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Neutron Activation Analytical Survey of Some Intact Medieval Glass Panels and Related Specimens

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The concentrations of 15 component oxides in medieval window glass were determined by instrumental thermal neutron activation analysis. Three groups of glass were studied: 52 specimens from a set of seven thirteenth-century French grisaille panels from a now demolished royal chateau at Rouen; 10 samples from a grisaille panel in the collection of the Princeton Museum; and a set of 32 random fragments of varied provenance. Significantly differing compositions were found. However the specimens from within individual and related groups of panels are compositionally similar even for different colors of glass. This similarity, therefore, indicates a common origin for the related pieces. Six of the random specimens had the same basic formulation as the specimens from the Rouen chateau panels.

The extent to which stained glass panels of the Middle Ages have been removed from their original settings in chapels and cathedrals, dismantled, and reconstructed with other glass to form new panels whose provenance must be established and the restoration pieces identified is often not appreciated. A window in the Princeton University Museum of Art is an excellent example of such reconstruction. The Princeton window depicts the martyrdom of Saint George (Figure 1). It was purchased for the art museum by the former Director, Frank Jewett Mather, Jr. in 1924. A similar window showing Saint George bound to a wheel

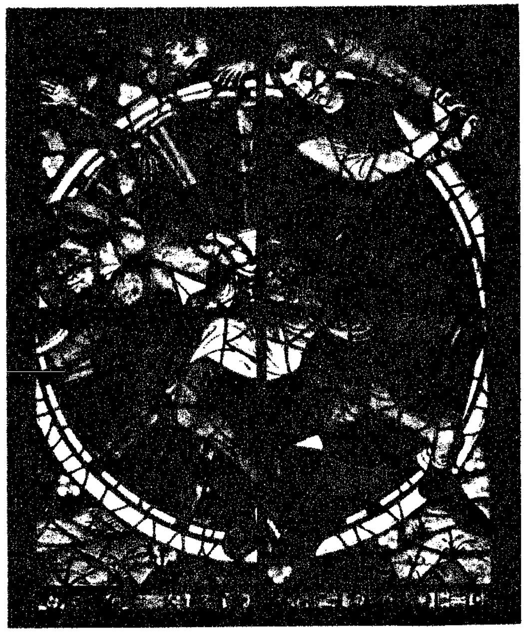

Figure 1. Stained glass from Chartres Cathedral (in the Museum of Art, Princeton University). The top left quarter is from a thirteenth-century window depicting the martyrdom of St. George. Accession No. 71.

in Archaeological Chemistry

Coutenay during the second decade of the thirteenth century (*1*). The Chartres window remained there until 1788 when the sculptor Bridan petitioned its removal to allow more light to fall on his work on the new high altar. There is no direct record of what happened to the Chartres window, but modern grisailles now fill the space. Several studies of the Princeton window were published by W. Frederick Stohlman and by Henry Graham (*2, 3, 4, 5*); they concluded that only the top left quarter is original glass, and that it and a panel which remains at Chartres (Figure 2) as part of a composite of panels were once together at Chartres in the de Courtenay window. The possible location of two quarters of the de Courtenay window is still unknown. This is an example of the complexity which can exist in studying thirteenth century glass windows.

A large portion, possibly all, of the glass originally in a medieval window would probably have been produced by a single workshop. Of course, special colors and types of glass may have been brought in from other sources specializing in their production. However, it is unlikely that the same type of glass—*e.g.*, grisaille—in a single panel originally would have many sources. Glass produced by a single source of manu-

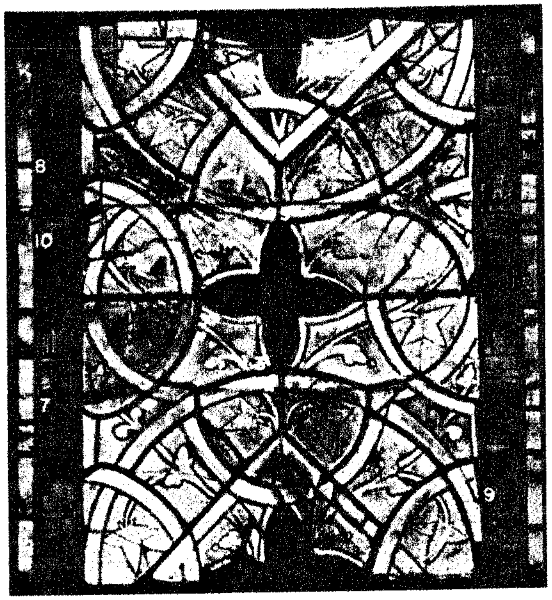

Figure 2. Thirteenth-century grisaille panels in the collection of The Cloisters Museum, New York. The panels came from the chateau of Rouen. Accession No. 69.236.2. Analytical data are in Table II. The numbers on the photograph correspond to sample numbers in the table.

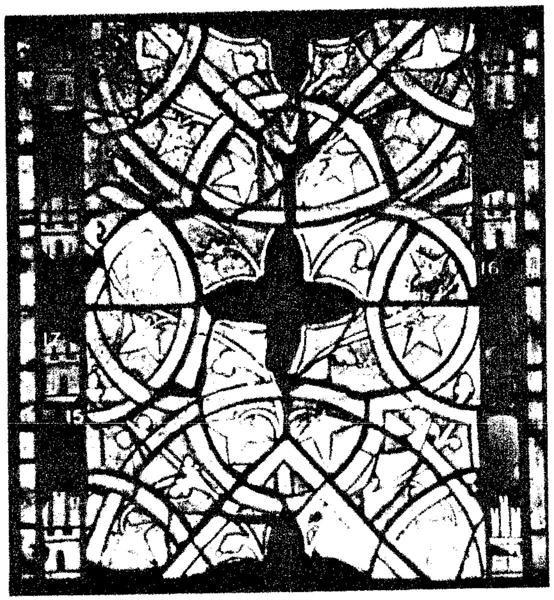

Figure 3. Accession No. 69.236.3 (see Figure 2)

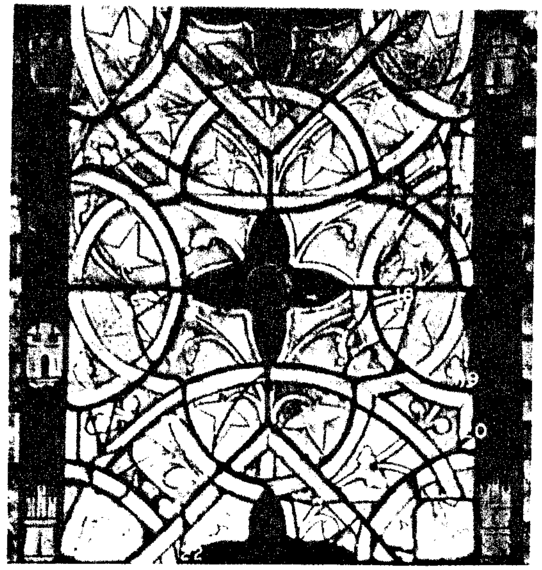

Figure 4. Accession No. 69.236.4 (see Figure 2)

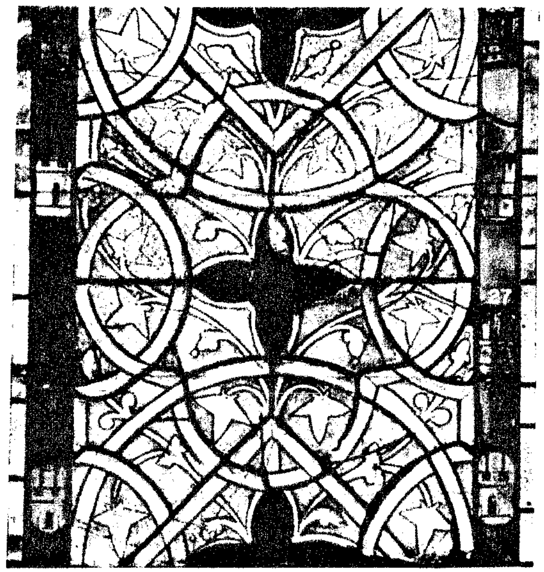

Figure 5. Accession No. 69.236.6 (see Figure 2)

facture at a given time would probably have been consistent in its composition, and hopefully this composition would differ significantly from that of glass produced elsewhere. The uniformity of glass from a given source can be studied well by multiple sampling of individual panels because the likelihood of encountering glass of related origins within them is great even if later changes were made.

It is likely not only that glass of the same manufacturer will be found in a single panel but that separate fragments of individual glass preparations will be encountered. Such pieces should be very closely related in composition and hence could be separated through analysis. The extent and nature of such close correlation should indicate the size and uniformity of individual batches.

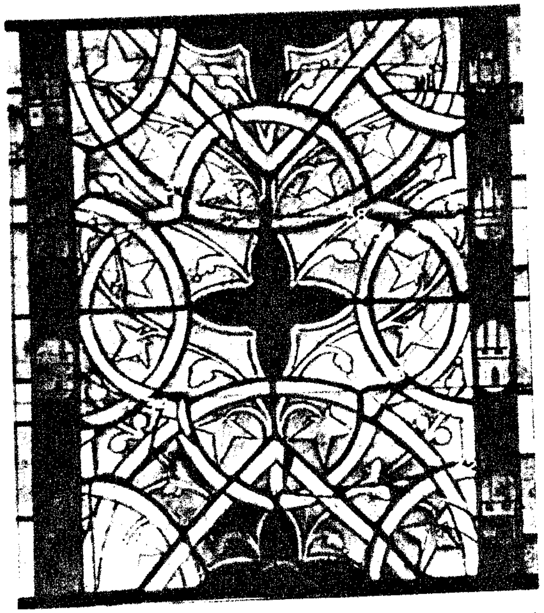

Figure 6. Accession No. 69.236.7 (see *Figure 2*)

This study was done to establish whether such correlations do exist and whether the distinctiveness of glass composition from different sources of glass manufacture will allow meaningful interpretation of observed correlations. A limited amount of historical information exists on the organization of the workshops which were the sources of stained glass in medieval Europe. In "A History of Technology" by Singer *et al.* reference is made to The Venerable Bede who in the eighth century stated in his "Historia Ablatum," that the French glaziers not only did the work required but taught the English how to do it. Frequent reference is made to the glazing of the church windows at Monkwearmouth,

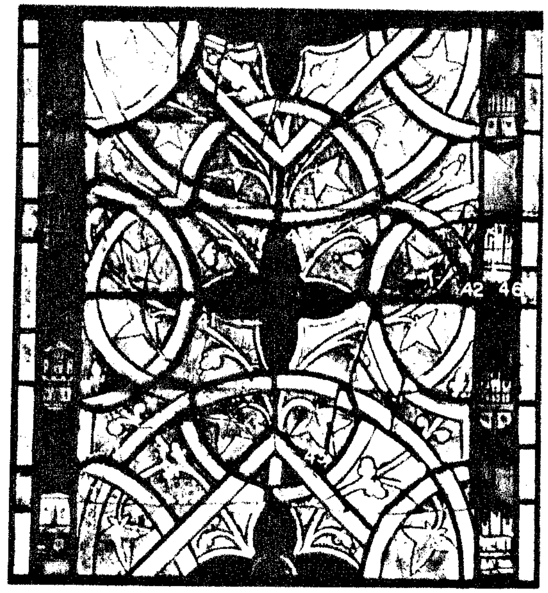

Figure 7. Accession No. 69.236.8 (see *Figure 2*)

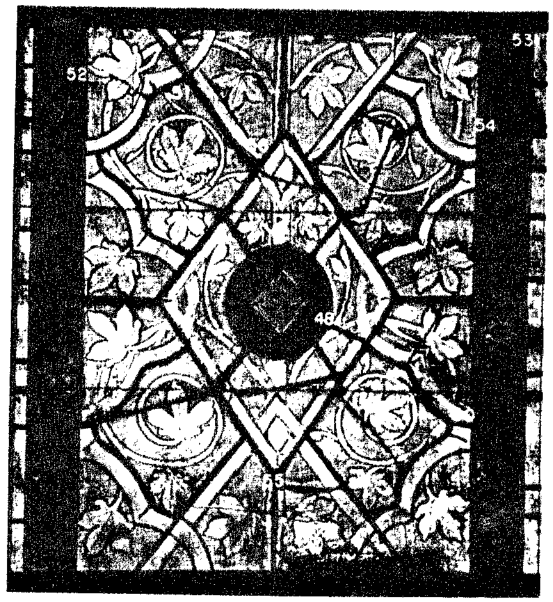

Figure 8. Accession No. 69.236.10 (see *Figure 2*)

England by French craftsmen who arrived in 675 A.D. Samples of window glass from the monastic site at Monkwearmouth have been excavated and analyzed by electron probe (*6*). Their sodium oxide concentrations range from 13.7 to 16.1%, and potassium oxide concentrations range from 0.24 to 1.12%. These alkalies are present in this glass in nearly the same proportions as in ancient Roman glass (*7*). In contrast, much of later medieval glass has been found by Geilmann and others (*8*) to have predominantly a potassium rather than a sodium composition. On the basis of this and other compositional considerations it has usually been concluded that wood ash was the main source of alkali in late medieval glass.

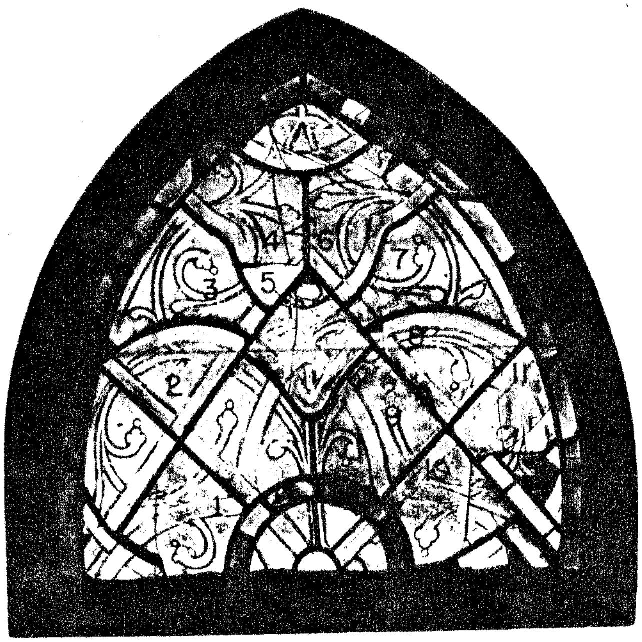

Figure 9. Thirteenth-century grisaille panel in the collection of the Museum of Art, Princeton University. Accession No. 43-65. Analytical data in Table V. The numbers on the photographs correspond to sample numbers in the table.

What we know of the techniques of glass making during the Middle Ages comes mainly from the description by Theophilus (*9*). According to him two parts of beechwood ashes and one part sand were mixed thoroughly and placed in a furnace to be fritted. The fritted mixture was distributed to white clay pots which were fired to melt the glass.

Analytical Procedure

Two procedures of sample activation were used in these analyses. In the first, samples of *ca.* 20 mg were weighed and heat-sealed in polyethylene tubing for a 20-sec activation at a flux of 1.5×10^{14} neutrons cm^{-2} sec^{-1} in the V11 facility of the high flux beam reactor at Brookhaven National Laboratory. ^{56}Mn was counted after about 4 hrs, and the ^{24}Na and ^{42}K were counted after 24 hrs. A second group of 50-mg samples was activated for 16 hrs at a flux of 1.5×10^{14} neutrons cm^{-2} sec^{-1}. After about two weeks the samples were poured from aluminum to glass vials for counting. The contents of the aluminum vials were washed into glass vials with ethyl alcohol for quantitative transfer. These samples were counted for 80–100 min for all other elements, using an automatic sample changer.

In the second procedure, one sample of *ca.* 40 mg was activated twice. The sample was first placed in a polyethylene vial and activated for 20 sec in the V11 facility at a flux of 1.5×10^{14} neutrons cm^{-2} sec^{-1}. After counting, the samples were transferred to quartz vials, reweighed, activated for 7 hrs at a flux of 2.8×10^{14} neutrons cm^{-2} sec^{-1} or 16 hrs at 1.5×10^{14} neutrons cm^{-2} sec^{-1}, and recounted in the quartz containers.

In both procedures, standard U.S. Geological Survey rocks G-2, GSP-1, AGV-1, BCR-1, PCC-1, and DTS-1 were weighed with each group of glass samples. Thus, glass samples and standard samples of similar weight were activated and counted simultaneously. Since these rock standards contained measurable amounts of all the elements determined in the glasses, they served as element-by-element monitors of the neutron flux densities and counting geometries encountered. For the rock standards we used the averages of all determinations reported after significantly deviant values had been eliminated by Chauvenet's criterion. For consistency we converted all elemental concentrations to oxide concentrations. The samples were counted using a 35-ml Ge(Li) detector; two 1600-channel SCIPP analyzers which could be connected in series to produce a 3200-channel spectra were used for the gamma-ray spectroscopy.

The data were collected on magnetic tape and fed into a CDC 6600 computer where a curve-fitting program, BRUTAL, was applied. BRUTAL output gave numerical values for the position and integrated intensity of each peak corrected for background. These intensities were punched on cards for each nuclide for each sample and standard. Using the CDC 6600 computer (in some cases the CDC 6400 computer of the Smithsonian Institution) and programs we have developed and named ELCALC and SAMPCALC, we calculate the oxide concentrations after correcting for radioisotope decay in both standards and samples. The specific activities of the U.S. Geological Survey rocks are calculated by ELCALC. They were used with the SAMPCALC program to compare the specific activities of each radioisotope in the samples and to calculate the oxide concentrations of the elements measured from these ratios.

Panels and Individual Pieces of Medieval Glass Studied

The first group we analyzed represents an extensive sampling—55 glass specimens from seven separate panels from the chateau of Rouen, built in the thirteenth century as a provincial residence for the French monarch. In the border of each panel appear castles of Castile, the well known insignia of Queen Blanche of Castile, mother of Louis IX. These panels are shown in Figures 2–8, in which the superimposed numbers indicate positions from which samples were removed. The chateau was demolished in the seventeenth century, and nine of its glass panels are now in the collection of The Cloisters Museum. We sampled seven of these panels, Accession Nos. 69.236.2, 3, 4, 5, 6, 7, 8, and 10, while they were disassembled for releading.

The second set consists of 11 samples from grisaille fragments in a panel which is part of the collection of the Princeton University Museum of Art (Accession No. 43-65) (Figure 9). Sampling was done when the panel was being releaded. At one time this panel was in the collection of a former curator of the Metropolitan Museum of Art, Bashford Dean.

Table I. Oxide Concentrations for Miscellaneous Non-Matching Group of Grisaille Fragments Identified Using Accession Numbers of The Cloisters Museum[a]

	Percent					Parts per Million										
Accession No.	Na_2O	K_2O	BaO	MnO	Fe_2O_3	Rb_2O	Cs_2O	Sc_2O_3	CeO_2	Eu_2O_3	HfO_2	ThO_2	Ta_2O_5	Cr_2O_3	CoO	Sb_2O_3
23.229.2-2	0.76	12.4	0.111	0.79	0.53	140	0.58	1.81	76	0.93	3.65	3.60	0.43	19.0	17.3	7.02
23.229.2-3	0.30	22.3	0.492	1.83	0.35	460	2.45	1.22	16	0.24	1.87	1.81	0.29	8.9	13.4	1.87
23.229.2-10	1.29	16.7	0.181	1.01	0.81	250	0.17	3.34	64	0.55	5.52	3.35	0.44	27.0	14.9	2.15
23.229.2-14	0.78	16.0	0.082	0.36	0.91	110	0.48	1.55	41	0.26	2.73	1.85	0.30	25.2	6.4	14.50
23.229.4-1	0.21	20.8	0.182	1.01	0.49	530	3.40	1.66	13	0.23	1.98	1.96	0.24	9.1	23.2	4.10
23.229.4-6	0.61	12.1	0.090	0.61	0.69	100	0.69	2.89	55	0.28	4.16	3.09	0.57	31.2	12.7	2.08
23.229.4-7	1.73	12.0	0.230	1.09	0.59	360	0.97	1.69	59	0.57	2.88	2.93	0.39	16.1	17.7	4.32
23.229.4-10	0.68	12.0	0.052	1.26	0.41	200	1.09	0.92	27	0.47	1.41	0.93	0.25	15.7	37.7	3.59
23.229.5-2	5.66	4.5	0.186	1.10	0.83	40	0.45	2.72	27	0.17	2.59	2.74	0.46	20.3	9.3	1.30
23.229.5-5	19.40	2.4	0.042	0.44	1.19	12	0.10	4.22	29	0.38	3.28	4.01	0.53	23.1	10.2	3.80
23.229.5-6	1.95	16.6	0.082	0.74	0.58	360	1.41	1.50	54	0.15	1.36	1.53	0.16	12.6	11.7	1.14
23.229.5-7	2.02	18.1	0.220	1.93	0.48	210	2.24	1.09	61	0.31	1.08	1.08	ND[b]	9.9	93.1	0.99
23.229.5-8	3.96	10.6	0.184	1.77	0.52	290	2.34	1.63	50	0.24	2.88	2.01	0.29	15.0	41.8	1.82
23.229.5-9	0.88	11.7	0.036	0.74	0.63	81	0.34	1.44	22	0.16	1.19	1.01	0.15	12.0	5.8	3.07
23.229.5-10	13.20	2.4	0.241	0.65	0.72	39	0.17	1.09	14	0.19	0.97	1.06	ND[b]	649.0	166.0	20.80
30.73.210	2.83	11.4	0.123	0.37	0.82	187	1.10	3.11	61	0.62	4.69	3.89	0.52	34.6	64.8	3.49
30.73.211	15.00	4.8	0.046	0.51	1.00	42	0.39	3.89	47	0.45	4.07	4.22	0.47	25.7	8.8	1.24
30.73.212	3.04	12.6	0.179	1.25	0.46	450	2.35	1.34	85	0.44	2.38	2.11	0.52	16.6	69.5	5.56
30.73.214	1.25	12.7	0.167	0.97	0.54	320	1.73	2.14	63	0.41	3.78	3.62	0.49	24.1	53.4	3.11
30.73.216	0.63	10.7	0.060	0.40	1.09	182	1.30	3.65	27	0.40	3.18	3.54	0.50	30.4	34.1	1.73
30.73.217	2.44	11.0	0.124	0.65	0.84	187	1.20	3.28	62	0.57	4.71	3.49	0.55	35.1	53.3	4.70
30.73.218	1.15	12.7	0.190	1.13	0.69	158	0.49	2.18	72	0.47	3.14	2.86	0.46	22.5	60.3	4.14

[a] See Figure 10.
[b] ND—Not determined.

Dean has published photographs of this panel (*10*), and it has also been discussed by Paul Frankl (*11*). Its specific origin has not been firmly established, but all who studied it regard it as an excellent example of thirteenth-century grisaille glass.

The final group consists of 32 pieces of medieval glass from various sources which were part of the collection of The Cloisters Museum and were donated to the Corning Museum of Glass. Since the provenances of these specimens are not well established, the data for them cannot be used to characterize particular structures or glass workshops. These samples show the extensive variation in composition which does exist in medieval stained glass from different sources. Some, however, can be grouped upon the basis of similar composition.

Sampling during Restoration

The panels were all releaded and restored by Dieter Goldkuhle of Reston, Va. When the individual panes were separated, corners of those selected for analysis were cleaned with a tungsten carbide burr grinding

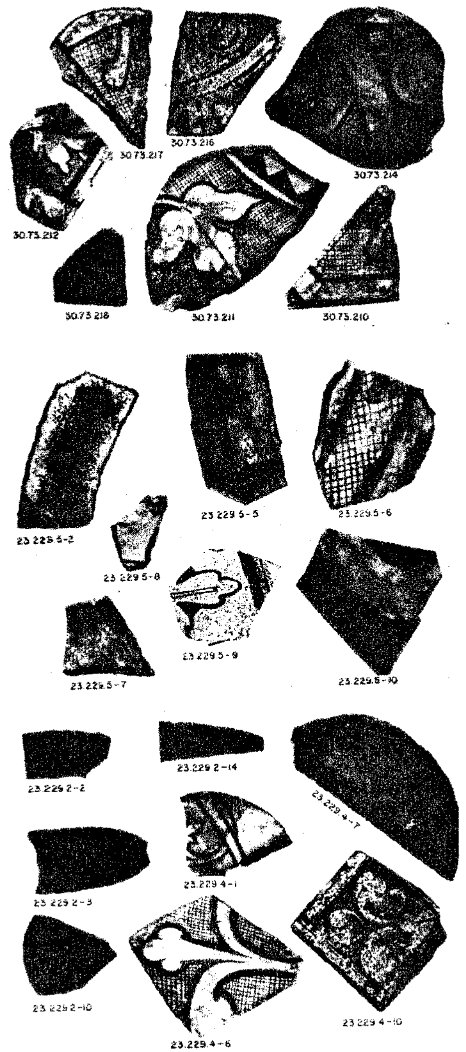

Figure 10. Pieces of grisaille glass from The Cloisters Museum. Analytical data are given in Table I.

Top: Accession numbers and attributions are 30.73.218: English, ca. 1290; 30.73.212: French or English, end XIII; 30.73.211: French or English, ca. 1300; 30.73.210: French or English, early XIV; 30.73.217: French or English, XIII-XIV; 30.73.216: French or English, ca. 1300; 30.73.214: French or English, end XIII-beginning XIV. Middle: Accession numbers and attributions are 23.229.5-2: French, XII; 23.229.5-5: Paris, XIII; 23.229.5-6: Bourges, XIII; 23.229.5-8: Rheims, XIV; 23.229.5-7: Paris, XIV; 23.229.5-9: Evereux, XIV; 23.229.5-10: Bourges, XIII. Bottom: Accession numbers and attributions are 23.229.2-2: striated red glass—Chartres, XII or XIII; 23.229.2-14: green glass—Paris, XIII; 23.229.4-7: Bourges, XIII; 23.229.2-3: glashed red glass—Paris, XIII; 23.229.4-1: Rheims, XIV; 23.229.2-10: Angers, XIII; 23.229.4-6: Bourges, XIII; 23.229.4-4: Bourges, XIII.

tool to remove the surface hydrolyzed layer. The corners were scratched with a carbid-tipped stylus, and samples of about 100 mg each were broken off. This amount can be taken, and the fragment can be placed into the new leading without noticeable change to the panel. This opportunity to sample panels during restoration should not be overlooked because of the simplicity of the procedure at that time. Glass samples from the already separate glass pieces of the third group of specimens were removed in a similar manner.

Analytical Results

Medieval stained glass is generally understood to have been made with sand, wood ash, and perhaps lime. Because the wood ash concentration of potassium is high relative to that of sodium, one expects a high concentration of potassium oxide. All but four of the specimens analyzed confirmed this expectation, with potassium oxide concentrations between 11 and 32%. The exceptional four specimens had potassium oxide concentrations of 2–5% and sodium oxide concentrations of 5–20% and clearly were formulated with a different alkali. In fact, great variation was generally observed in the relative concentrations of alkalies in medieval glass, a situation that contrasts with the relatively few formulations encountered in ancient glass (7).

Table I lists analytical data on specimens of our set of random samples (Figure 10) which were selected to show the range of compositions which can characterize medieval window glass. Because of the marked differences in the concentrations of the constituents shown in this table, it is not likely that medieval glass of unrelated origins would be closely similar in composition.

In contrast to the diversity in compositions encountered in the unrelated specimens above, all 45 samples of uncolored or amber glass with grisaille painting from the Chateau of Rouen were basically similar in composition. This glass contains about 15% potassium oxide and only about 3.5% sodium oxide (*see* Table II). Because these similar specimens came from the same building, a common source of manufacture seems likely. These data therefore support our belief that individual sources of glass produced compositionally consistent products.

Consider the data on the colorless glass from the seven Rouen Chateau panels, panel by panel, as shown in Table II. Within the specimens taken from individual panels there are groups of fragments with exceptionally similar compositions. This is not surprising since a number of fragments probably were produced from a single manufacturing batch, and the fragments from the same batch would probably be used in the same panel. This seems to be the most logical explanation of this exceptional uniformity among specimens. In Table II, very closely matched specimens are grouped and printed in roman type. In one panel, 69.236.4, we encountered only specimens with very similar compositions. It would be interesting to analyze all the fragments of this panel to determine

whether they were formed from a single batch of glass. In general, however, we have encountered either more than one exceptionally closely matched group or other specimens which show a higher order of difference in composition.

Table II. Concentration of Oxides in Glass from the Rouen Chateau Panels

	Specimen No.	Percent					Parts per Million									
		Na_2O	K_2O	BaO	MnO	Fe_2O_3	Rb_2O	Cs_2O	Sc_2O_3	CeO_2	Eu_2O_3	HfO_2	ThO_2	Cr_2O_3	CoO	Sb_2O_3
		Ivy Panel 69.236.2														
Colorless	R013 }	4.0	13.0	0.122	1.12	0.59	322	1.64	2.08	51	0.55	2.38	1.90	20.0	28.3	4.2
	R014 }	3.9	13.8	0.128	1.12	0.61	344	1.36	2.22	61	0.50	2.70	2.05	18.0	30.0	4.2
	R011	*3.6*	*16.1*	*0.115*	*1.10*	*0.49*	*288*	*1.37*	*1.74*	*54*	*0.48*	*2.77*	*1.89*	*15.6*	*20.0*	*3.5*
	R012	*2.3*	*15.7*	*0.128*	*1.24*	*0.49*	*225*	*0.56*	*1.73*	*44*	*0.47*	*3.60*	*2.13*	*16.6*	*20.2*	*4.0*
Amber	*R017*	*3.9*	*15.1*	*0.116*	*1.01*	*0.49*	*252*	*0.89*	*1.81*	*83*	*0.38*	*1.86*	*1.44*	*16.8*	*17.0*	*0.4*
Blue	*R015*	*4.5*	*12.5*	*0.083*	*0.97*	*0.98*	*255*	*1.05*	*1.86*	*41*	*0.48*	*1.88*	*3.96*	*27.0*	*870.0*	*39.4*
	R016	*2.3*	*16.5*	*0.132*	*1.01*	*1.66*	*141*	*0.92*	*2.10*	*78*	*0.41*	*2.79*	*5.65*	*30.5*	*1390.0*	*237.0*
		Ivy Panel 69.236.3														
Colorless	R019 }	3.2	14.9	0.116	1.05	0.49	331	1.03	1.74	54	0.41	2.31	2.06	13.4	17.3	2.9
	R023 }	3.5	15.5	0.103	1.13	0.49	336	1.15	1.70	55	0.35	2.33	1.67	15.3	20.9	2.3
	R020 }	4.1	16.1	0.126	1.07	0.58	388	1.16	2.25	63	0.62	2.55	2.13	17.9	25.2	3.3
	R022 }	4.1	16.0	0.136	1.05	0.57	383	1.18	2.12	60	0.59	2.45	2.16	19.2	24.0	3.1
	R018 }	4.1	14.6	0.125	1.16	0.57	370	1.28	2.12	61	0.58	2.76	2.07	18.2	26.0	4.2
	R021 }	4.0	12.6	0.118	1.02	0.57	384	1.17	2.20	61	0.52	2.45	1.92	17.1	24.4	2.9
	R024 }	4.4	14.5	0.114	1.20	0.56	341	0.82	2.10	55	0.59	2.73	1.91	15.3	25.8	4.3
		Ivy Panel 69.236.4														
Colorless	R028 }	4.2	15.8	0.124	1.17	0.56	365	1.24	2.10	58	0.50	2.69	2.32	13.3	28.3	4.0
	R029 }	4.1	15.2	0.110	1.09	0.55	345	1.01	2.02	52	0.49	2.40	1.94	15.5	26.6	3.9
	R030 }	4.0	17.7	0.115	1.07	0.55	353	1.06	2.09	57	0.51	2.69	1.98	15.4	27.8	3.7
	R031 }	3.9	13.9	0.117	1.08	0.55	345	1.29	2.13	55	0.56	2.65	2.10	20.3	25.6	4.0
		Ivy Panel 69.236.6														
Colorless	R01 }	4.1	13.4	0.122	1.12	0.59	322	1.20	2.12	56	0.58	2.84	1.83	18.6	26.2	4.2
	R02 }	4.3	14.1	0.119	1.24	0.61	329	1.75	2.75	53	0.56	2.76	2.06	19.2	29.3	4.5
	R03 }	4.5	14.3	0.118	1.14	0.61	340	1.28	2.26	59	0.61	2.45	1.91	18.3	24.7	3.5
	R04	*2.5*	*16.4*	*0.137*	*1.00*	*0.73*	*198*	*0.75*	*2.31*	*87*	*0.62*	*3.49*	*2.64*	*20.0*	*25.7*	*3.7*
	R05	*3.6*	*20.6*	*0.140*	*1.03*	*0.73*	*181*	*0.52*	*2.15*	*79*	*0.58*	*3.53*	*2.53*	*18.9*	*45.9*	*15.5*
	R06	*5.0*	*18.0*	*0.121*	*1.26*	*0.58*	*348*	*1.67*	*2.11*	*58*	*0.48*	*2.58*	*1.75*	*15.1*	*28.6*	*3.5*
Amber	*R09*	*4.4*	*13.8*	*0.133*	*1.09*	*0.56*	*210*	*0.68*	*1.96*	*73*	*0.48*	*2.84*	*1.95*	*14.9*	*24.1*	*3.2*
	R010	*2.8*	*17.0*	*0.131*	*1.02*	*0.65*	*173*	*0.62*	*1.90*	*77*	*0.48*	*3.15*	*2.07*	*15.7*	*16.8*	*2.4*
Blue	*R07*	*2.2*	*16.9*	*0.147*	*1.16*	*1.66*	*175*	*0.48*	*2.25*	*84*	*0.65*	*3.43*	*5.59*	*22.5*	*1220.0*	*177.0*
	R08	*2.5*	*18.3*	*0.106*	*1.12*	*1.43*	*75*	—	*1.09*	*49*	*0.51*	*1.94*	*4.13*	*16.1*	*890.0*	*132.0*
		Ivy Panel 69.236.7														
Colorless	R034 }	3.2	13.5	0.113	1.06	0.49	346	1.26	1.69	34	0.49	2.05	1.57	13.3	16.6	3.1
	R037 }	3.5	12.6	0.107	1.11	0.49	333	1.12	1.69	45	0.48	1.95	1.67	16.0	18.9	4.6
	R032	*2.2*	*16.3*	*0.126*	*1.14*	*0.48*	*228*	*0.55*	*1.62*	*35*	*0.34*	*3.68*	*1.96*	*14.8*	*19.5*	*2.9*
	R033	*4.2*	*14.6*	*0.123*	*1.15*	*0.57*	*359*	*1.08*	*2.16*	*45*	*0.61*	*2.55*	*1.77*	*17.6*	*25.5*	*4.5*
	R035	*2.4*	*15.2*	*0.133*	*1.06*	*0.55*	*221*	*0.55*	*1.97*	*53*	*0.46*	*2.40*	*2.28*	*14.2*	*25.5*	*0.3*
	R036	*4.0*	*15.3*	*0.142*	*1.19*	*0.67*	*207*	*0.75*	*2.04*	*84*	*0.58*	*3.17*	*2.22*	*16.7*	*21.3*	*1.4*
	R038	*2.6*	*14.8*	*0.126*	*1.34*	*0.45*	*243*	*0.53*	*1.64*	*40*	*0.39*	*1.86*	*2.75*	*12.6*	*19.1*	*5.8*

Table II.

	Specimen No.	Na_2O (Percent)	K_2O	BaO	MnO	Fe_2O_3
		Ivy Panel 69.236.8				
Colorless	R039	2.5	17.1	0.120	1.27	0.46
	R043	2.5	15.0	0.124	1.25	0.45
	R041	3.1	14.1	0.101	1.06	0.51
	R045	3.3	15.8	0.111	1.10	0.48
	R040	*2.2*	*17.2*	*0.129*	*1.15*	*0.57*
	R042	*3.9*	*13.7*	*0.121*	*1.09*	*0.55*
	R044	*3.1*	*14.9*	*0.094*	*1.07*	*0.45*
Blue	*R046*	*2.1*	*16.9*	*0.145*	*1.08*	*1.71*
		Acanthus Panel 69.236.10				
Colorless	R049	2.7	15.2	0.144	1.31	0.58
	R050	2.7	16.1	0.147	1.36	0.49
	R051	2.6	16.7	0.142	1.32	0.49
	R055	2.7	14.8	0.142	1.30	0.58
	R056	2.7	16.3	0.149	1.36	0.53
Red flashed	*R048*	*2.5*	*16.2*	*0.113*	*0.98*	*0.48*
Amber	*R052*	*2.4*	*15.8*	*0.107*	*0.84*	*0.41*
Green	*R053*	*3.0*	*15.8*	*0.122*	*1.00*	*0.60*
Blue	*R054*	*1.9*	*10.7*	*0.117*	*0.85*	*0.96*

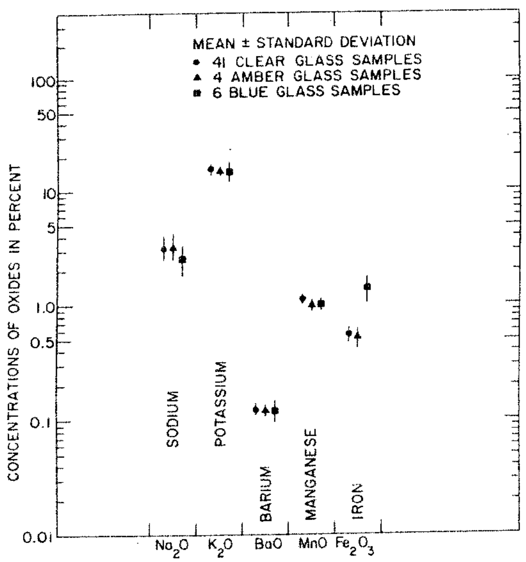

Figure 11. Comparison of mean concentrations of major and minor components in colorless, amber, and blue glass in the grisaille panels from the Chateau of Rouen

Continued

Specimen No.	Rb_2O (Parts per Million)	Cs_2O	Sc_2O_3	CeO_2	Eu_2O_3	HfO_2	ThO_2	Cr_2O_3	CoO	Sb_2O_3
					Ivy Panel 69.236.8					
R039	240	0.59	1.67	43	0.34	3.39	1.70	14.7	19.4	6.3
R043	241	0.59	1.61	39	0.45	3.18	1.73	13.1	18.7	4.4
R041	329	1.43	1.67	48	0.58	1.86	1.41	18.0	17.6	5.9
R045	330	1.22	1.64	42	0.41	2.02	1.63	16.8	16.9	2.3
R040	*252*	*0.82*	*1.99*	*65*	*0.39*	*3.15*	*2.48*	*19.8*	*20.9*	*1.4*
R042	*300*	*1.60*	*1.97*	*49*	*0.49*	*2.35*	*1.75*	*14.3*	*26.4*	*3.0*
R044	*316*	*1.21*	*1.56*	*33*	*0.46*	*1.85*	*1.44*	*12.3*	*14.5*	*1.6*
R046	*227*	*0.48*	*2.12*	*96*	*0.76*	*3.39*	*4.02*	*20.4*	*1170.0*	*130.0*
					Acanthus Panel 69.236.10					
R049	275	0.92	1.81	92	0.51	2.69	2.15	14.0	42.0	1.2
R050	284	0.70	1.75	91	0.50	2.46	2.14	10.0	42.1	1.7
R051	292	1.03	1.81	96	0.60	2.39	2.19	14.3	39.8	0.8
R055	359	0.87	1.94	103	0.56	2.66	2.14	15.2	45.5	1.8
R056	326	1.03	1.66	96	0.40	2.38	2.15	15.2	40.4	1.9
R048	*232*	*0.75*	*1.54*	*84*	*0.43*	*2.38*	*2.03*	*20.9*	*23.0*	*4.4*
R052	*266*	*0.83*	*1.49*	*75*	*0.37*	*2.61*	*2.11*	*14.7*	*14.0*	*0.3*
R053	*279*	*1.14*	*1.98*	*80*	*0.38*	*3.41*	*2.54*	*11.5*	*59.4*	*113.0*
R054	*264*	*0.47*	*1.77*	*92*	*0.50*	*1.59*	*4.76*	*19.4*	*1300.0*	*43.7*

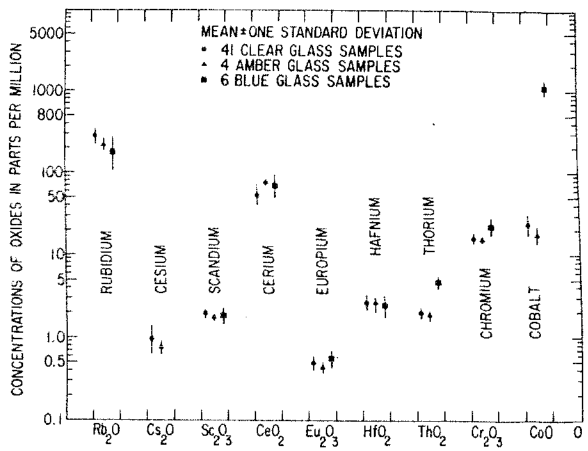

Figure 12. Comparison of mean concentrations of trace components in colorless, amber, and blue glass in the grisaille panels from the Chateau of Rouen

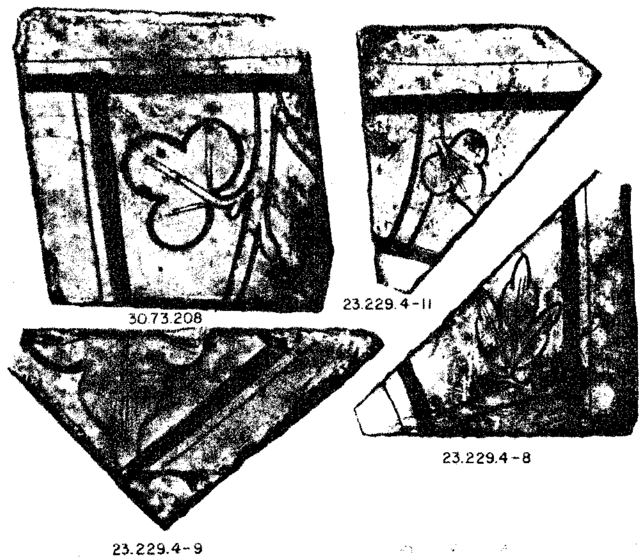

Figure 13. Pieces of grisaille glass from The Cloisters Museum. Accession numbers and attributions are 23.229.4-8: Paris, XIV; 23.229.4-9: Chartres ?; 23.229.4-11: Chartres, ? XIV; 30.73.208: French, ? XIII-XIV. Analytical data in Table III.

In comparing glass from different panels one observed in general only about the same order of difference that exists between different fragments in the same panel which do not correlate very closely. Most of those differences probably represent the normal variation between batches of glass from the same workshop.

A comparison among the average composition of the colorless, the amber, and some of the blue glasses from the Rouen Chateau is shown in Figures 11 and 12. For most elements the standard deviation ranges of concentrations encountered in all three colors overlap, and hence the average concentrations in each of the colors were not significantly different from each other. However, in the blue glasses the cobalt, iron, thorium, and chromium concentrations were all higher, but this could be a result of a cobalt-containing material added as a colorant. In all the colored glasses, and in the green and flashed red glasses analyzed, the same basic glass seems to have been used. Therefore, all of the above glass was probably produced by a single workshop.

Three additional pieces of blue glass were identified as restoration glass on the basis of their physical appearance before sampling. Samples R025, R026, and R027 were taken from these pieces which were all in panel 69.236.4 shown in Figure 4. Samples R025 and R026 are not shown because the entire top area of that panel was replaced during recent restoration. Figure 4 shows the recently restored panel. The concentra-

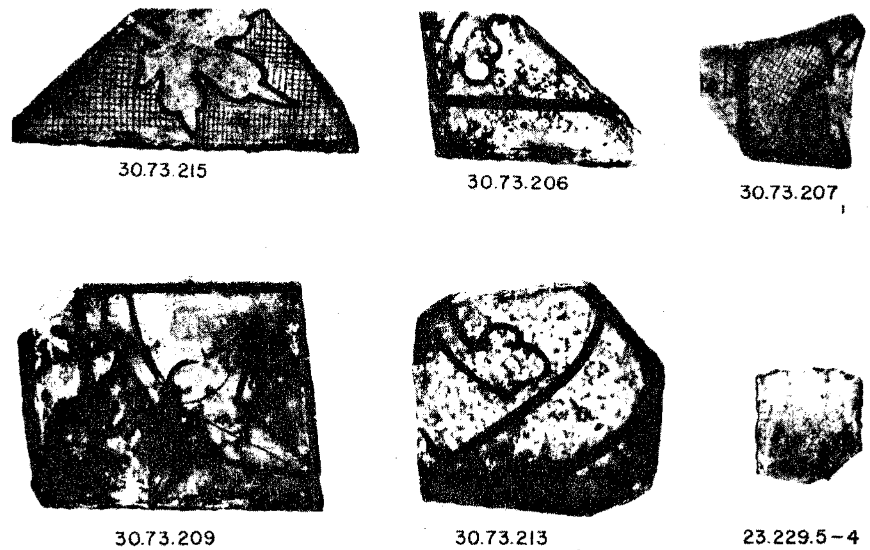

Figure 14. Grisaille glass from The Cloisters Museum. The accession numbers and attributions are 23.229.5-4: Chartres, XIV; 30.73.206: French or English, late XIII; 30.73.207: French or English, early XIV; 30.73.209: French or English, beginning XIV; 30.73.213: French, ? XIII-XIV; 30.73.215: French or English, XIV. Analytical data in Table IV.

Table III. First Matching Group of Grisaille Fragments Identified Using Accession Numbers of The Cloisters Museum (*See* Figure 1)

Accession No.	Percent: Na_2O	K_2O	BaO	MnO	Fe_2O_3	Parts per Million: Rb_2O	Cs_2O	Sc_2O_3	CeO_2	Eu_2O_3	HfO_2	ThO_2	Ta_2O_5	Cr_2O_3	CoO	Sb_2O_3
23.229.4-8	0.33	18.2	2.54	1.21	0.44	250	2.0	2.29	37	0.179	2.8	3.4	0.36	16.5	9.5	1.4
23.229.4-9	0.30	18.2	2.19	1.16	0.31	260	2.2	1.73	26	0.214	2.3	3.4	0.36	13.5	5.7	1.6
23.229.4-11	0.30	19.4	1.42	1.22	0.41	260	2.6	2.13	37	0.207	2.7	4.2	0.38	16.7	8.7	1.7
30.73.208	0.30	17.9	2.69	1.32	0.43	290	2.4	2.28	33	0.450	2.9	3.7	0.38	22.7	11.0	0.9
Mean	0.31	18.4	2.15	1.23	0.39	265	2.3	2.09	33	0.244	2.7	3.7	0.37	17.1	8.5	1.3
Group std dev., %	4.9	3.6	33.5	5.5	17.6	6.6	12.0	14.1	18.1	51.3	10.8	10.5	3.2	23.9	33.0	29.3

Table IV. Second Matching Group of Grisaille Fragments Identified Using Accession Numbers of The Cloisters Museum (*See* Figure 2)

	Percent					*Parts per Million*										
Accession No.	Na_2O	K_2O	BaO	MnO	Fe_2O_3	Rb_2O	Cs_2O	Sc_2O_3	CeO_2	Eu_2O_3	HfO_2	ThO_2	Ta_2O_5	Cr_2O_3	CoO	Sb_2O_3
23.229.5-4	2.5	14.1	0.135	1.01	0.51	220	0.62	1.74	61	0.76	3.2	2.1	0.31	14.5	61	5.7
30.73.206	2.7	14.5	0.147	1.23	0.52	240	0.68	1.70	82	0.45	2.8	2.0	0.30	16.4	8	2.1
30.73.207	3.1	14.9	0.127	1.08	0.51	230	0.95	1.75	79	0.51	3.1	2.2	0.31	16.8	33	1.1
30.73.209	2.6	15.3	0.141	1.05	0.51	240	0.90	1.62	71	0.44	2.7	2.4	0.31	13.5	48	3.1
30.73.213	2.6	13.6	0.146	1.03	0.50	250	0.86	1.67	66	0.40	2.7	2.3	0.25	16.4	48	3.3
30.73.215	4.0	12.5	0.138	1.00	0.53	250	0.77	2.00	58	0.52	2.3	2.2	0.33	18.5	40	4.8
Mean	2.9	14.1	0.139	1.06	0.51	238	0.79	1.74	69	0.50	2.8	2.2	0.30	15.9	42	2.9
Group std dev., %	19.5	7.5	5.6	7.9	2.0	5.1	18.2	7.6	14.9	25.3	12.5	6.7	10.0	11.9	32.7	83.1

tion of sodium oxide ranged from 0.5 to 3.21%, and the concentration of potassium oxide ranged from 5.27 to 8.55%. The marked difference for these two oxides between this glass and the remainder of the Rouen glass sampled (Table II) is evident.

From the random samples, two sets of compositionally related glass emerged. One set (Figure 13) is clearly stylistically related. The data for these four pieces of glass are given in Table III. The second set, composed of six compositionally matching pieces (Figure 14 and Table IV), are distinctly different in composition from the group of four. Figures 15 and 16 compare the average oxide concentration and standard deviation ranges of their variations for these two sets of glass. They show that the oxides of sodium, barium, cesium, cerium, europium, thorium, and cobalt are all significantly different in these two groups.

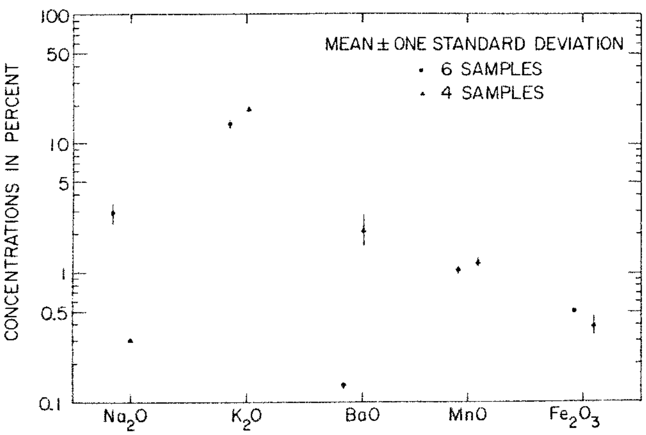

Figure 15. Comparison of mean concentrations of major and minor components in two sets of compositionally related pieces of glass from The Cloisters Museum. Specimens shown in Figures 13 and 14.

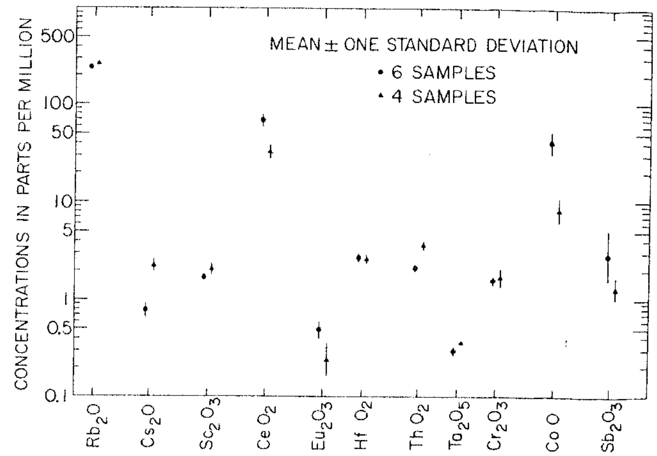

Figure 16. Comparison of mean concentrations of trace components in two sets of compositionally related pieces of glass from The Cloisters Museum. Specimens shown in Figures 13 and 14.

The matching set of six individual glass pieces is closely related compositionally to the glass of the Rouen Chateau panels. Figures 17 and 18 compare the compositions of these glasses. Obviously they cannot be distinguished on the basis of the elements determined. Thus, these six pieces of glass were probably produced by the same manufacturer as the Rouen Chateau glass.

The set of samples from a panel at the Museum of Art, Princeton University (Figure 9) have internal compositional consistencies which allow conclusions similar to those for Rouen panels. Eleven fragments from this panel were sampled and analyzed (Table V). Potassium oxide concentration was about 26%, and sodium oxide concentration was about 0.5%. This glass is completely different in composition from that

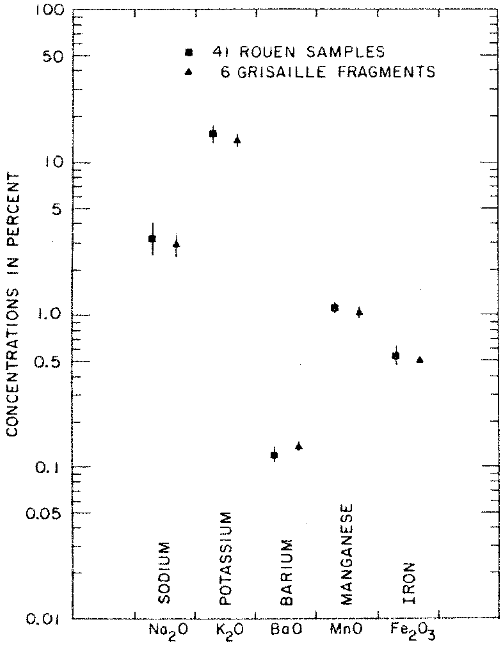

Figure 17. Comparison of mean concentrations of major and minor components in samples from the set of six matching pieces of glass shown in Figure 14 and the samples from the Rouen glass shown in Figures 2–8

of the Chateau of Rouen and all of the single pieces of glass analyzed. This lack of correlation demonstrates clearly the distinct differences in compositions observed for glasses from different sources.

This panel again shows that the composition for glass from a single source can be consistent. All specimens were so close in composition that

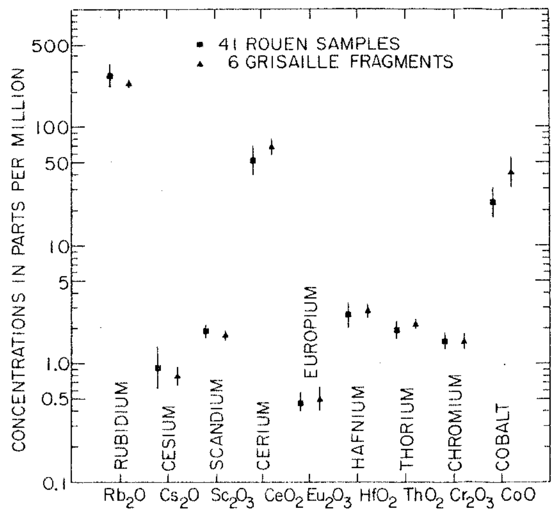

Figure 18. Comparison of trace components in samples from the set of six matching pieces of glass shown in Figure 14 and the samples from the Rouen glass shown in Figures 2–8

Table V. Grisaille Panel—Collection of the Princeton University Museum of Art, Accession No. 43-65

	Percent					Parts per Million									
Fragment No.	Na_2O	K_2O	BaO	MnO	Fe_2O_3	Rb_2O	Cs_2O	Sc_2O_3	CeO_2	Eu_2O_3	HfO_2	ThO_2	Cr_2O_3	CoO	Sb_2O_3
1	0.57	31	0.42	1.30	0.42	590	10.0	1.38	15.2	0.28	2.2	2.7	9.6	35	1.27
3	0.51	25	0.45	1.27	0.45	580	9.8	1.38	16.4	0.28	2.1	2.0	13.8	40	1.23
4	0.55	29	0.46	1.23	0.45	630	10.2	1.50	18.3	0.30	2.1	2.2	10.3	37	1.29
5	0.56	28	0.47	1.43	0.44	640	11.2	1.48	18.7	0.22	2.2	2.3	11.4	41	1.26
6	0.53	28	0.41	1.25	0.40	610	10.6	1.33	17.9	0.20	2.3	2.0	17.6	36	0.90
7	0.54	28	0.44	1.23	0.42	600	10.0	1.41	22.4	0.25	2.4	2.2	8.7	23	1.06
9	0.49	27	0.42	1.37	0.42	620	10.2	1.37	16.7	0.23	2.2	2.0	9.1	27	1.23
10	0.54	29	0.45	1.38	0.43	600	9.8	1.39	18.5	0.25	2.4	2.1	10.3	38	1.31
Mean	0.54	28	0.44	1.31	0.43	608	10.2	1.40	17.9	0.25	2.2	2.2	11.1	34	1.19
Group std dev., %	5.1	6.4	5.0	6.0	4.1	3.5	4.7	4.1	12.2	14.7	5.4	10.7	26.6	24.2	13.8
2	0.61	21	0.36	0.94	0.58	834	23.2	1.60	30.3	0.28	1.9	3.4	—	22	1.97
8	0.62	22	0.33	0.86	0.53	829	26.2	1.70	27.7	0.30	3.6	2.6	12.2	19	1.20
11	0.61	21	0.36	0.93	0.52	801	27.0	1.68	17.2	0.28	2.9	2.6	13.3	21	1.51
Mean	0.61	21	0.35	0.91	0.54	821	25.4	1.66	24.3	0.29	2.7	2.9	12.7	20	1.53
Group std dev., %	0.9	2.9	2.2	5.0	6.0	2.2	8.4	3.3	35.6	4.1	39.8	17.2	6.3	7.2	28.2

they indicated a common origin. However, as with the Rouen glass, they subdivided into groups so similar in composition that it seems they were from individual batches of glass preparation. The data in Table V are divided into two such closely related subgroups.

All of the data in this study indicate that the compositions of what are probably glasses from different workshops tend to be distinct from one another and consistent within themselves. Also, there is often enough original glass in medieval panels to establish the characteristic composition of the glass. When data have been collected on many samples of medieval glass, it should be possible to draw conclusions about the traditions and methods of the workshops and the extent to which the products were dispersed.

Acknowledgments

We thank Jane Hayward, Associate Curator of The Cloisters Museum for permitting us to sample seven panels from the Chateau of Rouen in their collection; Frances F. Jones, Curator of Collections, the Princeton University Museum of Art for allowing us to sample a thirteenth-century grisaille panel from their collection; and The Cloisters Museum and Corning Museum of Glass for additional samples of medieval glass.

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[a] Reported analyses of medieval stained glass.

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