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THE COMPOSITION AND MANUFACTURE OF EARLY MEDIEVAL COLOURED WINDOW GLASS FROM SION (VALAIS, SWITZERLAND)—A ROMAN GLASS-MAKING TRADITION OR INNOVATIVE CRAFTSMANSHIP?*

S. WOLF† and C. M. KESSLER

Department of Geosciences—Mineralogy and Petrography, University of Fribourg, Chemin du Musée 6, CH-1700 Fribourg, Switzerland

and W. B. STERN and Y. GERBER

Geochemical Laboratory, Institute of Mineralogy and Petrography, Bernoullistrasse 30, CH-4056 Basel, Switzerland

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Archaeological excavations between 1984 and 2001 at the early Christian cemetery church in Sion, Sous-le-Scex (Rhône Valley, Switzerland), brought to light more than 400 pieces of coloured window glass dating from the fifth or sixth centuries AD*. The aims of this paper are threefold: first, to characterize the shape, colour and chemical composition of the glass; secondly, to understand whether the production of the coloured window panes followed traditional Roman glazing techniques or was of a more innovative nature; and, thirdly, to provide some indications as to the overall design of these early ornamental glass windows. Forty samples of coloured glass have been analysed by wavelength-dispersive X-ray fluorescence. The results of the chemical and the technological studies showed that most of the glass was produced using recycled glass, particularly as a colouring agent. Some of the glass was made of essentially unmodified glass of the Levantine I type. The results taken together seem to confirm that raw glass from this region was widely traded and used between the fourth and seventh centuries* AD*. The artisans at Sion were apparently still making use of the highly developed techniques of Roman glass production. The colour spectrum, manufacture and design of the windows, however, suggest that they represent early examples of ornamental coloured glass windows.*

KEYWORDS: EARLY MEDIEVAL WINDOW GLASS, SWITZERLAND, COMPOSITION, PRODUCTION, DESIGN, X-RAY FLUORESCENCE

INTRODUCTION

The transfer of the Roman capital to Byzantium and the end of the West Roman Empire led to significant changes within the political, economic and cultural structures in the Mediterranean and central Europe during the second half of the first millennium AD. Increasing Church power resulted in the construction of churches and the development of innovative glazing techniques such as 'stained'-glass windows, which in turn led to an increasing demand for glass, and particularly coloured window glass. The newly founded early monasteries developed into significant cultural and economic hubs, which were also important as craft and production centres

* Accepted 15 November 2004.
† Current address: Lothringersstr. 97, CH-4056 Basel, Switzerland; email sophie.wolf@gmx.ch

(Wedepohl 2003, 84). These developments eventually led to changes in glass production technology and tradition that, at least partially, depended on the availability of raw materials and existing trade connections.

It is now well established that between antiquity and the early Middle Ages, most of the glass worked in western Europe was made in primary production centres on the eastern Mediterranean coast. This glass was traded as chunks, remelted and worked in smaller glassworks (Freestone *et al.* 2002). It is of a silica–soda–lime composition and is made from calcium-rich sand and mineral soda (natron). However, a period of transition in glass-making traditions and production processes probably began at the beginning of the Carolingian era. According to region and period, glass made from plant ash gradually started to replace natron-based glass (e.g., Wedepohl *et al.* 1997; Wedepohl 2001). Concurrently, hierarchically organized glass production, comprising primary production centres and secondary glassworks, began to be superseded by smaller independent 'ateliers complets', where both raw glass and end products were made (Foy 2000).

Yet, for entire regions in central and eastern Europe, there are gaps in our knowledge as to where and when these changes may have occurred. Switzerland is one of a number of regions where, until now, there has been little research into early medieval glass, and especially window glass. With the exception of analyses on Roman glass finds from Augst and Avenches (Rütti 1991; Amrein *et al.* 1995; Amrein 2001), no compositional data relating to glass from this period has been published. Furthermore, virtually nothing is known about early medieval window glass: the material sources, the manufacturing processes, the origin of the craftsmen or the trade routes across the Alps. Unlike in France, the United Kingdom or Italy (Lafond 1966, 26; Cramp 1975, 2000; Dell'Acqua 2003), the documentary references on glass-making or the glazing of windows in Switzerland are very meagre.

With the systematic study of window glass from Sion, Sous-le-Scex (Fig. 1), where one of the earliest and largest finds of coloured window glass north of the Alps was unearthed, our aim has been to better understand glass production traditions in this region. Together with the window glass from Müstair, the finds from Sion, Sous-le-Scex, form the focus of an interdisciplinary research project, which is funded by the Swiss National Science Foundation (Goll *et al.* 2003). The glass was first presented by Dr Jürg Goll (2001) at a conference in Lucca in 1999. The major aim of this paper is to present the results on the composition, colour, shape and manufacturing techniques of these early ornamental glass windows, as well as to attempt an interpretation as to their overall design. The four questions that are addressed in this study are as follows: First, what materials were used in the production of the coloured windows and what are the possible sources of raw materials? Secondly, which manufacturing processes may have been employed? Thirdly, did 'Roman' methods of window glass-making survive into the early medieval period, or were the techniques being used of a more innovative nature? And, finally, where were the window panes produced?

THE ARCHAEOLOGICAL CONTEXT AND THE GLASS FINDS

In the course of major construction works on a car park in Sion, Sous-le-Scex (Rhône Valley, Switzerland), workers came across the remains of an important early Christian cemetery church. The main building, which has a rectangular floor plan, dates from the first half of the fifth century and was built on a previously undeveloped site, well outside the Roman settlement of *Civitas Seduni*. Approximately one hundred burials took place here and the graves were placed closely side by side (Antonini 2002). The form is consistent with traditional early

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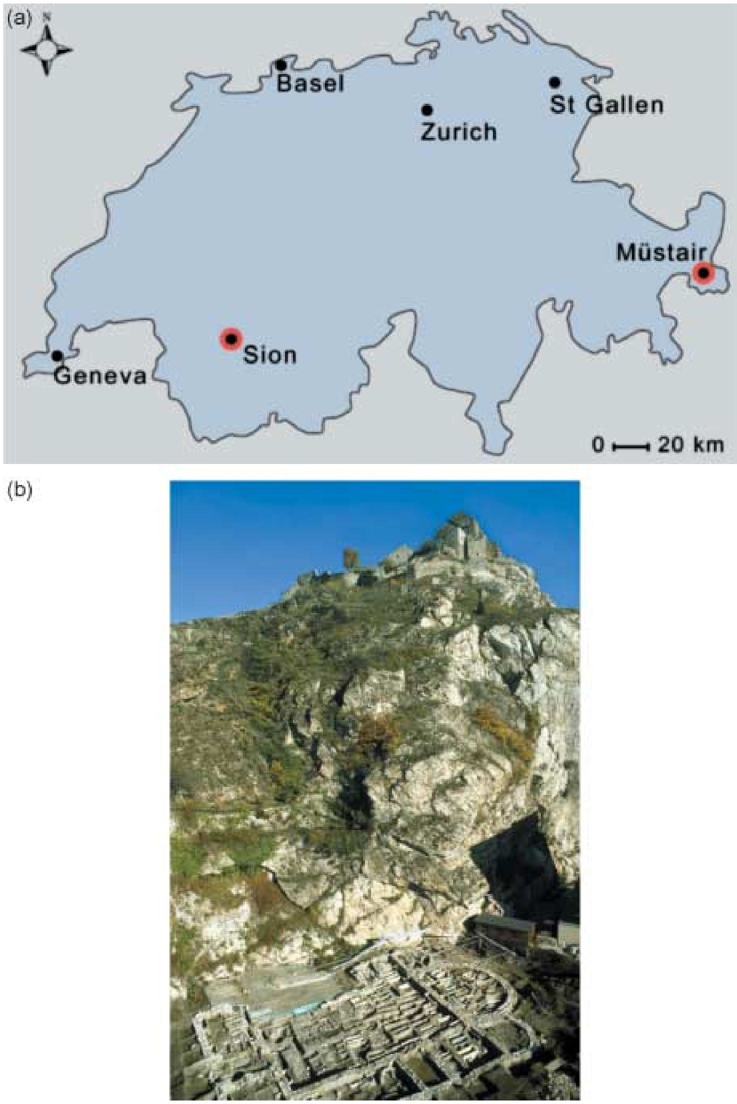

Figure 1 *(a) A map of Switzerland showing Sion (Valais) and Müstair (Graubünden). (b) A photograph of Sion, Sous-le-Scex (from Antonini 2002).*

Christian roofed cemeteries (*coemeterium subteglatum*). The building was enlarged and altered in several stages during the fifth and sixth centuries, involving additions to the nave, comprising a two-part eastern annexe, the northern apse, and quadratic north-wing and south-wing annexes. With the addition of further annexes to the west, south and north, as well as the construction of the southern apse after the middle of the sixth century, the site developed into a complex structure. The floor plan corresponds to that of a basilica, consisting of a nave with two aisles, and three apses forming the eastern side of the church. The church was renovated towards the end of the sixth century following a fire. Further careful renovations appear to have been carried out in around AD 700, possibly in connection with a change in function of

Figure 2 *Some window glass fragments from Sion, Sous-le-Scex (from Antonini 2002).*

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the building. Specifically, a new mortar floor was laid and a few rooms had vaulted ceilings put in. The entire church interior would have had white plaster walls, with the exception of the two eastern annexes, which were painted in colour. Furthermore, the windows in these annexes may have been glazed using coloured glass. Towards the end of the ninth century or at the beginning of the tenth, the church lost its importance. It was finally abandoned and used thereafter as a quarry, before it sank into complete obscurity.

In total, 406 pieces of coloured window glass were found during archaeological excavations between 1984 and 2001 (Antonini 2002). The window glass probably formed part of the original construction of the building, and dates, according to which annexe they belong to, from the fifth or sixth centuries AD (Fig. 2).

During subsequent excavations several hundred metres east of the church, the remains of a Roman villa, two memorials and a presumed workshop area dating from between the fourth and fifth centuries AD were discovered. Along with debris of glass and ceramics, a dozen fragments of glass production residues (glass chunks, droplets) have been unearthed (Antonini 2002); these fragments date back to the late fifth century AD according to datable ceramics found with them (Martin 1995 and pers. comm.). Three fragments of production residues were selected for analysis in order to verify whether the church window glass was produced at this site.

METHODOLOGY

Central to our methodological approach was the establishment of a database. This database allowed us to make statistical evaluations of our observations and results. The database comprises all available information on the archaeological context and age, a detailed description of the material (kind of material, thickness, size, shape etc.), compositional data and details of the analysis techniques used as well as observations defining the productions techniques of the studied fragments. And, finally, the database includes bibliographic references.

The chemical compositions were determined using wavelength-dispersive X-ray fluorescence equipped with a tungsten anode (Siemens-Bruker AXS, SRS-3400) at the Geochemical

Laboratory of the University of Basel, Switzerland. Small fragments of glass (~ 300 mg) were removed using a diamond-coated saw. The samples were ground into a fine powder in a boron carbide pistil mill. Glass beads with a diameter of 32 mm have been prepared by mixing 300 mg of glass powder, 4700 mg of $Li_2B_4O_7$ and 200 mg of $LiNO_3$ in an agate mortar. To increase the viscosity of the melt, one drop of LiBr was added. The mixture was fused in a platinum–gold crucible (Pt95–Au05) at a temperature of approximately 1000°C for 6 min using a fluxer (Claisse Fluxy). Analyses were carried out using a standardless method (Stern 1972, 2001). The X-ray intensities (line intensity of peak minus background) were quantified by means of the EVAL analysis program, supplied by Siemens-Bruker-AXS (Karlsruhe, Germany). The measurements were operated at 4 kW under vacuum conditions with a measurement time of 30 s per line. Accuracy was tested on reference materials including two silicate standards ('verre synthétique' VS-N and Lujavrit NIM-L; *Geostandards Newsletter* 1994, 18, pp. 21 and 35) and three glass standards from Corning (Corning B, C and D; Brill 1972, 1999). The lower limit of detection (LoD) was determined on standard materials (VS-N, NIM-L) and based on the sensitivity of each element (net counts per ppm) within a three-sigma confidence level. The LoD depends strongly on the preparation technique and the line energy. Using glass beads, the lower limits of detection are generally between 0.002 and 0.05 wt% for elements with energies < 4 keV and between 5 and 50 ppm for elements with energies between 4 and 17 keV (K-lines of Sc–Nb, L-lines of Cs–U).

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CHARACTERIZATION OF THE WINDOW GLASS

Glass materials and sources

In total, 40 samples of variously coloured glass fragments from Sion, Sous-le-Scex, as well as one sample of a glass droplet and fragments of two glass chunks from the excavation area east of the church have been chemically analysed. The results for major and minor elements are presented in Table 1. Figure 3 (a) demonstrates that the composition of all fragments corresponds to that of silica–soda–lime glass. The glass production residues, however, show a different composition than the window glass. They are higher in iron, manganese and titanium and lower in calcium (Table 1). We therefore assume that the production residues are not related to the production of the window glass.

Because of the low magnesium and potassium concentrations of the window glass (MgO and K_2O are < 1 wt%, except for deep blue glass; see later discussion), we suggest that mineral soda, so-called natron, which in Roman times was mainly extracted from dry salt lakes in the Egyptian desert, was the flux material used. There is general agreement that plant- or wood-ash glass has higher magnesium, potassium and calcium concentrations and correspondingly less sodium. The comparison with published data of Roman and early medieval glass has shown that the composition of the glass is typical of natron-based glass that has been in use in the Levant in the second half of the first millennium AD (Brill 1988; Gratuze and Barrandon 1990; Freestone *et al.* 2000, 2002). Among the five production groups recognized by Freestone *et al.* (2000, 2002), glass found in northern Israel, dating from the fourth to the seventh centuries AD, has the most similar composition to the window glass from Sion, Sous-le-Scex (Fig. 3 (b)). This group, which is referred to as the Levantine I group, includes glass from the workshops at Jalame; it is assumed to be made of Belus River sand, which was mentioned by Pliny in his *Natural history* XXXVI, or a similar sand source from the Levantine coast (Brill 1988; Freestone *et al.* 2000).

Table 1 *The compositions of coloured window glass from Sion, Sous-le-Scex, and of three glass production residues from the excavation east of the church, by XRD–WDS. Major element oxides are in weight % and trace elements are in ppm. Total Fe is given as Fe_2O_3*

Sample	*Munsell colour code*	SiO_2	Al_2O_3	Fe_2O_3	*MnO*	*MgO*	*CaO*	Na_2O	K_2O	TiO_2
SSS008	2.5PB 3/8 4/8	65.17	2.44	1.52	0.18	1.67	9.17	16.88	1.28	0.27
SSS010	2.5PB 3/8 4/8	65.71	2.48	1.55	0.17	1.68	8.72	16.91	1.20	0.25
SSS259	2.5PB 3/8 4/8	65.39	2.50	1.58	0.17	1.63	8.60	17.05	1.18	0.25
SSS036	5B 5/4, 7.5B 5/4; 7.5R 3/6, 3/8, 4/8	66.01	2.24	1.50	0.55	0.82	7.50	16.96	0.77	0.15
SSS040	5B 5/4, 7.5B 5/4; 7.5R 3/6, 3/8, 4/8	65.87	2.29	1.49	0.56	0.83	7.59	16.80	0.80	0.16
SSS041	5B 5/4, 7.5B 5/4; 7.5R 3/6, 3/8, 4/8	65.40	2.27	1.53	0.54	0.87	7.52	16.59	0.80	0.16
SSS042	5B 5/4, 7.5B 5/4; 7.5R 3/6, 3/8, 4/8	65.70	2.31	1.45	0.55	0.89	7.60	16.83	0.77	0.16
SSS047	5B 5/4, 7.5B 5/4; 7.5R 3/6, 3/8, 4/8	65.94	2.31	1.45	0.55	0.88	7.64	16.54	0.82	0.16
SSS050	5B 5/4, 7.5B 5/4; 7.5R 3/6, 3/8, 4/8	61.78	2.57	2.07	0.53	1.00	7.62	15.34	0.94	0.19
SSS166	10B 5/4	66.78	2.32	0.99	0.48	0.81	8.15	17.49	0.73	0.13
SSS172	10B 5/4	67.46	2.30	1.12	0.49	0.75	7.31	17.05	0.78	0.15
SSS099	5B 5/4; 7.5B 5/4	65.83	2.25	1.35	0.55	0.78	7.20	17.08	0.70	0.15
SSS104	5B 5/4; 7.5B 5/4	66.91	2.39	0.98	0.45	0.82	8.09	17.21	0.72	0.14
SSS113	5B 5/4; 7.5B 5/4	66.72	2.33	1.00	0.52	0.83	8.14	17.19	0.76	0.14
SSS120	5B 5/4; 7.5B 5/4	66.10	2.18	1.32	0.55	0.82	7.46	17.18	0.74	0.15
SSS131	5B 5/4; 7.5B 5/4	66.32	2.24	1.31	0.54	0.80	7.41	16.92	0.70	0.15
SSS132	5B 5/4; 7.5B 5/4	66.54	2.25	1.32	0.54	0.78	7.48	17.27	0.73	0.15
SSS150	5B 5/4; 7.5B 5/4	66.31	2.26	1.34	0.53	0.79	7.40	16.97	0.72	0.15
SSS090	5B 5/6	65.76	2.24	1.39	0.55	0.82	7.24	17.15	0.70	0.15
SSS102	5B 5/6	65.84	2.25	1.36	0.54	0.84	7.22	17.02	0.69	0.15
SSS059	10BG 7/4	67.65	2.85	0.76	0.29	0.86	9.55	16.17	0.87	0.12
SSS261	10BG 7/4	68.68	2.99	0.66	0.15	0.83	8.80	16.31	0.73	0.11
SSS001	2.5BG 2/2	67.51	2.57	1.20	0.49	0.86	7.96	16.20	1.10	0.14
SSS225	7.5BG 6/4	67.43	2.52	1.00	0.46	0.87	8.30	16.44	0.86	0.14
SSS229	7.5BG 6/4	67.27	2.56	1.02	0.44	0.86	8.23	16.40	0.88	0.14
SSS234	7.5BG 6/4	67.33	2.55	1.03	0.47	0.84	8.32	16.43	0.86	0.15
SSS226	7.5BG 5/4; 7.5R 3/6, 3/8, 4/8	66.93	2.49	1.21	0.58	0.86	8.12	15.83	1.19	0.14
SSS252	10BG 6/4; 7.5R 4/8	66.92	2.85	1.35	0.47	0.93	7.85	15.57	1.15	0.17
SSS068	5G 6/2	67.17	2.44	1.12	0.55	0.84	7.94	16.52	1.04	0.14
SSS069	2.5G 7/2	67.86	2.28	0.81	0.50	0.73	7.67	16.98	0.72	0.12
SSS074	2.5G 7/2	67.45	2.27	0.86	0.62	0.76	7.62	17.06	0.76	0.13
SSS076	2.5G 7/2	67.37	2.29	0.89	0.62	0.77	7.62	17.00	0.78	0.12
SSS077	2.5G 7/2	67.63	2.37	0.88	0.52	0.79	7.70	16.70	0.84	0.12
SSS015	2.5GY 7/4	67.34	2.95	0.57	0.03	0.76	10.91	15.95	0.54	0.11
SSS018	2.5GY 7/4	67.99	2.99	0.52	0.03	0.74	10.09	16.19	0.54	0.10
SSS020	5GY 6/6	67.69	2.87	0.72	0.22	0.89	9.69	15.96	0.82	0.12
SSS012	2.5Y 6/10	66.57	3.14	0.59	0.03	0.79	11.32	15.92	0.62	0.11
SSS978	2.5Y 6/10	69.83	2.97	0.44	0.03	0.77	8.44	16.21	0.50	0.09
SSS006	7.5Y 6/8; 10Y 7/6	69.32	2.89	0.44	0.02	0.70	8.90	16.23	0.56	0.09
SSS263	7.5Y 6/8; 10Y 7/6	68.88	3.09	0.56	0.03	0.77	9.37	16.12	0.59	0.09
Glass production residues from Sion, Sous-le-Scex (east)										
SSSE004	5GY 4/4 (glass chunk)	67.18	2.99	2.96	1.24	1.36	5.37	16.94	0.41	0.51
SSSE005	5GY 4/4 (glass chunk)	64.31	7.45	2.08	1.22	1.01	5.61	14.95	2.32	0.46
SSSE006	2.5GY 4/6 (glass droplet)	64.80	2.81	2.19	1.90	1.27	6.72	18.10	0.57	0.49

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Table 1 *Continued*

Sample	P_2O_5	SO_3	*Cl*	*Sum*	*Ba*	*Co*	*Cu*	*Ni*	*Pb*	*Rb*	*Sb*	*Sn*	*Sr*	*Zn*	*Zr*
SSS008	0.23	0.11	0.41	99.3	414	371	1 555	90	3 004	<10	<50	<50	712	97	159
SSS010	0.24	0.31	0.13	99.3	359	345	1 422	102	1 562	50	<50	<50	765	107	185
SSS259	0.22	0.33	0.32	99.2	373	410	1 672	103	<50	<10	<50	<50	747	93	190
SSS036	0.08	0.09	0.24	96.9	442	272	3 340	58	20 372	22	325	1 563	487	654	132
SSS040	0.08	0.09	0.25	96.8	446	266	3 217	61	21 809	23	152	1 423	501	737	162
SSS041	0.08	0.07	0.17	96.0	404	274	5 408	49	22 215	50	1 671	3 608	511	822	156
SSS042	0.10	0.09	0.23	96.7	430	271	4 301	87	20 626	<10	859	1 881	519	773	130
SSS047	0.11	0.08	0.20	96.7	370	223	3 964	47	21 923	<10	196	1 599	516	729	154
SSS050	0.22	0.08	0.16	92.5	313	259	6 124	117	50 318	55	<50	5 875	526	3 128	227
SSS166	0.07	0.13	0.55	98.6	475	224	2 782	17	5 741	66	1 247	672	517	212	85
SSS172	0.00	0.13	0.45	98.0	395	245	4 421	43	4 467	70	5 261	1 346	474	188	101
SSS099	0.06	0.16	0.45	96.5	491	262	5 680	57	15 998	35	3 468	3 356	509	558	146
SSS104	0.02	0.12	0.54	98.4	433	158	2 642	46	9 034	55	844	816	512	234	103
SSS113	0.08	0.12	0.55	98.4	399	185	2 666	16	8 834	64	821	956	518	272	92
SSS120	0.06	0.17	0.51	97.2	395	274	4 106	28	15 037	47	2 107	1 800	505	526	108
SSS131	0.09	0.17	0.56	97.2	393	250	3 797	43	15 877	21	2 047	1 802	486	530	122
SSS132	0.07	0.08	0.23	97.4	295	286	3 312	73	15 212	39	929	1 345	495	533	122
SSS150	0.08	0.16	0.56	97.3	417	285	4 111	68	14 686	46	2 029	1 990	478	554	115
SSS090	0.07	0.12	0.51	96.7	353	276	4 494	41	18 193	51	2 299	2 554	526	620	154
SSS102	0.08	0.17	0.22	96.4	417	274	5 593	48	16 682	14	3 053	3 011	515	566	142
SSS059	0.03	0.06	0.37	99.6	367	<50	1 934	<10	<50	68	172	350	536	89	52
SSS261	0.00	0.12	0.37	99.7	520	<50	1 177	<10	131	<10	<50	<50	545	148	100
SSS001	0.07	0.10	0.39	98.6	502	188	2 384	54	6 601	<10	1 658	743	495	224	69
SSS225	0.07	0.09	0.43	98.6	338	130	3 019	27	5 666	38	1 447	844	509	285	89
SSS229	0.05	0.10	0.47	98.4	500	126	3 108	28	6 528	65	1 757	1 105	493	267	86
SSS234	0.06	0.10	0.48	98.6	403	110	2 869	32	6 105	69	1 265	945	503	247	107
SSS226	0.15	0.11	0.37	98.0	594	135	3 410	40	8 921	61	1 662	1 614	507	349	83
SSS252	0.15	0.12	0.37	97.9	439	142	3 446	44	10 008	43	1 966	1 646	491	367	106
SSS068	0.06	0.13	0.43	98.4	499	85	3 846	32	5 982	37	1 813	1 327	522	186	91
SSS069	0.10	0.13	0.51	98.4	407	69	3 297	53	6 035	54	2 140	1 204	474	165	77
SSS074	0.15	0.13	0.47	98.3	435	80	3 197	26	7 332	52	1 934	1 381	504	162	114
SSS076	0.16	0.14	0.44	98.2	394	108	3 462	34	7 036	41	2 399	1 766	514	165	105
SSS077	0.15	0.11	0.41	98.2	439	74	2 810	30	8 583	37	2 014	1 288	510	150	96
SSS015	0.00	0.07	0.59	99.8	413	72	1 351	<10	79	<10	<50	60	585	67	35
SSS018	0.00	0.07	0.54	99.8	499	<50	1 496	17	91	<10	<50	58	466	65	33
SSS020	0.03	0.07	0.52	99.6	375	<50	1 305	19	1 799	<10	<50	268	516	97	52
SSS012	0.02	0.07	0.51	99.7	524	<50	1 837	8	114	<10	150	258	490	55	43
SSS978	0.00	0.06	0.41	99.8	448	<50	944	12	<50	26	<50	<50	524	65	88
SSS006	0.00	0.07	0.63	99.8	419	128	1 112	<10	83	<10	<50	<50	450	60	65
SSS263	0.00	0.05	0.15	99.7	585	<50	888	42	<50	<10	<50	<50	521	78	90
Glass production residues from Sion, Sous-le-Scex (east)															
SSSE004	0.00	0.23	0.58	99.8	476	<50	1 142	44	<50	31	<50	<50	490	111	317
SSSE005	0.00	0.18	0.00	99.6	715	<50	843	<10	<50	80	<50	<50	427	89	326
SSSE006	0.00	0.33	0.41	99.6	1 383	64	973	16	<50	22	<50	<50	597	69	324

Colour code from Munsell colour charts: B, blue; G, green; P, purple; R, red; Y, yellow.

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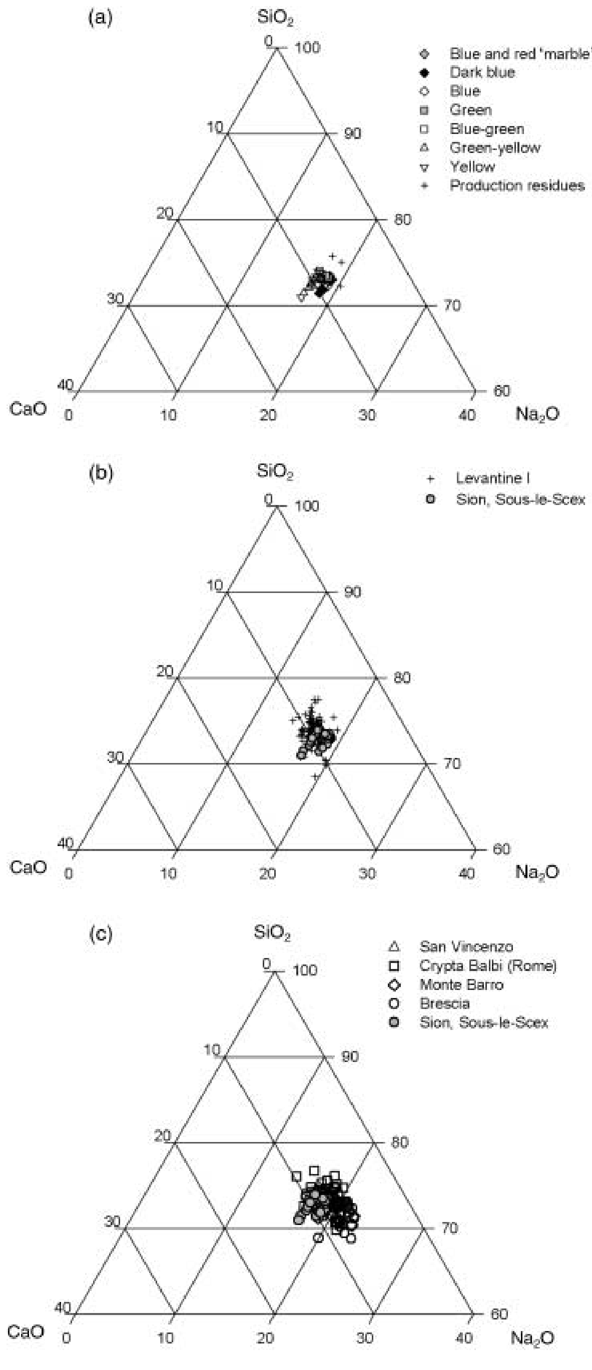

Figure 3 *(a) The composition of glass from Sion, Sous-le-Scex (grouped by colour), and of three glass production residues from the excavation east of the church in a triangular plot of* SiO_2 *versus* NaO_2 *versus CaO. (b) A comparison of glass from Sion, Sous-le-Scex, with natron-based glass from the Near East dating from the fourth to the seventh centuries AD (Levantine I group) (data from Freestone* et al. *2000). (c) A comparison of glass from Sion, Sous-le-Scex, with Italian vessel and window glass (data from Mirti 2002; Uboldi and Verità 2003).*

Other examples of comparable glass compositions include contemporary window and vessel glass from Brescia, Monte Barro and Monte San Martino (Uboldi and Verità 2003) as well as seventh-century glass from Crypta Balbi in Rome (Mirti *et al.* 2000; and see Fig. 3 (c)). Although the authors make no suggestions as to the sources of the glass materials used to produce the Italian glass, the similarity with the Levantine I glass suggests that it is also largely derived from the Near East. Equally, Freestone *et al.* (2002) assume that some of the window glass from the monastery at Jarrow (Northumbria, UK), dating from the seventh century AD, was made from essentially unmodified glass of the Levantine I type. The results taken together seem to confirm that raw glass from this region was widely traded and used between the fourth and seventh centuries AD.

On the basis of the elevated trace metal concentrations, such as lead, cobalt and copper (Figs 4 (a) and 4 (b); Table 1) we suggest that not only primary glass but also recycled material was used to produce the window from Sion, Sous-le-Scex. Consistent with arguments presented by Mirti *et al.* (2000), the presence of significant concentrations of antimony in the transparent blue, blue–green and green glass, as well as the blue and red fragments (Fig. 4 (a)) points to the re-use of recycled opaque glass; the antimony is most probably the relict of calcium antimonate, which was commonly used as an opacifier until the late first millennium AD. In contrast to the intensely coloured blue, blue and red and green glass, the green–yellow and yellow windows seem to be produced of mostly unrecycled material, because their contents of antimony and lead are comparatively low (i.e., near the detection limit). This leads us to assume that the recycled glass was particularly used as a colouring agent. Figure 3 (a) provides a piece of evidence that seems to confirm our hypothesis. This diagram reflects the composition of the uncoloured base glass. Looking at it in more detail, we can observe that the glass is chemically grouped according to colour. The green yellow and yellow fragments, for example, show higher calcium and lower sodium concentrations than the blue. Therefore, it seems a likely supposition that strongly coloured opaque glass, such as glass mosaic stones (tesserae), was intentionally added to colour the base glass. The addition of such colorants is further substantiated by mass balance calculations made by Wedepohl (2003, 91). On the basis of the chemical data concerning Roman glass tesserae and coloured glass from early medieval sites, he calculated that to produce an intensely coloured transparent glass, tesserae had been mixed with only four to ten times the quantity of raw glass. According to which colour is being produced, the addition of such considerable amounts of glass mosaic stones (or coloured glass) is likely to affect the composition of the base glass to various degrees, as shown in Figure 3 (a). The recycling of coloured glass, and particularly the colouring of glass with tesserae, is definitely confirmed by the discovery of remains of partly molten tesserae in glass-melting crucibles from Müstair and San Vincenzo, dating from between the eighth and ninth centuries AD (Dell'Acqua 1997; Goll 2001); such 'colorants' were apparently used in locally produced vessels and/or window glass. Finally, there is Theophilus who, in his treatise *De diversis artibus* (Brepohl 1999), attests to the use of coloured glass or tesserae in the production of coloured glass.

Regarding the re-use of tesserae, it seems important to note that Freestone *et al.* (1990) and Shugar (2000) identified compositional categories of Byzantine glass tesserae that each are supposed to be consistent with a single source. If our assumption that the base glass was coloured with glass mosaic stones is correct, then it is possible that tesserae from more than one particular source were used to colour the window glass from Sion. In this respect, the composition of the few dark blue transparent glass fragments is particularly interesting. Figures 4 (c) and 4 (d) show that these pieces have significantly higher concentrations in magnesium, phosphorus and

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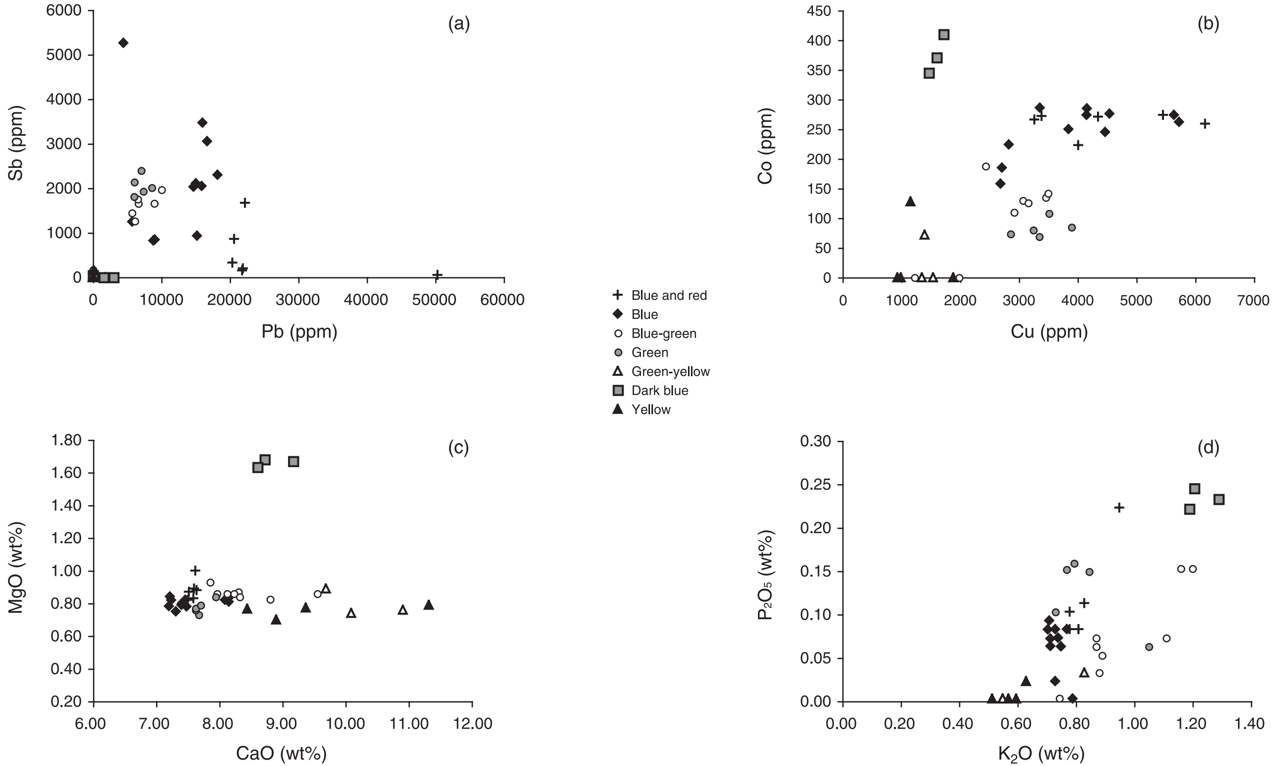

Figure 4 *Trace and minor element concentrations in glass from Sion, Sous-le-Scex: (a) Sb versus Pb; (b) Co versus Cu; (c) MgO versus CaO; (d) P_2O_5 versus K_2O.*

potassium than the other coloured glass fragments. These results, taken together with the low antimony and high cobalt concentrations (Figs 4 (a) and 4 (b)), suggest that a transparent plant-ash based silica–soda–lime glass type containing elevated amounts of cobalt was used as colorant.

To conclude, interpretations as to the recycling of tesserae must be treated with caution. When now considering the presence of additives in the composition of these glass fragments, the degree of conscious control over their use is difficult to assess. The high concentrations of colouring transition metals that were observed could partially be the result of an 'accidental' introduction through the re-use of cullet.

The colour of the glass and colouring agents

Although the colour of glass is best defined in transmitted light or using optical techniques such as reflectance spectroscopy (e.g., Sanderson and Hutchings 1987; Mirti *et al*. 2000), it has proved to be effective to use standard paint charts and to define a range of hues under one term (Cramp 2000). The colours of the 406 glass fragments were determined using the Munsell colour charts. In contrast to the analytical approach, this technique has the advantage of being still relatively objective, fast and readable for the lay person. Figure 5 illustrates the range of colours and their relative distribution. The spectrum comprises a large number of colours that are unevenly distributed: transparent blue (5B 5/4 and 5/6; 7.5B 5/4; 10B 5/4), blue–green (2.5BG 2/2; 7.5BG 5/4 and 6/4; 10BG 6/4 and 7/4) and green (2.5G 7/2; 5G 6/2) tones are dominant, followed by green–yellow (2.5GY 7/4; 5GY 6/6) and yellow tones (7.5Y 6/8 and 7/4; 10Y 7/6). The dull opaque-red (7.5R 3/6, 3/8 and 4/8) is also frequent, but occurs only in combination with the transparent blue glass (5B 5/4; 7.5B 5/4). These two colours were probably combined to give the glass a 'marble'-like texture (see Fig. 3). Deep blue (2.5PB 3/8 and 4/8) and amber yellow (2.5Y 6/10) are rare and truly colourless glass is virtually absent. Two per cent of the fragments are strongly weathered and completely opaque.

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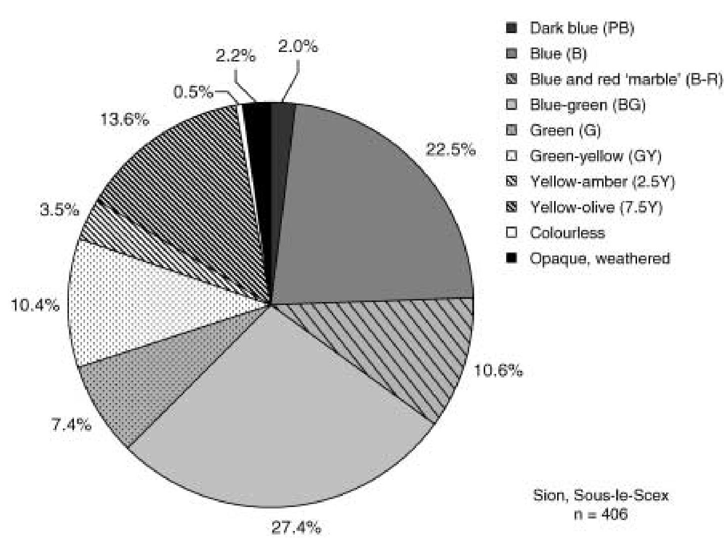

Figure 5 *The distribution of colours in glass fragments from Sion, Sous-le-Scex.*

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In general, we have to distinguish between intentionally and naturally coloured glass: the first is made by adding coloured glass to the melt or colouring agents; for example, metals or their oxides. The colour of naturally tinted glass is due to small concentrations of metals that are originally present in the glass raw materials (e.g., in the sand).

With the exception of one fragment, the green–yellow and yellow pieces most certainly belong to the naturally coloured glass. The colours are mostly the result of the natural iron concentration in the raw glass and its presence as either ferrous or ferric iron in different ratios (Newton 1978; Mirti *et al.* 2000). Their total iron content (Fe_2O_3) ranges between 0.5 wt% and 0.7 wt%; their manganese concentrations are below 0.03 wt%. However, the different shades of green–yellow and yellow are probably the result of the detected small amounts of copper or cobalt (Fig. 4 (b)). Both copper and cobalt could have been introduced by the recycling of cullet.

The dark blue, the blue and opaque red, as well as most of the blue–green and green fragments, belong to the category of intentionally coloured glass. In general, these fragments contain considerable amounts of cobalt and more copper, iron and manganese than the green–yellow and yellow glasses (Figs 4 (b) and 6 (a)). The dark blue glass contains 350–400 ppm of Co, approximately 0.15 wt% of Cu and 0.2 wt% of MnO; both blue and opaque red glasses contain slightly lower concentrations of cobalt, but higher concentrations of copper and manganese; the blue–green and green fragments are both lower in cobalt and copper than the blue and red, but have comparable iron and manganese concentrations (Fig. 6 (a)).

The dull opaque red colour, which forms part of the 'marbled' glass fragments, is produced either by tiny cuprite crystals (Cu_2O), that precipitate from the glass melt under reducing

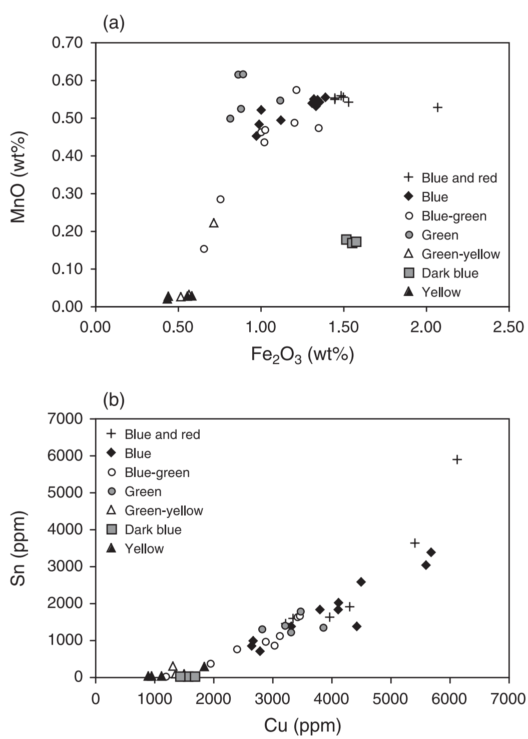

Figure 6 *(a) MnO versus Fe_2O_3. (b) Sn versus Cu.*

conditions (Cable and Smedley 1987; Freestone 1987) or, according to more recent studies, by small copper metal particles (Brun *et al.* 1991). Although we favour the arguments presented in the latter study, only additional analyses by scanning and transmission electron microscopy could help to clarify whether cuprous oxide or metallic copper are responsible for the opaque red coloration of the 'marbled' glass fragments. Nevertheless, in both cases the colour is mainly determined by the state of oxidation of copper, which depends in turn on two parameters: the proportioning of elements, in particular Cu, Fe and Pb and, to a lesser extent, the melting conditions (Brun *et al.* 1991). Lead and iron displace the redox equilibrium of cupric copper to the cuprous state. Tin and antimony appear also to act as reducing agents. The quantities of lead and antimony that were detected (see, e.g., Fig. 5 (a)) may have helped to reduce the copper and inhibit devitrification of the glass on cooling (Cable and Smedley 1987; Brun *et al.* 1991). During cooling, the oxidation state of copper remains largely unaffected because of the low diffusion coefficients of gas—that is, air—in the glass.

According to Brill's discussion of Mesopotamian recipes for opaque red, the copper was added in the form of molten bronze (Brill 1970). This assumption is supported by a strong correlation of copper and tin, which is shown in Figure 6 (b).

Interestingly, the copper content of the blue parts in the 'marbled' fragments is very similar to that of the red; the transparent blue colour probably results from cupric copper, although the presence of iron could also be a contributing factor. Considering the different oxidation states of copper in the blue and the red parts, the melting conditions of the blue parts must have been more oxidizing than that of the red parts. It seems therefore likely that the blue and the red glass were produced separately and mixed in the crucibles as suggested by Evison (1983, 71), or just before, or while, manufacturing the plate glass.

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THE WINDOW GLASS MANUFACTURING PROCESSES

The earliest glass window panes were probably produced by the Romans in the first century AD (Foy and Nenna 2001; Whitehouse 2001). In general, Roman window glass was either cylinder-blown or cast: the first technique involves a glass blower, who blows a cylinder, which is then cut and flattened to produce a sheet of glass. With the casting technique, the panes are produced by pouring the fully molten and viscous glass on to a flat surface made of polished rock, metal or maybe wood. Various material characteristics allow us to distinguish between these two production techniques, such as the thickness of the glass, the shape and orientation of bubbles, the profile of the edges and the structure of the surface (e.g., Haevernick 1954; Harden 1961; Strobl 1990; Dell'Acqua 1998). However, there is some disagreement as to the interpretation of these material features; and some characteristics seem to be common to both techniques. For example, Harden (1961) set out his criteria for identifying Roman cylinder-blown glass, while Boon (1966) considered that cast glass could exhibit most of the same attributes. Likewise, we concluded that for the windows from Sion, Sous-le-Scex, most parameters employed to identify the manufacturing techniques of early medieval window glass elsewhere—for example, in the United Kingdom or Italy (Strobl 1990; Verità and Vallotto 1991; Cramp 2001; Dell'Acqua 2001)—seem not to constitute conclusive criteria. Most of the fragments from Sion (n = 335) show no consistency in terms of thickness, shape of bubbles or the edge profiles. The thickness of the fragments ranges from one to four millimetres and can vary several millimetres within a single fragment. Bubbles are often, but not always, elongated. Some edges are sharp, while others are flame-rounded or show more complex profiles, which seem to result from the rims of glass sheet having been folded over. Some other features that were observed, including rippling, uneven top surfaces, flat undersides and bubbles in no particular direction, are unquestionably characteristics of cast panes (Taylor 2000 and pers. comm.).

The surface structures, in our opinion, seem to give the most reliable and a more detailed hint as to the casting technique. The great majority of the fragments from Sion (80%) show two clearly distinguishable surfaces: one is flat and smooth, sometimes glossy (fire-polished?); the other is mat and shows structures that have been described as 'swirling layered surfaces' by Cramp (2001). These structures have been interpreted as impressions of wood grain by some authors (e.g., Strobl 1990), while others have described them as 'wave patterns' resulting from of the fast cooling of the glass in air (Dell'Acqua 2001). According to Mark Taylor (pers. comm.), these structures are weathered 'cord'. Cord consists of inhomogeneous glass and occurs when glass is melted or refined at too low temperatures (or kept for too short a time at the correct temperature). Since weathering in soil normally affects all surfaces of glass fragments, we would expect 'swirls' on the upper and underside, but this is not the case with the Sion glass. As far as the Sion glass is concerned, these interpretations, so far, seem to be inappropriate, because the observed structures are irregular, discontinuous and on one side only; they seem to emphasize the flowing and viscous behaviour of the molten glass (Fig. 7). Therefore, we suggest that these structures have been caused by the molten glass being poured and then flattened and spread with a tool, which Harden (1961) referred to as the casting or roller-moulding technique. According to this interpretation, the smooth surface would be the lower side of the glass sheet, whereas the mat and structured surface would be the upper.

As a further complication, Foy and Nenna (2001), in their work on the production of Roman window glass, as well as Theophilus (Brepohl 1999), have noted that the wooden work surfaces would have been covered in sand. In Sion, the absence of impressions of sand grains or remaining sand on the glass surface, together with the smoothness of the lower surface, have led us to believe that polished rock (e.g., marble), was used for this purpose. Such polished marble slabs (*spolia*) were found in the early medieval monastery of San Vincenzo and were possibly used as work surfaces (Dell'Acqua 2001).

Figure 7 *A photograph of a glass fragment from Sion, Sous-le-Scex. Note the 'swirling layered' surface structure and grozed edges.*

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The observed ‘swirling’ structures are missing on 14 glass fragments. These fragments show features that, according to Strobl (1990), are characteristic for blown glass and thus might be produced by the cylinder technique: both surfaces are smooth and glossy; the glass is full of elongated bubbles and the thickness of the glass is less than 2 mm. The characterization of the remaining 56 glass fragments was impossible because of their small size or because of strongly weathered surfaces.

Subsequent to the annealing and cooling of the panes, the glass sheets were carefully cut with a sharp tool and then trimmed to appropriate size and geometrical shapes with pincers or grozing irons. The technique of grozing—that is, nibbling away small bits of glass—was described by Theophilus (II.17–18; see Brepohl 1999). A typical example of a grozed edge is shown in Figure 7. Pincers and grozing irons of various sizes might have been used, because some of the finer glass is particularly finely grozed. In contrast to later medieval window glass, the grozing was not done systematically, because the grozing marks point in different directions; that is, the pieces were trimmed from one side and then the other (reverse grozing). More details on the manufacture and the shaping of the Sion window glass are given in Kessler *et al.* (2005).

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THE SHAPE OF THE FRAGMENTS AND THE DESIGN OF THE WINDOWS

More than half of the glass pieces—that is, 63%—are highly fragmented and could not be identified. Although incomplete, 15% of the fragments retained identifiable angles or edges; 22% of the pieces were intact. Of these mainly geometrical forms, it is the triangular and quadrangular shapes that are predominant. The right-angled triangle is the most common shape (44%), followed by isosceles and equilateral triangles, which together represent 26% of all shapes. Quadrangles (rectangles, squares and rhomboids) make up 11% and circle or arc segments 13% of the total. Curved shapes with one or more rounded edges are an exception. Most such shapes, representing 6% of the total, only occur once, such as a ‘drop-shaped’ glass piece. The size of the glass pieces can vary as much as 10% within a particular shape type, making the use of stencils unlikely.

Regarding the identifiable shapes, it seems obvious that the windows were composed of geometrical patterns. In order to get a better idea of the overall design of the windows, we have made some efforts to reconstruct patterns. Figure 8 shows two of many possible basic patterns that use isosceles triangles and combine two colours. The number of possible combinations is increased the more colours that are added. More complex patterns can also be achieved by combining different shapes. However, the number of possible designs is restricted because only a few forms have aspect ratios that are consistent with each other, and could therefore be combined to form new patterns. Unfortunately, the dimensions of the windows are unknown. The reconstructed designs are therefore only propositions for possible patterns. It is interesting to note that 62% of the glass fragments were found in the side annexes. A fifth was discovered in the apses. As for the colour distribution in these parts of the church, we observed that green and yellow tones are predominant in the apses, whereas blue, blue–green and ‘marbled’ glass is more abundant in the side annexes. The rare ‘cobalt’-blue glass was apparently used only in the apses.

Regarding the mounting technique of the windows at Sion, Sous-le-Scex, the given evidence is scarce. Indirect evidence for the use of lead to assemble the ornamental windows is perhaps the varying thickness and size, as well as the irregular edges of the glass pieces: lead is a soft and malleable material and suitable for correcting irregularities in size or small blemishes. An

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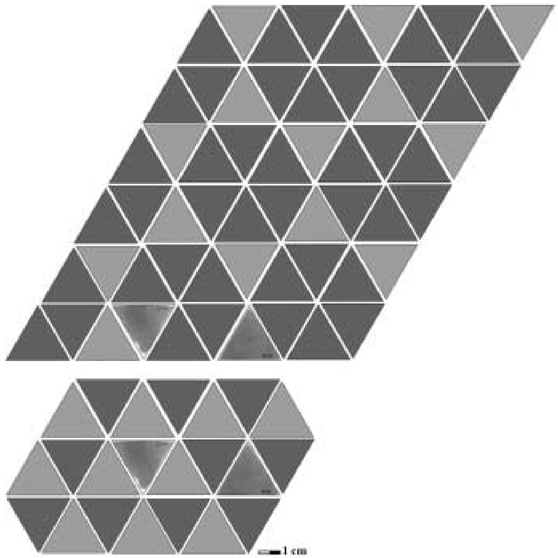

Figure 8 *Examples of possible designs.*

element mapping experiment using SEM–EDS did not allow us to confirm this hypothesis. We analysed the lead concentrations on the surface of two Sion glass fragments and on a fragment of late medieval window glass previously set in lead. On the Sion samples the lead concentrations were homogeneous across the fragments, whereas on the reference sample lead concentrations increased towards the rim that was previously in contact with the lead. Lead cames are known from as early as the sixth century AD. That 'stained' glass became more common in later periods is confirmed by the discovery of lead cames in Rouen, Jarrow, Müstair, Farfa and San Vincenzo; this, of course, does not necessarily prove that lead was used in Sion.

At least two other ways of setting the windows have to be considered: setting in wooden frames or in plaster, stone or wood *transennae*. Plaster residues that suggest the use of the latter setting technique have been observed on seventh-century window fragments from Crypta Balbi (Mirti *et al.* 2000). Cramp (2000) wonders whether the glass at Jarrow was set in wooden frames, especially for simple geometrical forms. The remains of two wooden cames and panes from Roman *Vindonissa* (Schweizerisches Landesmuseum Zürich) are rare examples of windows set in wood in Switzerland. However, at Sion neither lead cames nor remains of wooden frames or plaster were found together with the glass fragments. It is therefore difficult to come to a conclusion on the framing techniques used on these glazed windows.

MODELS AND LOCATIONS OF THE WINDOW GLASS PRODUCTION

Finally, we want to address the question of where the coloured glass windows would have been produced. The results of chemical analysis of the three samples of production residues showed that, although composed of silica–soda–lime glass, they are unrelated chemically to the window glass from the church. So, with respect to the location of the church's window glass production, these results only confirm that during the fifth century AD glass destined for elsewhere was worked at this place. Likewise, the discovery in the church of two other objects that might be related to glass production, a single green tessera and a fragment of a so-called 'Glaskuchen' (a smooth, round glass object) of uncertain age, are hardly sufficient proof of the local production of the window glass. There was some debate as to whether these 'Glaskuchen' might be smoothing tools or glass ingots (Macquet 1990; Schmaedecke 1998), but new compositional studies have shown that they appear to have been made from slag and are thus unrelated to glass production (Gratuze *et al*. 2003).

Despite the lack of concrete evidence, the combined results of material analysis and descriptions suggest two scenarios for the production of the window glass. The first would involve the import of finished products; that is, coloured glass panes or ready-cut glass pieces. In this case only the assembling of the windows would have been done *in situ*. This possibility seems likely in view of the fact that finished quarry shapes for trade were recently found on a third-century shipwreck near Toulon in France (Foy 2003, 165). In addition, Cramp (2000) refers to a manuscript that mentions the importation of ready-made windows by the Northumbrian bishops in the eighth century at Whithorn. The second scenario, which is equally plausible, is that chunk glass and cullet were imported, and that the melting of the glass, the casting and the cutting of the glass sheets was done locally. This scenario corresponds with the situation in Müstair, where the finding of glass melting crucibles, raw glass and tesserae attest to the presence of a glass workshop.

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CONCLUSIONS

This study has shown that the glass fragments from Sion, Sous-le-Scex, represent one of the largest findings yet of coloured window glass from the fifth and sixth centuries AD. Together with the findings from Müstair (Graubünden, Switzerland) dating from the eighth to the tenth centuries AD, these are among the earliest discoveries of such material north of the Alps.

The systematic description and chemical characterization of the glass allowed us to draw conclusions on the nature and source of materials used, the processes of production employed and the design of the glazed windows. On the basis of the analytical results, we suggest that the production of the window panes at Sion, Sous-le-Scex, were made from naturally coloured glass, which consisted of natron-based glass that was in use in the Levant until the second half of the first millennium AD. The intense colours were most probably produced by adding opaque glass, possibly in the form of glass tesserae. Some of the glassy colorants might have been imported from a different glass production than the base glass. But although the data is consistent with the addition of coloured opaque glass, no strong evidence can be presented to prove this, except for the archaeological evidence from sites such as Müstair and San Vincenzo. Several features of the glass, such as the discontinuous 'swirling' patterns on the surface, indicate that the majority of the flat sheets were produced by casting. Subsequently, they were cut into pieces and trimmed into different geometrical shapes, before being assembled within wooden frames, plaster or using lead cames. Unfortunately, we have been unable to come to any conclusions as to the location of production, as the production residues found to the east of the church show no chemical relationship to the window glass.

The study showed that the recipes, colorants and manufacturing techniques all correspond to the Roman methods of glass-making, which therefore appears to have survived into the early medieval period. The glazed Roman thermal baths in Sion and in nearby Martigny bear witness to this tradition. But, in contrast to the single-pane, uncoloured glazing of the thermal baths, the windows at Sion, Sous-le-Scex, had intense colours and complex geometrical designs. Thus, in terms of colour and design, these windows verify the emergence of innovative techniques and represent perhaps the earliest examples of ornamental glass windows found north of the Alps. In addition to their functional purpose, the windows acquired new aesthetic attributes. We can find comparable patterns in other genres of art, particularly in the contemporary mosaic floors of the baptistery in Riva San Vitale or in Geneva Cathedral.

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