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The origin of the Taveyannaz sandstone: arguments from whole-rock and clinopyroxene composition

by *Meinert Rahn*^{1,2}, *Willem B. Stern*¹ and *Martin Frey*¹

Abstract

For the Taveyannaz sandstone of the Glarus Alps, whole-rock analyses are presented and compared with data from the literature. Compositional changes due to detrital input and Alpine metamorphism can be estimated by optical and microprobe investigations. Major-element distributions support a basaltic to basalt-andesitic composition for the volcanogenic part of the sandstone. Magmatic clinopyroxene composition and whole-rock minor and trace element contents for which no increase nor decrease by detrital input and metamorphism can be assumed, indicate a calc-alkaline character and a subduction-related volcanic arc as the source of the volcanics.

Keywords: Taveyannaz sandstone, greywacke, Glarus Alps, calc-alkaline basalt, volcanic arc, geochemistry.

Introduction

In 1853, STUDER first suggested a volcanic origin for part of the material in the Taveyannaz greywacke, a sandstone of lowermost Oligocene age from the Helvetic part of the Alps (LATELTIN and MÜLLER, 1988; RUFFINI et al., 1993). NIGGLI (1922) and DE QUERVAIN (1928) published detailed microscopic descriptions of the Taveyannaz greywackes. VUAGNAT (1952) provided an excellent overview for all the outcrops along the Swiss Alpine arc and divided the sandstones into four types I–IV according to their content of volcanic material and the presence of alteration minerals (Tab. 1). A modified classification that distinguishes between primary sedimentary and secondary metamorphic features has been proposed by RAHN et al. (1995).

Taveyannaz-type sandstones are found within the Helvetic nappes and the North Helvetic flysch units. In the Glarus Alps, they are found within the Wageten slice at the Northern Alpine border, and within the North Helvetic flysch below the Glarus thrust plane (Fig. 1). The extensive amount of basic volcanic material within the

Taveyannaz sandstone favoured the growth of critical minerals under low-grade metamorphic conditions and made these rocks an important indicator of metamorphism in the external parts of the Alps (MARTINI and VUAGNAT, 1965; MARTINI and VUAGNAT, 1970; SAWATZKI and VUAGNAT, 1971; COOMBS et al., 1976; FREY, 1986; RAHN et al., 1994, 1995). Within the Glarus Alps, four different metamorphic assemblage types 1–4 can be defined (Fig. 1, Tab. 1), corresponding to the zeolite (type 1), prehnite-pumpellyite (types 2, 3), and pumpellyite-actinolite facies (type 4). Types 2 and 3 are distinguished by a strong replacement of detrital K-feldspar and volcanic clinopyroxene by white mica and calcite found only in type 3 (Tab. 1, RAHN et al., 1994).

One of the remaining problems concerning the Taveyannaz sandstone is the unknown origin of the volcanogenic part of these rocks (NIGGLI, 1922; DE QUERVAIN, 1928; WAIBEL, 1993). Apart from a majority of basaltic or andesitic fragments, DE QUERVAIN (1928) and VUAGNAT (1952) also described other rock fragments such as dacitic and rhyolitic material. However, the lack of any closely related source rocks within the

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Tab. 1 Taveyannaz sandstone classification after VUAGNAT (1952) and metamorphic assemblage typology after RAHN et al. (1994). Critical metamorphic minerals are only found within Taveyannaz sandstone types IIb and III.

type	description											
I	true andesites, basalts, type does not exist in Switzerland											
IIa	50-90 % of andesitic material, mafic minerals (augite, amphibole) present, no alteration of volcanogenic material. Type not found in the Glarus Alps											
IIb	} } }	50-90 % of andesitic material, metastable mafic minerals still present, partial alteration of volcanogenic material										
III		50-90 % of andesitic material, mafic minerals absent, strong alteration of the volcanogenic material										
IV		> 50 % of andesitic material, no primary mafic minerals, alteration into albite, chlorite, calcite, no Ca-silicates										
		<table border="1"> <thead> <tr> <th>assemblage type</th> <th>metamorphic facies</th> </tr> </thead> <tbody> <tr> <td>1</td> <td>zeolite (laumontite)</td> </tr> <tr> <td>2</td> <td>prehnite-pumpellyite</td> </tr> <tr> <td>3</td> <td>prehnite-pumpellyite, absence of K-feldspar and magmatic clinopyroxene</td> </tr> <tr> <td>4</td> <td>pumpellyite-actinolite</td> </tr> </tbody> </table>	assemblage type	metamorphic facies	1	zeolite (laumontite)	2	prehnite-pumpellyite	3	prehnite-pumpellyite, absence of K-feldspar and magmatic clinopyroxene	4	pumpellyite-actinolite
assemblage type	metamorphic facies											
1	zeolite (laumontite)											
2	prehnite-pumpellyite											
3	prehnite-pumpellyite, absence of K-feldspar and magmatic clinopyroxene											
4	pumpellyite-actinolite											

Alpine arc does not allow to define a clear origin. The presence of Taveyannaz and equivalent sandstones along the Alpine arc from the Swiss Alps to the French Alps and within the Apennines down to Sicily (STALDER, 1979) can hardly be explained by a large central source volcano. A more reasonable model is an extended volcanic island arc system along the Alpine front (TRÜMPY, 1960; DICKINSON, 1970) that could be related to an underlying subduction zone.

In modern geochemistry a wide variety of chemical fingerprints of basaltic rocks are used to distinguish the geotectonic settings (PEARCE, 1984; CONDIE, 1989). The usefulness of geochemical interpretation of whole-rock analyses from the Taveyannaz sandstone, however, is limited by the presence of detrital, non-volcanogenic material and by the metamorphic overprint. Thus, any interpretations depend on assumptions that are made concerning the changes in chemical element concentrations during mixing with detrital material and the mobility of elements during low-grade metamorphism.

The aim of this contribution is (1) the presentation of 40 new whole-rock analyses of the Taveyannaz sandstone and related sandstones from the Glarus Alps, together with a review of earlier published analyses from Taveyannaz sandstone and related rocks from the literature, (2) an estimation of enrichment/depletion of all major and a group of minor elements during sedimentation and metamorphism and (3) an attempt to recover informations about the original composition of the volcanic source rock and the geotectonic context of the volcanoes.

Methods

40 samples of Taveyannaz and flysch sandstones (including one Verrucano sample and one sandstone from the Subalpine Molasse, Tab. 2) were analysed by wavelength-dispersive X-ray fluorescence (WD-XFA) at the Geochemical Laboratory, Mineralogisch-Petrographisches Institut of the University of Basel. The material was

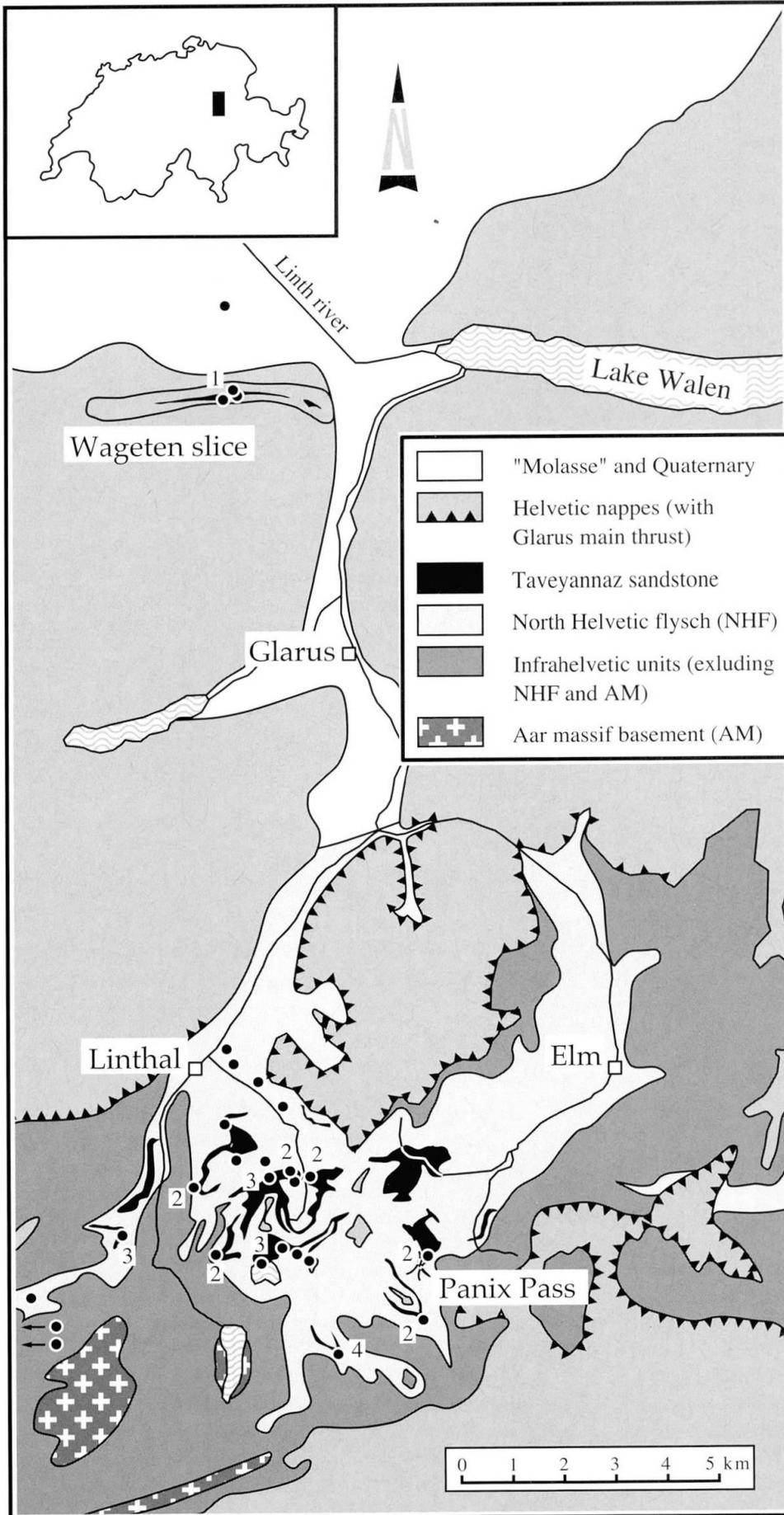


Fig. 1 Tectonic sketch of the Glarus Alps with outcrops of Taveyannaz sandstones and metamorphic assemblage types after RAHN et al. (1994). Sample localities of whole-rock analyses are indicated with small dots.

Table 2 Sample description of the whole-rock specimen from the Glarus Alps, Switzerland. Abbreviations: TS = Taveyannaz sandstone, NHF = North Helvetic flysch. I-IV: Taveyannaz sandstone types after VUAGNAT (1952), 1-4: metamorphic assemblage types after RAHN et al. (1994). *: sample from the summit of the Clariden, given by M. BURKHARD (Neuchâtel).

Sample nr.	Swiss coordinates		altitude (m)	lithology	tectonic unit	I-IV	1-4
MR T 5	709.800	191.500	1740	TS	NHF	II b	2
MR T 9	722.460	191.650	3100	Verrucano	Permian, Glarus nappe		
MR T 12	722.190	191.920	2940	TS	NHF	IV	
MR T 14	721.660	192.190	2670	TS	NHF	IV	
MR T 17	720.900	191.820	2455	TS	NHF	III	3
MR T 24	721.140	197.360	2245	TS	NHF	III	3
MR T 27	720.900	195.100	2030	TS	NHF	IV	
MR T 29	720.100	195.250	1750	sandstone	NHF		
MR T 32	719.910	196.620	1560	TS	NHF	IV	
MR T 34	719.850	198.360	725	sandstone	NHF		
MR T 37	720.330	198.380	1020	sandstone	NHF		
MR T 39	721.740	197.000	1380	sandstone	NHF		
MR T 41	721.140	197.360	1190	sandstone	NHF		
MR T 47	717.810	219.400	1435	TS	Wageten slice	II b	1
MR T 49	718.870	219.770	1610	TS	Wageten slice	II b	1
MR T 52	718.950	223.000	740	sandstone	Chattian, Subalpine Molasse		
MR T 69	716.660	192.940	1570	TS	NHF	III	3
MR T 82	722.670	193.370	1905	TS	NHF	II b	2
MR T 84	722.530	194.570	1495	TS	NHF	III	3
MR T 96	726.950	190.810	2410	TS	NHF	II b	2
MR T 114*	ca. 709	ca. 189	ca. 3200	TS	NHF	II b	2
MR T 121	723.350	188.930	2800	TS	NHF	II b	4
MR T 127	719.460	192.380	2190	TS	NHF	II b	2
MR T 141	714.260	191.150	2260	TS	NHF	II b	2
MF 755	719.460	195.360	1420	TS	NHF	II b	2
MF 776	722.400	194.500	1490	TS	NHF	II b	2
MF 778	722.400	194.500	1490	TS	NHF	II b	2
MF 806	725.900	189.600	2390	TS	NHF	II b	2
MF 1134	718.870	219.770	1610	TS	Wageten slice	II b	1

crushed in an iron mortar and a sub-sample milled in a boron-carbide pistill-mill. The Loss on Ignition (LoI) was determined with 1 g of dry powder (dried at 105 °C) ignited for one hour at 1000 °C. The ignited material was then fused to glass beads according to STERN (1972).

The analyses were performed with a Siemens SRS-303 spectrometer using a Rh end-window tube. The analytical routine was calibrated with international rock and mineral standards, and optimized for major elements. Some trace element data (measured by XFA) are also reported; they are considered to be tentative values.

The measuring conditions used for the clinopyroxene microprobe analyses were those reported in RAHN et al. (1994).

Chemical changes during sedimentation and metamorphism

"True" Taveyannaz sandstones are characterized by the presence of more than 50 vol.% of andesitic material (VUAGNAT, 1952); within types II and III this amount can reach values around 90 vol.% (Tab. 1). Thus, non-volcanogenic detrital material in most cases comprises about 10, but rarely more than 20 vol.%. The predominant amount of this detrital material is quartz, K-feldspar and calcite. Additional detrital phases (less than 1 vol.% of the rock) are detrital plagioclase (partially or completely rounded grains), white mica, chlorite, and in very small quantities also detrital biotite, rutile, epidote, garnet and tour-

maline. From fission track analysis it is evident that zircons are also of detrital origin, since they show no young source ages (RAHN, 1994). Detrital components thus imply a distinct increase of SiO₂ (quartz, K-feldspar), K₂O (K-feldspar, muscovite, biotite), Al₂O₃ (K-feldspar, muscovite, epidote), CaO (calcite, epidote), moderate increase of Na₂O, FeO, MgO (detrital plagioclase, biotite), and small increases of TiO₂ (rutile), Fe₂O₃ (epidote), ZrO₂ (zircon). There is no phase adding MnO during sedimentation. Also P₂O₅ (apatite) is assumed to have remained constant, as separated apatites generally are euhedral (RAHN, 1994).

During metamorphism main processes are: (i) a total replacement of the volcanogenic plagioclase (of unknown composition for the Glarus Alps) by albite, (ii) replacement of the volcanogenic matrix by chlorite, the formation of laumontite and a strong replacement of K-feldspar by white mica and calcite in assemblage type 3 (Tab. 1). Of minor volume is the partial replacement of the clinopyroxenes by mainly chlorite and quartz, the formation of prehnite and pumpellyite within albite, pumpellyite within the matrix, and formation of titanite replacing former rutile. Newly grown minerals such as laumontite, pumpellyite, and titanite vary in composition within a few mm; this indicates, that chemical equilibrium was only reached in a very small area. For these minerals the chemical composition seems to depend on the surrounding minerals or the composition of the replaced phases. A total mobility during metamorphism can only be assumed for Si and Na due to the complete albitization (RAHN et al., 1994).

Comparison of previous and new analyses

Apart from the 40 whole-rock analyses of Taveyannaz and flysch sandstones from the Glarus Alps (Fig. 1, Tab. 2), there are 43 analyses given in STALDER (1979), 16 analyses in NIGGLI et al. (1930) and one analysis from WINTERHALTER (1933). All analyses include data for SiO₂, Al₂O₃, Fe₂O₃ (for the Glarus Alps = Fe_{tot}), MgO, CaO, Na₂O, K₂O, TiO₂, P₂O₅, and LoI. Analyses from STALDER (1979) and NIGGLI et al. (1930) and WINTERHALTER (1933) also include FeO and the latter two (with one exception) also MnO; the new data from the Glarus Alps also include MnO, Ba, Rb, Sr, V, Y, and Zn.

While analyses from STALDER (1979) include only Taveyannaz sandstones and similar metagreywackes from the Swiss/French Alps and Apennines, the data set from NIGGLI et al. (1930)

and WINTERHALTER (1933) also includes two analyses from flysch sandstones (Attinghausen UR, Matt GL). Within the new data pattern there are five analyses of flysch sandstones ("Aldorfer Sandstein", MR T 29, 34, 37, 39, 41) with less than 50 vol.% of volcanic material, one analysis of a Verrucano sandstone from the Ruchi summit (MR T 9), and one analysis of a Chattian sandstone from the Subalpine Molasse (MR T 52). Analyses from "true" Taveyannaz sandstones comprise four analyses of type IV sandstones (MR T 12, 14, 27, 32), and 29 analyses from type II and III sandstones from 18 localities. For two localities (MR T 47 and 121), several analyses were executed in order to test the homogeneity of the sandstone and the influence of grain size on the whole-rock analysis. Data are presented in table 3.

The possible precursor

Data show a SiO₂ range between 52 and 62 wt% for the "true" Taveyannaz sandstones from the Glarus Alps; data from Clumanc sandstones and from Passo del Cerreto are slightly lower in SiO₂ (STALDER, 1979). "Andesitic" fragments were analysed by DE QUERVAIN (in NIGGLI et al., 1930) and indicate values between 42 and 55 wt%. As a result, an increase around 10 wt% SiO₂ may be suggested for the Taveyannaz sandstones during sedimentation and mixing with detrital input. This is consistent with a mean detrital part of 10%, mainly represented by quartz and K-feldspar. Plotted data in classification diagrams (Figs 2 and 3) show a basaltic andesite to andesite to latite composition, but with the suggested correction for the original SiO₂ content, results rather indicate a basaltic to basalt-andesitic composition for the igneous precursor. This estimation is in agreement with anorthite contents of 60% for the initial plagioclase, found in the Western Alps (MARTINI, 1968). Although relics of primary plagioclase were not found in the Glarus Alps, the total albitization of the former plagioclase might have caused an additional increase of the SiO₂ content during metamorphism.

The Al₂O₃ content of the "true" Taveyannaz sandstones generally scatter between 14 and 17 wt%, which is rather low for subduction-related arc basalts (CONDIE, 1989). A decrease of Al, however, may be assumed due to the total replacement of a former basic plagioclase by albite. Also CaO and Na₂O should be influenced by this replacement, but released Ca probably has been incorporated into newly-formed calcite and laumontite, while Na either has been derived from

Tab. 3 Whole-rock data from the Glarus Alps. Each analysis represents the average of two measurements. *Fe₂O₃ = Fe_{tot}. For typology and sample localities, see table 2.

Sample nr.	Analysis nr.	SiO ₂	Al ₂ O ₃	*Fe ₂ O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅	Ba	Rb	Sr	V	Y	Zn	LoI	Σ
MIR T 5	XV 8258	55.73	16.91	7.805	0.135	3.56	6.11	4.56	0.74	0.70	0.23	0.0320	0.0037	0.0222	0.0236	0.0006	0.0129	3.37	99.95
MIR T 9	XV 8280	69.99	12.80	2.810	0.082	1.52	2.66	3.70	2.21	0.38	0.13	0.0545	0.0104	0.0164	0.0147	0.0011	0.0098	3.56	99.94
MIR T 12	XV 8278	57.69	16.52	6.190	0.117	2.81	4.13	6.75	0.48	0.58	0.18	0.0303	0.0031	0.0426	0.0185	0.0000	0.0110	4.41	99.95
MIR T 14	XV 8276	54.80	17.08	8.027	0.143	2.64	5.04	3.52	2.69	0.74	0.22	0.0378	0.0113	0.0426	0.0222	0.0009	0.0116	4.93	99.95
MIR T 17	XV 8244	54.93	17.29	7.321	0.114	3.25	7.25	3.10	1.08	0.66	0.22	0.0300	0.0052	0.0264	0.0186	0.0001	0.0129	4.65	99.94
MIR T 24	XV 8242	59.01	15.69	5.841	0.125	2.89	5.00	4.07	1.62	0.61	0.21	0.0593	0.0075	0.0403	0.0129	0.0005	0.0115	4.75	99.95
MIR T 27	XV 8274	60.03	14.31	6.043	0.101	3.68	4.12	4.70	0.64	0.65	0.21	0.0209	0.0047	0.0301	0.0157	0.0004	0.0111	5.37	99.95
MIR T 29	XV 8272	61.34	13.59	4.685	0.082	2.34	5.59	4.15	1.40	0.51	0.17	0.0404	0.0081	0.0326	0.0145	0.0029	0.0095	5.98	99.94
MIR T 32	XV 8270	60.18	14.99	5.763	0.123	3.97	4.26	4.93	1.45	0.57	0.17	0.0566	0.0064	0.0352	0.0141	0.0005	0.0110	4.42	99.95
MIR T 34	XV 8268	50.45	9.74	3.183	0.165	1.75	15.48	2.82	2.17	0.39	0.13	0.0376	0.0084	0.0578	0.0082	0.0009	0.0100	13.55	99.95
MIR T 37	XV 8266	55.76	12.78	5.163	0.102	3.29	6.34	3.35	1.58	0.56	0.19	0.0398	0.0074	0.0361	0.0145	0.0010	0.0096	10.71	99.94
MIR T 39	XV 8264	58.71	10.89	5.233	0.077	3.23	10.73	1.77	1.83	0.44	0.15	0.0227	0.0091	0.0353	0.0107	0.0009	0.0102	6.79	99.94
MIR T 41	XV 8262	57.83	14.75	6.035	0.117	3.58	5.34	4.17	1.51	0.61	0.21	0.0340	0.0080	0.0528	0.0124	0.0007	0.0126	5.69	99.96
MIR T 47	XV 8240	60.25	16.22	7.007	0.125	2.90	2.50	4.30	2.07	0.74	0.16	0.0834	0.0066	0.0295	0.0222	0.0015	0.0112	3.55	99.96
MIR T 47A	XV 8292	60.27	16.04	7.179	0.126	2.84	2.57	4.20	2.10	0.75	0.17	0.0789	0.0073	0.0287	0.0215	0.0007	0.0114	3.55	99.94
MIR T 47B	XV 8294	60.35	16.12	7.047	0.123	2.86	2.54	4.21	2.08	0.75	0.18	0.0850	0.0070	0.0283	0.0216	0.0008	0.0101	3.55	99.94
MIR T 47C	XV 8224	60.39	16.31	6.950	0.127	3.04	2.23	4.43	2.06	0.74	0.19	0.0904	0.0067	0.0252	0.0250	0.0005	0.0070	3.34	99.94
MIR T 47D	XV 8226	60.00	16.44	7.025	0.129	3.00	2.38	4.36	2.05	0.74	0.20	0.0874	0.0065	0.0273	0.0243	0.0001	0.0072	3.47	99.95
MIR T 47E	XV 8238	60.49	16.15	6.963	0.126	2.95	2.45	4.19	2.07	0.75	0.18	0.0838	0.0072	0.0279	0.0237	0.0011	0.0069	3.47	99.95
MIR T 47F	XV 8230	60.91	16.02	6.906	0.124	2.99	2.31	4.16	2.02	0.75	0.19	0.0865	0.0063	0.0264	0.0237	0.0010	0.0063	3.43	99.95
MIR T 47G	XV 8232	59.13	16.69	7.594	0.138	3.24	2.23	4.43	1.97	0.77	0.16	0.0879	0.0067	0.0256	0.0235	0.0007	0.0065	3.44	99.95
MIR T 49	XV 8260	61.79	14.99	6.602	0.112	2.71	3.67	3.91	1.93	0.72	0.15	0.0538	0.0071	0.0264	0.0233	0.0004	0.0098	3.24	99.94
MIR T 52	XV 8246	55.01	4.98	1.755	0.066	3.06	15.52	0.71	1.60	0.25	0.08	0.0191	0.0062	0.0259	0.0034	0.0009	0.0077	16.86	99.96
MIR T 69	XV 8256	55.83	16.49	6.226	0.101	2.98	5.68	4.54	1.73	0.56	0.21	0.0561	0.0089	0.0587	0.0156	0.0001	0.0120	5.45	99.95
MIR T 82	XV 8254	57.95	16.66	6.468	0.123	2.40	6.11	3.77	1.97	0.62	0.23	0.0491	0.0060	0.0383	0.0183	0.0003	0.0121	3.54	99.95
MIR T 84	XV 8252	52.69	18.82	7.518	0.130	2.72	9.19	2.94	1.24	0.71	0.25	0.0333	0.0036	0.0175	0.0206	0.0005	0.0123	3.65	99.95
MIR T 96	XV 8238	60.02	15.63	7.489	0.125	3.33	4.27	4.22	0.65	0.83	0.21	0.0224	0.0034	0.0171	0.0244	0.0008	0.0113	3.10	99.95
MIR T 114	XV 8250	57.99	16.45	6.868	0.124	2.86	6.70	3.40	1.14	0.67	0.18	0.0383	0.0047	0.0211	0.0218	0.0005	0.0122	3.47	99.95
MIR T 121	XV 8236	59.28	15.09	6.996	0.119	2.87	6.26	3.49	1.33	0.76	0.17	0.0304	0.0054	0.0155	0.0207	0.0005	0.0111	3.52	99.95
MIR T 121A	XV 8216	58.59	14.74	7.309	0.134	3.21	5.92	3.72	1.43	0.78	0.24	0.0430	0.0052	0.0168	0.0261	0.0006	0.0081	3.76	99.95
MIR T 121B	XV 8218	58.72	14.93	7.567	0.125	3.15	6.04	3.57	1.33	0.80	0.23	0.0504	0.0051	0.0159	0.0297	0.0003	0.0077	3.37	99.94
MIR T 121C	XV 8220	59.30	15.15	6.877	0.117	2.94	6.11	3.66	1.35	0.77	0.19	0.0463	0.0047	0.0148	0.0279	0.0005	0.0070	3.38	99.94
MIR T 121D	XV 8222	59.56	15.04	6.736	0.115	2.85	6.37	3.48	1.33	0.75	0.21	0.0449	0.0047	0.0142	0.0273	0.0006	0.0065	3.40	99.94
MIR T 127	XV 8248	56.82	15.76	6.898	0.124	3.22	5.82	4.80	0.59	0.65	0.23	0.0310	0.0040	0.0348	0.0192	0.0005	0.0114	4.94	99.97
MIR T 141	XV 8234	55.47	17.24	8.214	0.157	3.58	4.64	3.93	1.17	0.75	0.22	0.0390	0.0051	0.0247	0.0211	0.0005	0.0132	4.50	99.98
MF 755	XV 8282	53.53	11.41	5.324	0.175	1.86	11.71	2.43	3.20	0.57	0.15	0.0643	0.0087	0.0529	0.0115	0.0009	0.0099	9.45	99.97
MF 776	XV 8284	57.80	17.03	6.610	0.129	2.40	5.01	5.24	1.54	0.61	0.25	0.0457	0.0051	0.0430	0.0163	0.0007	0.0113	3.20	99.95
MF 778	XV 8286	56.85	16.59	7.303	0.134	2.57	6.19	3.93	1.91	0.69	0.25	0.0523	0.0060	0.0286	0.0190	0.0007	0.0125	3.41	99.96
MF 806	XV 8288	60.00	15.72	7.096	0.103	3.12	4.91	4.01	1.02	0.72	0.16	0.0203	0.0041	0.0198	0.0177	0.0006	0.0117	3.04	99.97
MF 1134	XV 8290	59.66	14.63	7.217	0.117	2.77	5.04	2.91	1.29	0.81	0.18	0.0249	0.0047	0.0327	0.0226	0.0004	0.0102	5.23	99.95

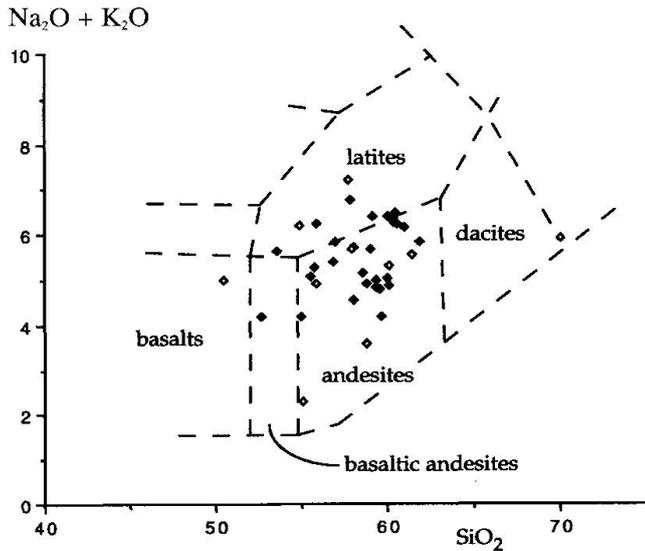


Fig. 2 SiO_2 - $(\text{Na}_2\text{O}+\text{K}_2\text{O})$ -plot of the Glarus Alps whole-rock analyses with classification fields according to COX et al. (1979). Filled diamonds represent type II to IV Taveyannaz sandstones (TS), open diamonds are flysch sandstones ("grés de Val d'Iliez" after VUAGNAT, 1952). For interpretation see text.

parts of volcanogenic glass (now replaced by chlorite), or has been transported into the rock by a salt-rich fluid (STALDER, 1979). These data indicate a basaltic andesite or andesite composition assuming that the latite composition of some analyses is due to the slight enrichment of the alkaline elements (Figs 2, 3). STALDER (1979) assumed a slight loss of K_2O due to albitization, thus, the enrichment of the alkaline elements might have been restricted to Na. The enrichment of the Na is also shown in a Na_2O versus CaO diagram (VALLANCE, 1974), where some of the "true" Taveyannaz sandstone samples plot in the spilitic part (Fig. 4). Data from STALDER (1979), NIGGLI et al. (1930) and WINTERHALTER (1933) also plot on both sides of the spilitic/non-spilitic boundary.

Whole-rock composition and content of volcanic material

Several trends can be seen between "true" Taveyannaz sandstones and typical flysch sandstones (VUAGNAT, 1952), the latter normally being depleted in Al, Fe, Mn, P, and V, and enriched in Ca and Sr (Figs 2-4). These trends can be explained by the increase of the calcite content, and the impoverishment of mafic phases. However, with the exception of the Verrucano and the sandstone from the Subalpine Molasse, chemical differences are very slight and mean values are

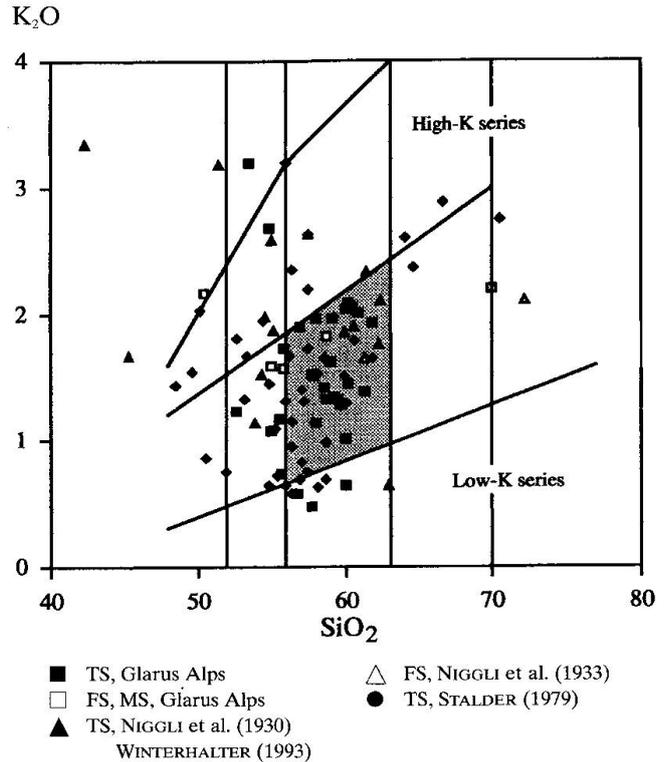


Fig. 3 SiO_2 - K_2O -plot with classification fields after LE MAITRE (1989) with all existing TS analyses. Note, that data from "andesitic" fragments within the Taveyannaz sandstones (in NIGGLI et al., 1930) plot within the field of basaltic to basalt andesitic composition. The dotted area is the compositional field for andesites. FS: flysch sandstones, MS: Molasse sandstone.

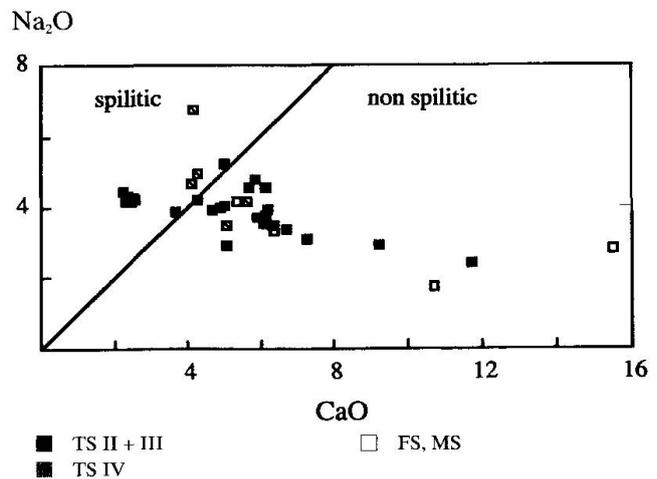


Fig. 4 Na_2O versus CaO diagram with boundary between typical values of spilitized and non-spilitized basaltic rocks after VALLANCE (1974). Samples are divided into Taveyannaz sandstones showing critical minerals (TS II + III), bearing no critical minerals (TS IV) and flysch sandstones. For abbreviations see figure 3.

commonly identical within the variation ranges (Figs 2, 3). Only vanadium contents are statistically higher within the Taveyannaz sandstones.

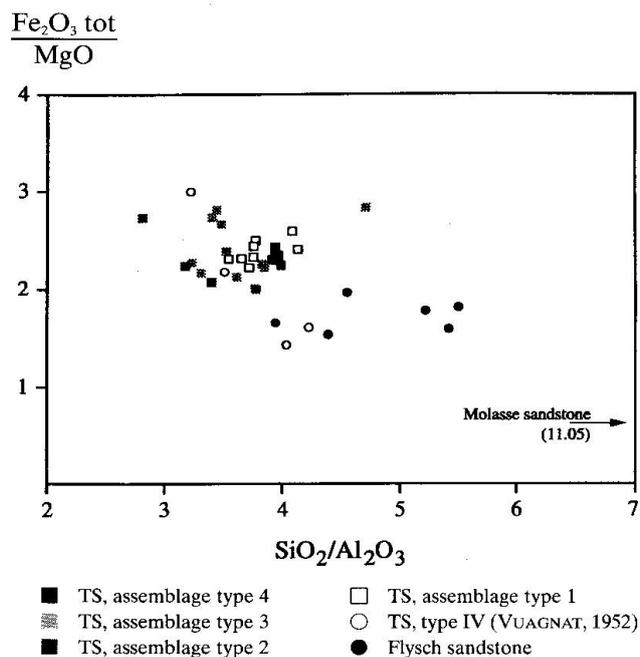


Fig. 5 Si/Al versus Fe^{3+}/Mg diagram of the Glarus Alps Taveyannaz and flysch sandstones. The assemblage types 1–4 and type IV of the Taveyannaz sandstone (TS) are defined in table 1, all Flysch sandstones contain less than 50 vol.% of volcanic material.

Vanadium generally is a strongly compatible element within mafic minerals (SHERVAIS, 1982).

Similarity is even more evident for the different metamorphic assemblage types of Taveyan-

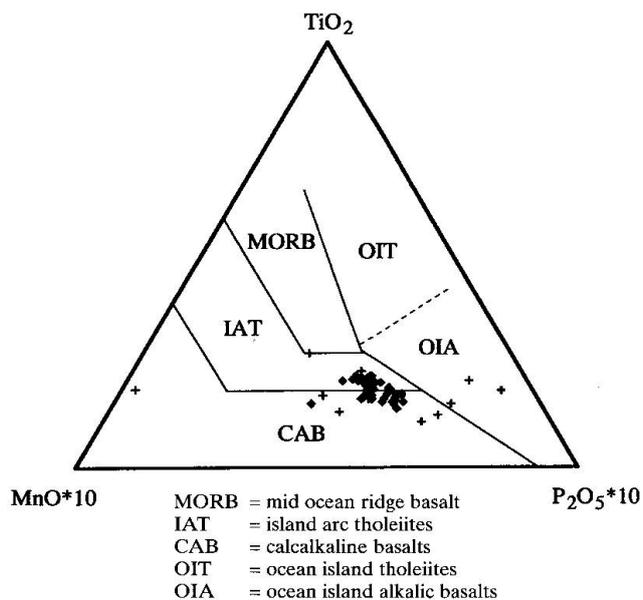


Fig. 6 Ti-Mn*10-P*10-ternary diagram with discriminant fields for basalts from different tectonic settings. Taveyannaz sandstones from the Glarus Alps are given as filled diamonds, analyses from NIGGLI et al. (1930) and WINTERHALTER (1933) as crosses. For interpretation see text.

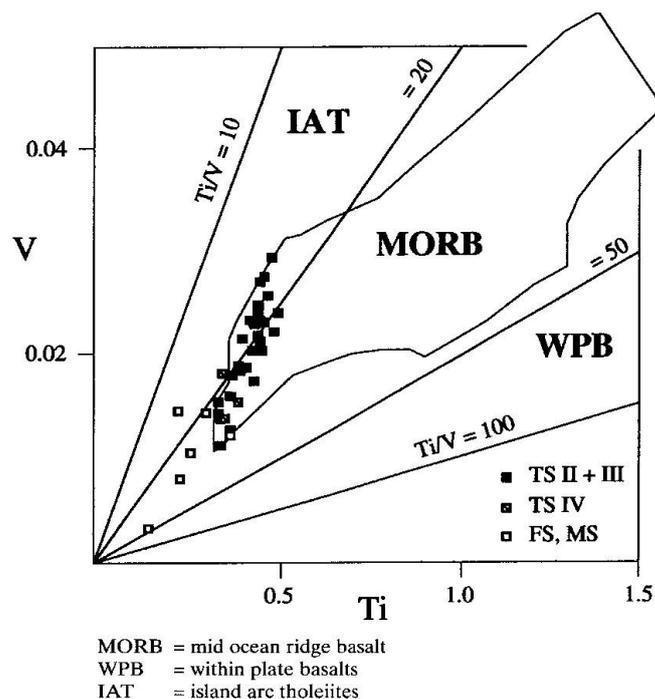


Fig. 7 Ti versus V diagram with discrimination areas for basalts of different tectonic settings. The shown area of MORB basalts represents 131 analyses from the Pacific and Atlantic Ocean and the Red Sea (SHERVAIS, 1982). Abbreviations as before.

naz sandstones (Tab. 1). Chemical results of the different metamorphic assemblage types of the Taveyannaz sandstone according to RAHN et al. (1994) are compared with Taveyannaz sandstones of type IV (VUAGNAT 1952, cf. Tab. 1) and flysch sandstones in figure 5. The strong compositional similarities of the assemblage types and of types II/III (bearing critical minerals) and IV (without critical minerals, Tab. 1) contradicts the assumption that the formation of critical minerals is mainly dependent on the whole-rock composition. Thus, the crystallization of the critical metamorphic minerals has to be considered as the result of locally limited chemical conditions (within the vicinity of one or a few grains), rather than of a large scale bulk rock composition favourable for the formation of these minerals. Such a mechanism can be documented by the formation of actinolite on former clinopyroxene grain boundaries (RAHN et al., 1994, Fig. 2d). However, the compositional conditions necessary for the formation of critical minerals such as laumontite, pumpellyite or prehnite remain unclear.

The geotectonic context

Several minor and trace elements can be used for the discrimination of different geological contexts (Figs 6 and 7). However, in the Taveyannaz

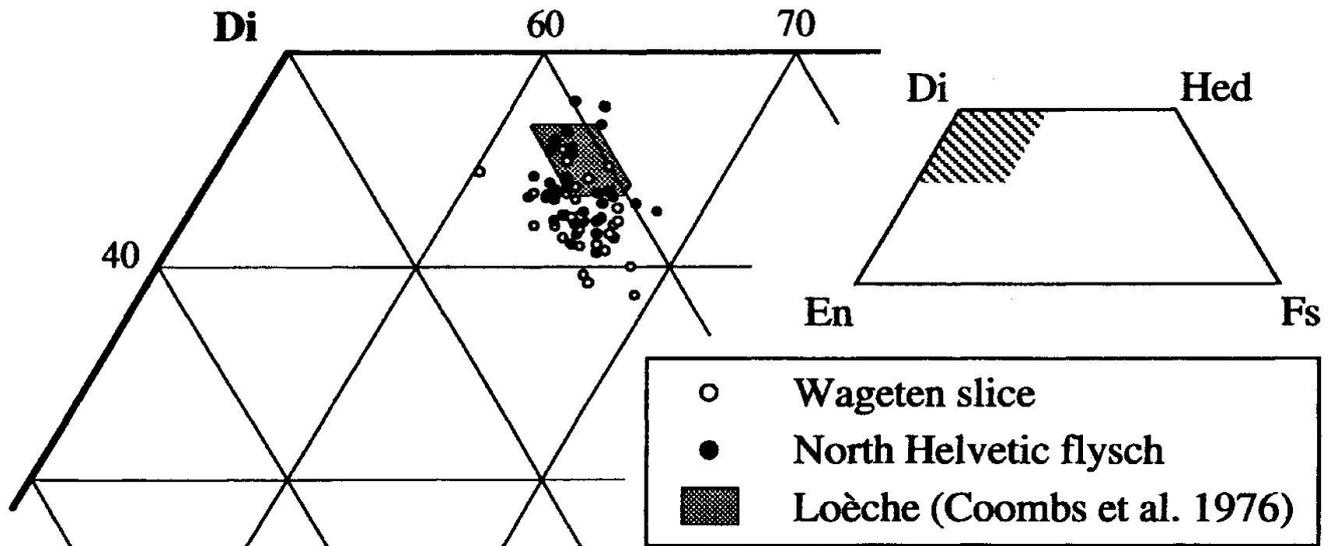


Fig. 8 Comparison of clinopyroxene compositions from the Glarus Alps and Loèche (COOMBS et al., 1976) in the clinopyroxene quadrilateral. Representative data are given in table 4.

sandstones the use of Zr must be avoided (see above), and Nb, which is commonly used for this purpose, has not been measured.

The Ti–Mn–P ternary system has been established with the help of more than 500 analyses (MULLEN, 1983) as a discriminant diagram for basalts and basaltic andesites, i.e. for rocks between

45 and 54 wt% SiO₂, a range that is suggested to represent the original SiO₂ content of the volcanic precursor of the Taveyannaz sandstone (see above). In this diagram analyses from the Glarus Alps have a very restricted range, while data from NIGGLI et al. (1930) and WINTERHALTER (1933) scatter with a constant TiO₂ content

Tab. 4 Representative clinopyroxene analyses from the Taveyannaz greywackes of the Glarus Alps. For measurement conditions, see RAHN et al. (1994), same abbreviations as in table 2.

Sample nr.	MR T 47	MF 1134	MR T 96	MF 776	MR T 121
Analysis	35.44	6.12	26.14	22.12	27.33
Tectonic unit	Wageten	Wageten	NHF	NHF	NHF
SiO ₂	51.61	51.84	52.50	52.51	52.84
TiO ₂	0.61	0.59	0.56	0.27	0.53
Al ₂ O ₃	2.03	2.51	2.24	1.52	2.17
FeO	9.99	10.50	8.34	8.26	9.99
MnO	0.53	0.47	0.36	0.84	0.41
MgO	14.95	14.99	14.56	14.73	14.35
CaO	19.94	18.75	20.53	21.05	19.39
Na ₂ O	0.23	0.29	0.39	0.33	0.29
K ₂ O	0.00	0.00	0.00	0.00	0.00
∑ (oxides)	99.89	99.94	99.48	99.51	99.77
Si	1.931	1.933	1.955	1.962	1.964
Ti	0.017	0.017	0.016	0.008	0.015
Al	0.090	0.110	0.098	0.067	0.095
Fe	0.312	0.327	0.260	0.258	0.310
Mn	0.017	0.015	0.011	0.027	0.013
Mg	0.834	0.833	0.808	0.820	0.795
Ca	0.799	0.749	0.819	0.843	0.772
Na	0.017	0.021	0.028	0.024	0.021
K	0.000	0.000	0.000	0.000	0.000
∑ (cations)	4.017	4.005	3.995	4.009	3.985

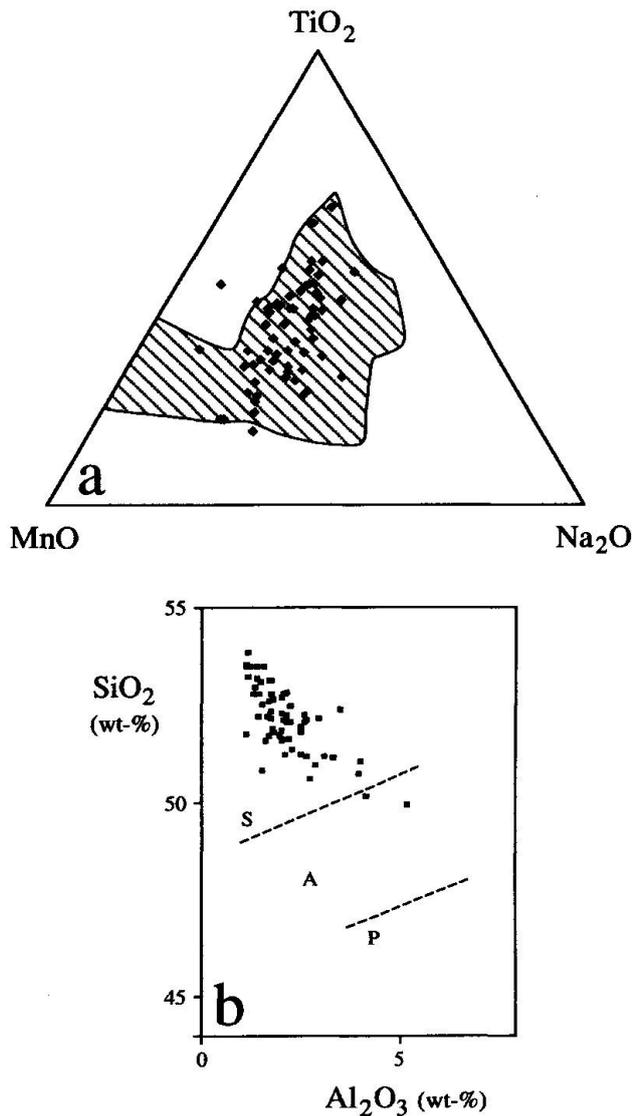


Fig. 9 Discrimination diagrams for igneous clinopyroxenes with analyses from the Glarus Alps Tavayannaz sandstones. (a) Ti-Mn-Na ternary plot with hatched area for typical volcanic arc basalts (VAB) after NISBET and PEARCE (1977). (b) Si versus Al diagram with boundaries between sub-alkaline (S), alkaline (A) and per-alkaline (P) magmatism (LE BAS, 1962). Typical volcanic arc basalts have been shown to mainly plot within the sub-alkaline field.

(Fig. 6). One of the most important Ti-phases is rutile (during metamorphism replaced by titanite), which has epitactically grown on flakes of former detrital biotite (RAHN et al., 1994). In addition, newly grown leucoxene grains can be found within the matrix. Thus, a slight increase of the whole-rock TiO_2 content can be assumed during sedimentation. Data therefore indicate a typical pattern for calc-alkaline basalts and can be compared with chemical compositions of very young material from the Marianas, Aleutians, or

Antilles that all represent volcanic island arc basalts (MULLEN, 1983).

In a Ti-V-diagram data of types II and III Tavayannaz sandstones plot partly within the area of typical recent atlantic MORB basalts and show a rather constant Ti/V ratio (Fig. 7). Both elements are thought to behave similarly during alteration or low-grade metamorphism (SHERVAIS, 1982). If, in addition, a slight enrichment in Ti during sedimentation is considered (small amounts of detrital rutile), i.e. data from the original volcanic material plotting at slightly lower Ti values, they shift into the range of typical calc-alkaline suites with $\text{SiO}_2 < 58$ wt% from recent island arc ridges (IAT, SHERVAIS, 1982, Fig. 2). The increasing amount of detrital material coincides with the depletion of Ti and V.

Clinopyroxene as source indicator

Clinopyroxene is the only primary volcanic phase that is still present and was not altered during Alpine metamorphism (RAHN et al., 1994). In figure 8 the compositions of clinopyroxenes from the Glarus Alps and Loèche (COOMBS et al., 1976) are compared and are identical within the analytical scattering (Fig. 8). Thus, clinopyroxenes display a close relationship between different Tavayannaz greywacke occurrences today separated by some 120 km. Representative analyses of clinopyroxenes from the Glarus Alps are given in table 4.

There have been several successful attempts to relate the chemical composition of igneous clinopyroxenes to the nature of their host rocks (KUSHIRO, 1960; LE BAS, 1962; COOMBS, 1963). NISBET and PEARCE (1977) used clinopyroxene microprobe analyses from different basalts in order to define several areas within a Ti-Mn-Na ternary system and to distinguish between contrasting tectonic settings. For volcanic arc basalts (VAB), they showed that clinopyroxenes commonly have TiO_2 values below 1.5 and SiO_2 values above 47 wt%.

Clinopyroxenes from the Tavayannaz sandstones of the Glarus Alps are plotted in the diagrams of NISBET and PEARCE (1977) and LE BAS (1962) (Fig. 8). The data correlate best with chemical pattern of VAB. In the ternary system, clinopyroxenes mainly plot within the overlapping fields between different tectonic settings, but the scatter is very similar to the range of VAB data in NISBET and PEARCE (1977). In the SiO_2 - Al_2O_3 diagram, most analyses plot above the sub-alkaline/alkaline boundary (LE BAS, 1962), which points to an evolved basalt compo-

sition, as is typical for fractionation within volcanic arcs. The low Ti values are typical for the absence of a thick continental crust, clinopyroxenes from within plate basalts are generally Ti-rich (PEARCE, 1976).

Conclusions

Whole-rock analyses from the Taveyannaz sandstones of the Glarus Alps indicate a basaltic to basalt-andesitic composition for the volcanogenic precursor of the Taveyannaz sandstone. Compositional changes due to detrital input during sedimentation and mineral reactions during Alpine metamorphism are characterized by a 10 wt% enrichment of SiO₂, a slight depletion of Al₂O₃, FeO, and a slight enrichment of Na₂O, K₂O, and TiO₂.

Minor- and trace-element distributions suggest a calcalkaline magmatism, which is typical for island arc volcanic systems found above a subduction zone (CONDIE, 1989). The same origin is suggested by clinopyroxene analyses. The compositional pattern is similar to those of clinopyroxenes from recent volcanic arc basalts, and points to an evolved magma that was not influenced by the presence of a thick continental crust.

A comparison with former whole-rock analyses (STALDER, 1979; NIGGLI et al., 1930; WINTERHALTER, 1933) indicates a very constant composition for all Taveyannaz greywackes and related sandstones within the Alpine arc and the Apennines. Data show no clear chemical boundary between "true" Taveyannaz sandstones (type II and III) and type IV. Thus, the formation of critical metamorphic minerals was not mainly influenced by whole-rock composition, but most probably determined on a very small scale by the presence of volcanic material (vitreous fragments) and minerals such as primary clinopyroxene, that became metastable during low-grade metamorphic conditions.

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