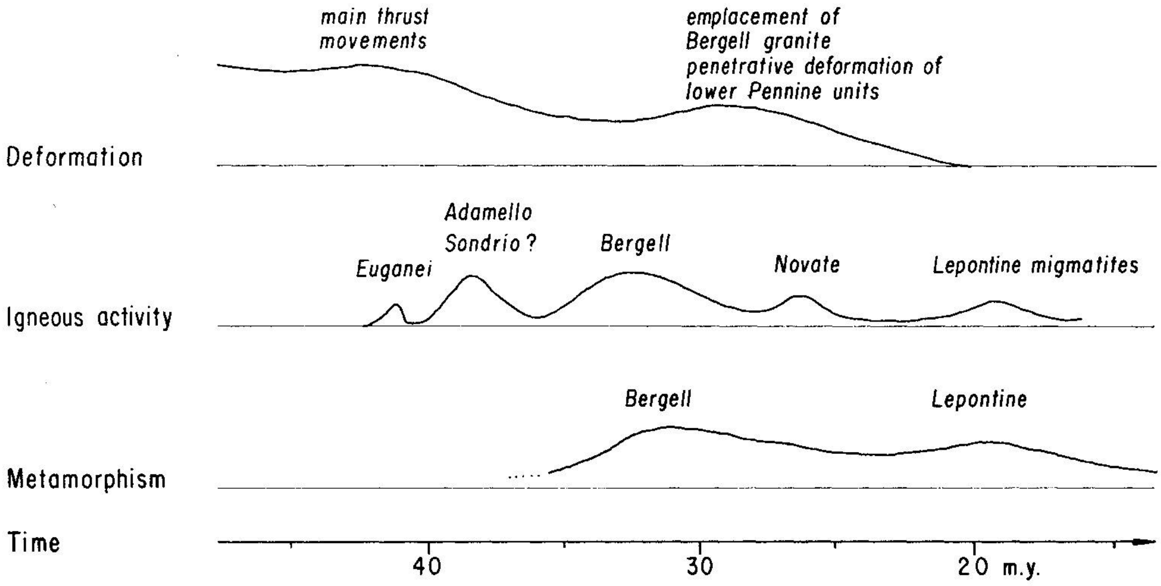


Fig. 12. Schematic diagram illustrating the geological evolution in the Central Alps. Intensity of deformation, igneous activity and metamorphism are indicated.

lized and recrystallized during a slow upward motion. Metamorphism started as a subductive type with high pressure assemblages which are not preserved, and changed later – through uplift of warm material – into a thermal metamorphism. In the Bergell area, thermal regional metamorphism, granite formation, contact metamorphism and deformation are closely related, giving rise to very complicated structures which are unique in the Alps – with steep metamorphic gradients and juxtaposition of low and high pressure assemblages (H.-R. WENK et al., 1974). Farther west, in the Lepontine area, where granites did not reach the presently exposed surface, the thermal metamorphism is younger and outlasted tectonic movements as evidenced by widespread annealing textures. The foregoing model does not agree with the assumption of JÄGER (1973), recently summarized by FREY et al. (1974) that metamorphism and anatexis in the Lepontine are older than igneous activity in the neighboring Bergell Alps. Assuming that deformation was simultaneous in the two areas this hypothesis is neither reconcilable with structural data (E. WENK, 1956 in the Lepontine, H.-R. WENK, 1973 in the Bergell), nor with isotopic evidence (U/Pb ages of monazites: KÖPPEL and GRÜNENFELDER, 1975). In fact an extension of the Lepontine regional metamorphism has probably overprinted an earlier contact metamorphism and caused extensive recrystallization of the igneous rocks in the Bergell Alps comparable to the metamorphic recrystallization in the Western Alps (WETZEL, 1972). We also disagree with HÄNNY et al. (1975) who proposed that the areal coincidence of the zone of highest grade metamorphism with the occurrence of migmatites is accidental. The Bergell massif is the best example to demonstrate the close relationship between igneous activity, mobilization, and metamorphism.

This geochemical survey has not "solved" the Bergell enigma, but we hope that we have contributed further data to make scientific discussions more definite and constrain the possibilities.

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SMPM = Schweiz. mineral. petrogr. Mitt.

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