Elemental Characterization of Medieval Limestone Sculpture from Parisian and Burgundian Sources

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The compositional patterns of limestone from quarries beneath the city of Paris, France, and of Romanesque sculpture from the Paris basin and Burgundy were characterized by neutron activation analysis and multivariate statistics. Stone from three locations in the Lutetian limestone formations of Paris is found to be consistent and significantly different from Burgundian limestone.

Elemental analysis is combined with traditional art-historical approaches to solve problems of grouping sculptural fragments, assigning places of origin, and establishing authenticity.

Introduction

Many stone sculptures in public collections have long been dissociated from the monuments for which they were first designed. Their sources may have been obscured so that assignment of geographical origins must be based primarily on stylistic, iconographic, and technical criteria. The combination of the traditional approaches of the art historian with those of the analytical laboratory often makes possible the grouping of stone fragments and, in some cases, their assignment to a place of origin or their authentication. In this study neutron activation analysis has been used to characterize the limestone of a Parisian formation that supplied material for monumental sculpture in the Middle Ages, and as a technique for solving art historical problems.

Recent progress on origin-oriented studies of limestone has been reported at international symposia and in the literature.[1] A pilot study of limestone sculpture published by Meyers and van Zelst[2] indicated the potential for neutron activation analysis and multivariate statistical techniques for the grouping of limestone objects and the determination of their origins. Petrography and neutron activation analysis enabled French, Sayre, and van Zelst[3] to characterize limestone quarries in the Dordogne region of France and to establish the uniformity of one limestone formation over a large area and at different levels of deposition. Their work related now-separated medieval French reliefs to each other and to these quarries.

This investigation focuses on the elemental composition patterns of Parisian limestone sources in use during

1. Garman Harbottle, "Activation Analysis in Archaeology," in G. W. A. Newton, ed., *Radiochemistry: a Specialist Periodical Report* (The Chemical Society, Burlington House: London, 1976); Jean M. French, E. V. Sayre, and L. van Zelst, "Nine Medieval French Limestone Reliefs: the Search for a Provenance," *Proceedings of the Fifth Seminar on the Applications of Science in the Examination of Works of Art, September 1983* (Museum of Fine Arts: Boston, in press); E. V. Sayre, "Characterization of Stone Artifacts: Analytical Techniques," *Proceedings of the Symposium in Honor of Robert Maddin, December 1983* (University of Pennsylvania: Philadelphia, in press).

2. P. Meyers and L. van Zelst, "Neutron Activation Analysis of Limestone Objects: a Pilot Study," *Radiochimica Acta* 24 (1977) 197–204.

3. French, Sayre, and van Zelst, op. cit. (in note 1).

the Middle Ages and on architectural fragments in museum collections thought to be from the Paris basin and from centers of Romanesque sculpture in Burgundy (FIG. 1). Through the generous cooperation of members of the Equipe d'Histoire des Sciences of the Université de Paris I, Panthéon-Sorbonne, we analyzed stone fragments from three separate sites in the Lutetian limestone formation that lies beneath the city of Paris. In addition we tested a nearly comprehensive sampling of limestone sculpture in The Metropolitan Museum of Art and The Cloisters, both in New York City; as well as objects in the Glencairn Museum (formerly Pitcairn Collection), Bryn Athyn, Pennsylvania; the Musée Carnavalet, Paris; and the Fogg Art Museum, Boston.

The data show that the composition of stone from the Parisian formation is consistent and significantly different from that of Burgundian limestone. A number of medieval sculptures thought to be Parisian on stylistic grounds proved to be compositionally consistent with the quarry specimens. Fragments that were once part of the facade of Nôtre-Dame Cathedral were found to match each other but not the compositional profile of the Parisian quarry specimens. Several carvings, possibly made for the Abbey of Saint-Denis, formed a compositionally consistent group differing from the Paris quarry group. Matches in composition between a pair of heads testified to their authenticity and to the origin of both in a serial sculpture at Mantes. A close correspondence between Paris quarry material and a fragment said to be from Vézelay reinforced doubts about the authenticity of the fragment. Tests on groups of objects attributed to the abbeys of Moutiers-Saint-Jean and Cluny showed each assemblage to be internally consistent in composition. Variations within each of the compositional groups are small compared to the differences among groups. The finding that a carving of disputed origin in The Cloisters collection resembles Cluny stone in composition may add to the art historian's knowledge of the training and wanderings of individual medieval craftsmen.

The analytical results derived from testing sculpture from other areas of France will be presented in a future publication. Meanwhile, data and descriptions of the objects sampled will be available for reference in the Smithsonian Archaeometric Research Archives and Records (SARCAR).

Sampling

The stone fragments selected for study were taken from three areas in the Lutetian limestone deposit below the city of Paris: two galleries in the Val-de-Grâce quarry about one km south of the left bank of the Seine, and one from the Port Mahon quarry approximately 1.5 km further to the SW near the Place Denfert Rochereau (FIG. 2). These sites were probably exploited during the 13th-14th centuries for the construction of public and ecclesiastical buildings. The geological and historical context of these medieval quarries is described by Pomerol and

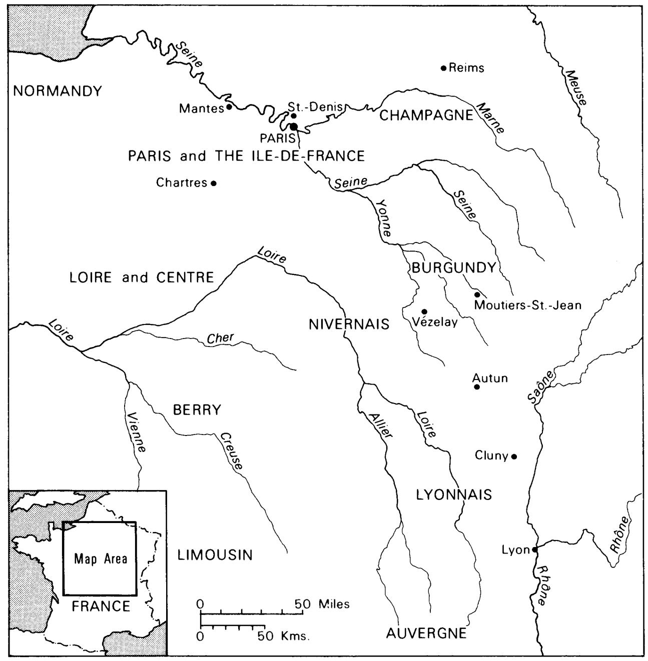


Figure 1. Map of France, showing localities mentioned in the text.

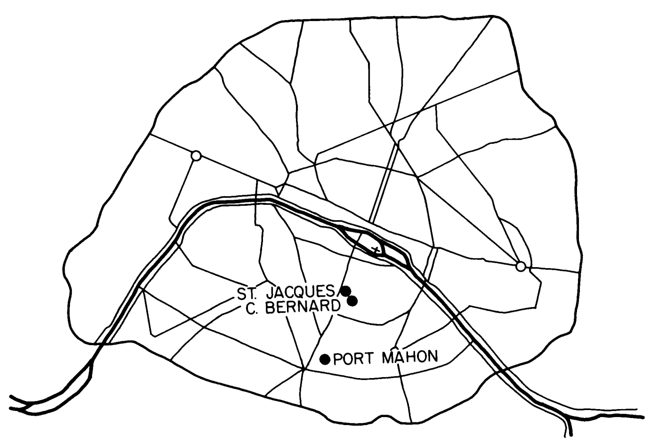


Figure 2. Map of Paris showing sources of quarry samples. Two galleries lie in the Val-de-Grâce area (one north of the Church of Saint-Jacques du Haut-Pas; another beneath the Maison de la Géologie at 77 rue Claude Bernard). The Port Mahon gallery represents a second area, 1.5 km to the SW, between Port Mahon and Place Denfert Rochereau.

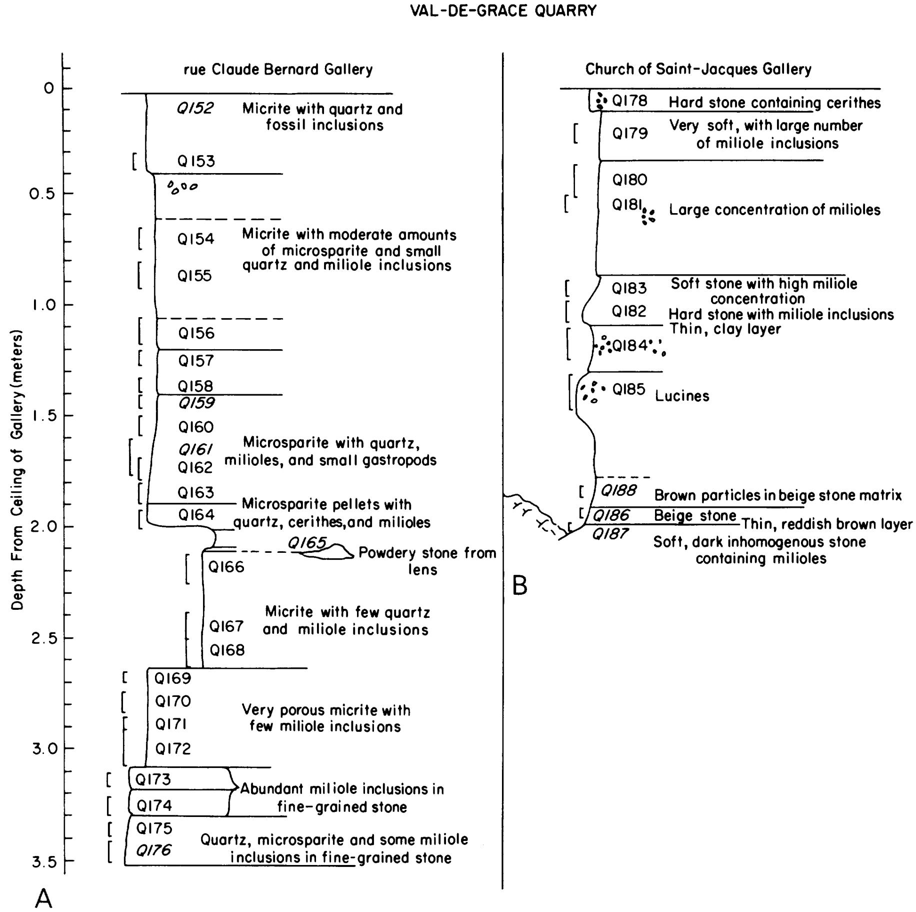


Figure 3. A. Stratigraphic cross-section of Val-de-Grâce quarry gallery beneath the Maison de la Géologie. Numerals represent Brookhaven National Laboratory (BNL) identification numbers (Q series). Cross-section diagrams and descriptions based on information from the Université de Paris I, Panthéon-Sorbonne. B. Stratigraphic cross-section of Val-de-Grâce quarry gallery, NW of Church of Saint-Jacques du Haut-Pas.

Feuguer,[4] and in detail in a paper presented to the 26th International Geological Congress, Paris,[5] by members of the Equipe d'Histoire des Sciences et des Mouvements Intellectuels of the Université de Paris I, who generously provided samples for this investigation. Medieval limestone sources in the Paris area have been most recently described by Viré.[6]

Of the stone analyzed, one group of 37 fragments came from the Val-de-Grâce galleries. Of these, 25 were taken from a typical quarry site located 11–12 m beneath the Maison de la Géologie at 77 rue Claude Bernard (FIG. 3A). Eleven additional samples were from a location NW of the church of Saint-Jacques du Haut-Pas (FIG. 3B), approximately 300 m from the first. For comparison, a second group of fourteen samples was chosen to learn whether the geochemical variations in the large Lutetien limestone deposit of Paris are sufficiently great to permit distinctions among quarry locations. This second group of samples came from the Port Mahon quarry (FIG. 4). In every case, samples were taken at regular vertical intervals from a gallery two or more m high. The cross-section of each gallery indicates layers apparently different in thickness, appearance, hardness, nature of the limestone particles, and type of inclusions.

The comprehensive description of the rue Claude Bernard gallery[7] details the variation in the nature of the limestone deposit: micrite (ultra-fine-grained material formed by inorganic and biochemical precipitation within the limestone basin, approximately 1–4 microns in diameter) near the top to microsparite (neomorphic crystal mosaic with crystal diameters from 4–10 microns or larger)[8] toward the bottom.

4. C. Pomerol and L. Feuguer, *Bassin de Paris. Guides Géologiques Régionaux*, 2nd edn. (Masson et Cie.: Paris 1974) 55–56.

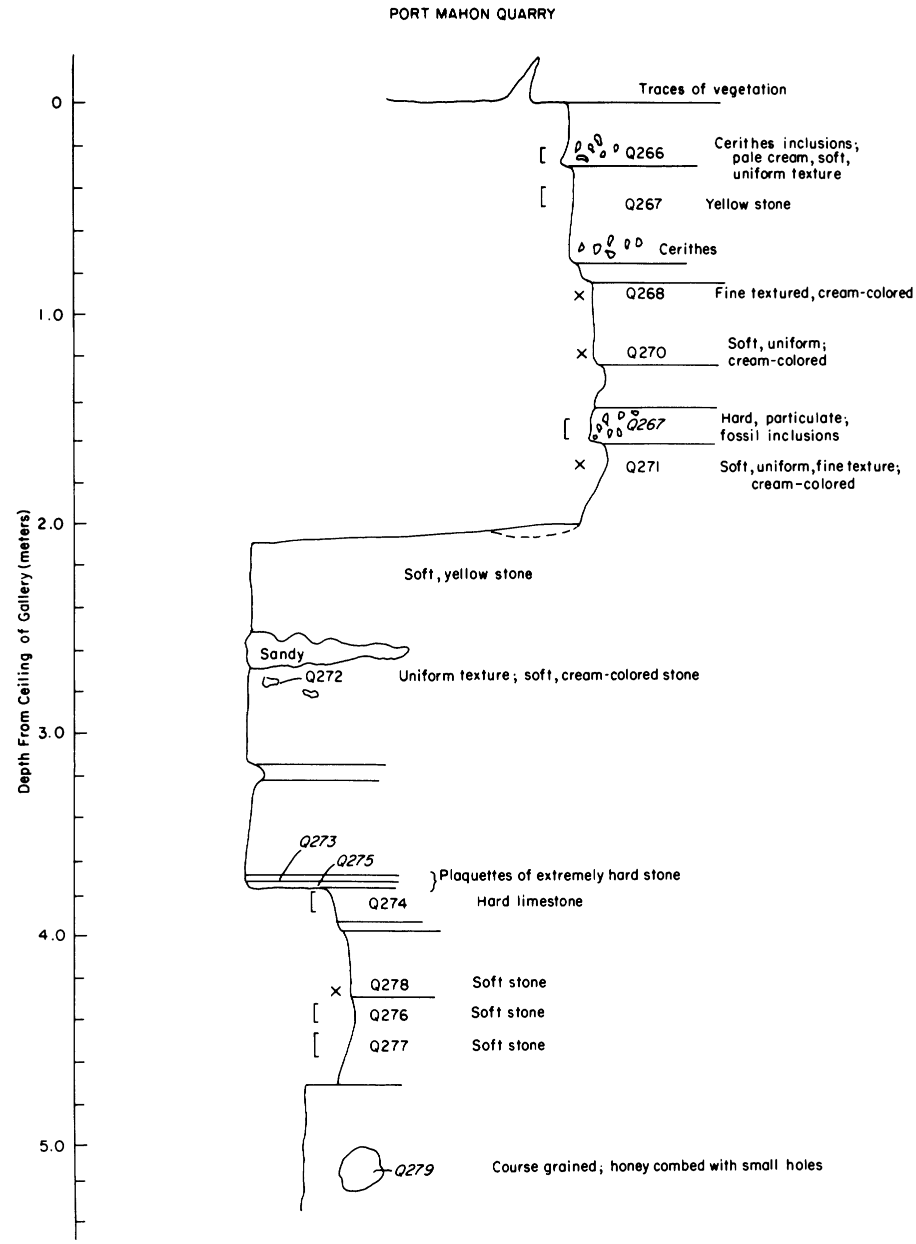
5. François Ellenberger, J. Marvy, and Marc Viré, "Les Anciennes Carrières Souterraines de Paris," *Bulletin d'Information Géologues du Bassin de Paris* (Paris 1980) No. h–s.

6. Marc Viré, "Les Anciennes Carrières de Pierre à Paris au Moyen-Age," in P. Benoit and P. Braunstein, eds., *Carrières et Métallurgie dans la France Médiévale* (Editions du Centre Nationale de la Recherche Scientifique: Paris 1983) 395–406.

7. Ibid.

8. H. Blatt, G. Middleton, and R. Murray, *Origin of Sedimentary*

Figure 4. Stratigraphic cross-section of quarry gallery near Port Mahon.



In addition to the quarry samples, the program of analysis included fragments of Gallo-Roman, Merovingian, and medieval sculpture found in Paris and now housed in the Musée Carnavalet, as well as numerous samples of stone from Romanesque objects in American museum collections. The Romanesque sculptures tested included groups of known origin, such as objects from Cluny and Moutiers-Saint-Jean in Burgundy, in order to establish the difference between Parisian stone and stone from outside the Paris formation. These museum objects are identified and described in Table 1. The analytical data for these samples are presented in Table 2.

Discussion

Most of the specimens from three limestone galleries quarried by medieval stonemasons form one compositional group. Those samples taken from the Val-de-Grâce galleries cannot be distinguished from each other on the basis of elemental composition, regardless of differences in stratigraphy. Furthermore, no statistically significant chemical differences are observed between

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Rocks, 2nd edn. (Prentice-Hall: Englewood Cliffs, N.J. 1980) 482–483.

Table 1. Sculpture from the collections of The Metropolitan Museum of Art, New York (M,C); the Raymond Pitcairn Collection, Glencairn Museum, Bryn Athyn, Pennsylvania (P); the Fogg Art Museum, Harvard University, Cambridge, Massachusetts (B); and the Musée Carnavalet, Paris (F). Samples are identified by their BNL identification numbers and museum accession numbers.

Brookhaven Sample Identification	*Museum Accession Number*	*Description of Object*
M01	MMA 38.180	Head of King David, Portal of St. Anne, Notre-Dame Cathedral, Paris
P06	Glencairn 09.SP.271	Capital
P10	Glencairn 09.SP.196	Capital: figures and arcade
P16	Glencairn 09. SP.11	Head
P20	Glencairn 09.SP.12	Impost block
P23	Glencairn 09.SP.14	Capital: harpy
F51	Hôtel Moreau	Body fragment: King David
M51	MMA 20.157	Jamb Statue: Old Testament king
C68	MMA 47.101.20	Fragment of relief: angel
M74	MMA 13.152.1	Capital, impost block
C125	MMA 13.152.1	Capital, impost block (second sample)
C122	MMA 47.101.23	Spandrel fragment
C123	47.101.23	Spandrel fragment
C133	MMA 40.51.1,2	Doorway, Abbey of Moutiers-Saint-Jean
C134	MMA 40.51.1,2	Doorway, Abbey of Moutiers-Saint-Jean: Clovis statue
C135	MMA 40.51.1,2	Doorway, Abbey of Moutiers-Saint-Jean: Clothar statue
C141	MMA 47.84	Right window of Cluny house
C142	MMA 47.84	Left window of Cluny house
	Carnavalet AP147	Medieval sculpture: basin and wall niche with arcades, Church of St. Bernardins, 14th century [cat. no. 124]
F193	(M100)	top left
F194	(M101)	lower left
F195	(M102)	stone beneath lavabo
F196	(M103)	lower right
	Carnavalet AP315	Medieval sculpture: pier base for engaged columns, 14th century (cat. entry no. 246)
F197A	(M110)	top element
F197B	(M111)	middle element
F197C	(M112)	bottom element
	Carnavalet AP289	Medieval sculpture: three foundation bases, Church of St. Bernardins, 14th century (cat. entry no. 125)
F198A	(M114)	top element
F198B	(M113)	middle element
F198C	(M115)	bottom element
	Carnavalet AP650	Merovingian sarcophagus (cat. entry no. 113)
F199	(M105)	lid
F200	(M106)	basin
F201	Carnavalet AP14 (M107)	Gallo-Roman stela

Table 1. (cont.)

Brookhaven Sample Identification	*Museum Accession Number*	*Description of Object*
F201 (cont.)	Carnavalet AP19	Gallo-Roman sculpture: angled pilasters excavated at Hôtel-Dieu
F202A	(M108)	top
F202B	(M109)	bottom
P207	Glencairn 09.SP.94	Pilaster capital
C212	MMA 40.51.1,2	Doorway, Abbey of Moutiers-Saint-Jean: Clovis statue
C213	40.51.1,2	Clovis statue
C214	40.51.1,2	Clovis statue
C215	MMA 1980.263.1	Relief, Cluny
C216	1980.263.1	Relief, Cluny
C217	1980.263.1	Relief, Cluny
C218	1980.263.1	Relief, Cluny
C219	1980.263.1	Relief, Cluny
P220	Glencairn 09.SP.144	Pilaster capital (upper right)
P221	Glencairn 09.SP.144	Pilaster capital (upper right)
B243	Fogg 1922.23	Capital
B244	Fogg 1922.24	Capital
B245	Fogg 1922.25	Capital
B246	Fogg 1922.26	Capital
B247	Fogg 1922.27	Capital
B248	Fogg 1922.17	Capital
B249	Fogg 1922.16	Capital
B250	Fogg 1922.18	Capital
B251	Fogg 1922.19	Capital
B252	Fogg 1922.20	Capital
B253	Fogg 1922.21	Capital
B254	Fogg 1922.22	Capital
B255	Fogg 1925.9.1	KAM—pilaster
B256	Fogg 1925.9.1	Waterspout
B261	Fogg 1949.47.71	Fragment: eagle
B265	Fogg 1949.47.70	Relief: roundel
M280	MMA 29.100.29	Head of a king
F283	Louvre R.F.2308	Head of a king

the Val-de-Grâce specimens and those from the Port Mahon quarry, other than in the concentrations of the oxides of calcium and manganese; these oxide concentrations showed small but consistent deviations.

A systematic sampling of the gallery beneath rue Claude Bernard provided stone specimens, most of which were chemically indistinguishable on the basis of thirteen elements judged to characterize the stone (TABLE 2A). This is true even though there are differences in lithology. For example, a specimen (Q160) taken from a stratum that contains a large number of voids and fossil remains is still similar in composition to other specimens from the same gallery. Those specimens differing markedly from the compositional profile of the gallery also differ notably in hardness, color, the extent of clay inclusions, or their proximity to the top or bottom of the gallery. For instance, five aberrant specimens represent fragments from the highest and lowest levels of the exploited regions.

Comparison of the data for stone from the rue Claude Bernard with those from the Church of Saint-Jacques shows that samples from both belong to the same population, without regard to stratigraphy and even though the galleries lie 300 m apart (TABLE 2B). This can be illustrated most simply by comparing the standard deviation ranges for the concentrations of the oxides, presented in Figure 5.

The chemical similarity of stone from the Val-de-

Table 2. Composition of limestone samples. Concentrations are reported for the oxides of the following elements: calcium (CaO), strontium (SrO), barium (BaO), sodium (Na_2O), potassium (K_2O), rubidium (Rb_2O), cesium (Cs_2O), chromium (Cr_2O_3), manganese (MnO), iron (Fe_2O_3), scandium (Sc_2O_3), lanthanum (La_2O_3) cerium (CeO_2), samarium (Sm_2O_3), europium (Eu_2O_3), ytterbium (Yb_2O_3), lutetium (Lu_2O_3), hafnium (HfO_2), thorium (ThO_2) and, in six cases for the Val-de-Grâce quarry, magnesium (MgO). Concentrations are presented in micrograms of oxide per g sample (ppm), except for CaO, Fe_2O_3, and MgO, reported as percentages, and Lu_2O_3, reported as nanograms of oxide per g sample (ppb). Missing values either were not determined or represent concentrations below the detection limit.

Sample ID	*CaO pct*	*SrO ppm*	*BaO ppm*	*Na_2O ppm*	*K_2O pct*	*Rb_2O ppm*	*Cs_2O ppm*	*Cr_2O_3 ppm*	*MnO ppm*	*Fe_2O_3 pct*	*Sc_2O_3 ppm*	*La_2O_3 ppm*	*CeO_2 ppm*	*Sm_2O_3 ppm*	*Eu_2O_3 ppm*	*Yb_2O_3 ppm*	*Lu_2O_3 ppb*	*HfO_2 ppm*	*ThO_2 ppm*	*MgO pct*
A. Val-de-Grâce Quarry: Gallery beneath Maison de la Géologie, 77 rue Claude Bernard																				
Q152	45.7	1140.	47.	1120.	0.335	-	0.321	27.5	36.	0.38	1.33	5.4	9.2	1.05	0.158	0.337	52.	0.92	1.34	-
Q153	50.4	490.	35.3	700.	0.195	5.0	0.332	16.3	49.	0.31	0.79	4.1	10.1	0.78	0.174	0.237	48.	0.260	0.91	5.5
Q154	51.9	660.	29.0	670.	0.110	-	0.235	9.6	42.	0.181	0.51	5.5	11.8	1.04	0.230	0.270	47.	0.153	1.23	-
Q155	50.4	670.	43.	700.	0.203	5.3	0.233	16.0	35.	0.296	0.80	5.8	13.4	1.03	0.195	0.262	47.	0.475	1.11	-
Q156	42.9	780.	98.	1190.	0.46	12.7	0.49	29.6	39.	0.52	1.55	8.0	17.5	1.48	0.285	0.43	77.	1.59	2.11	-
Q157X	46.2	690.	64.	920.	0.330	9.6	0.60	29.3	35.	0.48	1.43	6.8	14.8	1.26	0.237	0.43	75.	1.60	1.90	-
Q158	48.8	650.	43.	800.	0.261	7.1	0.305	25.3	37.	0.50	1.40	6.1	12.9	1.19	0.211	0.395	65.	1.04	1.38	-
Q159	47.0	670.	44.	810.	0.285	7.6	0.47	24.8	38.	0.43	1.41	6.1	14.7	1.18	0.267	0.64	102.	1.21	1.86	-
Q160	50.8	440.	28.5	540.	0.131	-	0.358	13.2	33.	0.223	0.72	3.72	9.8	0.73	0.160	0.215	39.5	0.259	0.80	8.9
Q161	49.4	560.	21.5	690.	0.194	3.6	0.208	19.5	43.	0.270	0.85	3.47	3.98	0.70	0.094	0.198	42.	0.310	0.64	-
Q162	51.6	490.	56.	580.	0.166	8.6	0.277	19.1	36.	0.300	1.01	5.9	13.2	1.11	0.215	0.278	53.	0.50	1.20	-
Q163	49.7	510.	43.	600.	0.109	5.7	0.45	20.2	36.	0.34	1.21	6.3	14.3	1.16	0.201	0.336	50.	0.55	1.32	-
Q164	51.1	440.	25.5	540.	0.155	10.4	0.329	15.1	35.	0.297	0.88	5.7	14.1	1.09	0.238	0.274	45.	0.53	0.90	-
Q165	52.8	4290.	-	1100.	0.167	-	0.51	20.9	29.2	0.41	1.21	6.3	16.0	1.12	0.166	0.326	47.	0.380	1.57	-
Q166	50.5	2040.	31.1	960.	0.194	4.8	0.148	15.1	30.9	0.36	1.15	8.1	16.8	1.42	0.278	0.364	63.	0.57	1.52	-
Q167	48.5	440.	58.	660.	0.158	7.2	-	14.3	36.	0.179	0.62	3.76	8.0	0.79	0.184	0.237	42.	0.375	0.76	-
Q168	48.8	1030.	36.5	560.	0.080	2.55	-	13.4	34.	0.142	0.55	3.65	8.9	0.79	0.165	0.270	47.	0.250	0.78	-
Q169	46.5	-	58.	800.	0.187	4.5	0.188	20.5	36.	0.246	0.90	4.4	10.1	0.97	0.245	0.279	44.	0.55	1.20	-
Q170	51.1	460.	31.7	620.	0.122	3.5	0.094	19.3	36.	0.155	0.67	4.3	11.7	0.91	0.128	0.232	41.	0.389	1.09	-
Q171	51.8	470.	30.4	520.	0.098	2.38	0.097	16.6	41.	0.145	0.56	3.26	9.4	0.70	0.142	0.201	36.1	0.259	0.70	6.4
Q172	48.8	330.	32.7	480.	0.091	-	0.115	12.9	44.	0.151	0.45	2.48	5.8	0.58	0.099	0.182	29.1	0.255	0.47	-
Q173	48.4	450.	41.	640.	0.141	5.0	0.233	17.7	47.	0.55	0.76	4.2	9.1	0.88	0.197	0.267	47.	0.257	0.84	-
Q174	46.8	690.	55.	1020.	0.272	10.7	0.268	31.2	40.	0.48	1.18	7.0	15.0	1.41	0.243	0.46	69.	1.20	1.75	-
Q175	49.7	380.	34.4	690.	0.154	5.5	0.277	15.3	42.	0.277	0.75	4.1	10.5	0.83	0.132	0.265	52.	0.51	0.80	-
Q176	49.4	480.	-	630.	0.128	6.2	0.163	14.5	41.	0.231	0.70	3.85	5.2	0.84	0.130	0.334	55.	0.55	0.79	-
Q177	50.1	470.	48.	620.	0.138	7.7	0.171	14.4	37.	0.232	0.58	3.85	8.7	0.82	0.133	0.318	50.	0.50	0.74	-
B. Val-de-Grâce Quarry: Gallery beneath the Church of Saint-Jacques du Haut-Pas																				
Q178	49.7	410.	45.9	540.	0.157	-	0.172	12.3	38.	0.251	0.54	3.26	8.0	0.70	0.113	0.196	32.9	0.283	0.64	-
Q179	43.8	930.	66.	1030.	0.313	11.1	0.313	29.0	43.	0.48	1.31	5.6	11.6	1.14	0.188	0.328	58.	0.79	1.83	-
Q180	47.1	730.	28.1	720.	0.222	6.0	0.349	17.4	32.	0.290	0.84	3.64	7.3	0.87	0.171	0.239	39.6	0.282	1.08	8.2
Q181	-	530.	25.3	550.	0.168	5.3	0.314	13.1	36.	0.219	0.75	3.75	7.4	0.86	0.157	0.215	33.4	0.208	0.76	-
Q182	-	490.	30.6	650.	0.224	6.0	0.245	12.6	39.	0.268	0.78	4.5	8.9	0.94	0.162	0.222	37.0	0.397	1.04	-
Q183	51.9	800.	34.3	950.	0.335	9.6	0.47	16.4	35.	0.33	1.09	5.3	10.0	1.07	0.196	0.289	49.	0.91	1.45	7.8
Q184	47.6	670.	33.8	720.	0.253	10.0	0.42	21.3	36.	0.35	1.19	4.8	9.1	1.00	0.210	0.283	48.	0.68	1.14	8.1
Q185	-	560.	29.1	570.	0.170	8.3	0.328	18.6	35.	0.274	0.97	3.85	7.2	0.90	0.142	0.264	42.	0.45	0.91	-
Q186	-	910.	29.6	970.	0.381	10.0	1.04	19.2	47.	0.56	1.90	7.4	14.0	1.36	0.295	0.42	68.	0.49	2.27	-
Q187	-	970.	28.2	770.	0.234	7.1	0.321	13.8	40.	0.43	0.82	5.8	10.9	1.18	0.234	0.46	73.	0.57	1.40	-
Q188	-	1370.	47.	2160.	0.72	26.6	2.34	52.	29.1	1.68	4.35	7.2	14.9	1.27	0.260	0.42	76.	0.93	3.6	-
C. Quarry Site near Port Mahon																				
Q266	51.8	830.	27.0	700.	0.144	2.86	0.164	10.8	51.	0.086	0.59	5.0	9.6	1.08	0.194	0.320	49.	0.280	1.08	-
Q267	55.0	1150.	31.6	790.	0.130	3.08	0.176	12.0	55.	0.63	0.66	5.1	9.4	1.15	0.197	0.242	36.2	0.130	1.09	-
Q268	51.6	720.	45.	780.	0.235	6.9	0.357	24.2	67.	0.41	1.16	5.4	10.2	1.15	0.203	0.321	52.	0.52	1.32	-
Q269	55.2	510.	19.6	680.	0.027	2.17	0.156	5.0	62.	0.166	0.390	2.64	4.5	0.292	0.089	0.164	29.0	0.060	0.50	-
Q270	52.7	780.	47.	800.	0.211	7.1	0.50	23.4	55.	0.47	1.50	6.8	13.5	1.47	0.240	0.36	57.	0.306	1.48	-
Q271	47.6	1160.	47.	1000.	0.248	5.3	0.264	28.9	43.	0.58	1.19	5.4	10.2	1.24	0.224	0.36	53.	0.51	1.54	-
Q272	51.6	730.	31.6	670.	0.175	5.3	0.361	19.6	46.	0.33	0.93	4.4	8.1	1.09	0.169	0.276	39.8	0.44	0.94	-
Q273	52.8	320.	26.0	550.	0.242	6.3	0.309	18.8	134.	0.35	0.89	3.01	5.7	0.89	0.121	0.281	52.	0.51	0.68	-
Q274	53.1	390.	28.5	600.	0.182	5.8	0.240	19.5	113.	0.34	0.87	3.84	7.0	1.03	0.129	0.228	35.4	0.50	0.87	-
Q275	51.6	410.	33.9	570.	0.205	4.3	0.319	19.3	126.	0.35	0.89	3.45	6.2	1.08	0.122	0.296	47.	0.48	0.80	-

Table 2. (cont.)

Sample ID	*CaO pct*	*SrO ppm*	*BaO ppm*	*Na_2O ppm*	*K_2O pct*	*Rb_2O ppm*	*Cs_2O ppm*	*Cr_2O_3 ppm*	*MnO ppm*	*Fe_2O_3 pct*	*Sc_2O_3 ppm*	*La_2O_3 ppm*	*CeO_2 ppm*	*Sm_2O_3 ppm*	*Eu_2O_3 ppm*	*Yb_2O_3 ppm*	*Lu_2O_3 ppb*	*HfO_2 ppm*	*ThO_2 ppm*	*MgO pct*
C. Quarry Site near Port Mahon (cont.)																				
Q276	53.3	670.	33.4	710.	0.241	7.1	0.381	27.0	74.	0.68	1.32	4.9	9.5	1.19	0.180	0.276	49.	0.281	1.02	-
Q277	52.5	690.	29.1	810.	0.146	5.1	0.210	18.2	70.	0.42	0.81	4.6	8.6	1.13	0.163	0.243	38.7	0.350	0.97	-
Q278	54.1	740.	31.6	820.	0.162	4.5	0.199	18.0	79.	0.41	1.02	4.7	8.9	1.14	0.173	0.269	43.	0.40	1.20	-
Q279	53.5	460.	24.0	580.	0.061	2.37	0.086	11.4	86.	0.282	0.49	2.99	5.2	0.89	0.126	0.182	30.0	0.248	0.57	-
D. Moutiers-Saint-Jean: Sculpture Fragments																				
C133	50.6	380.	13.3	193.	0.077	3.26	0.344	7.4	47.	0.186	0.50	2.07	2.04	-	0.055	0.211	35.4	0.041	0.184	-
C134	52.8	400.	29.0	196.	0.037	1.3	0.155	7.4	47.	0.193	0.50	2.07	1.98	-	0.058	0.223	40.	0.031	0.184	-
C135	53.5	400.	11.5	199.	0.056	1.83	0.250	7.5	47.	0.246	0.55	2.14	2.07	-	0.056	0.230	38.3	0.038	0.205	-
C212	56.5	330.	29.0	155.	0.032	-	0.164	7.5	51.	0.221	0.44	1.85	1.71	0.380	0.054	0.193	36.9	-	0.163	-
C213	52.8	390.	17.4	192.	0.035	2.85	0.229	8.7	54.	0.249	0.50	1.94	1.36	0.382	0.076	0.200	33.9	-	0.183	-
C214	56.2	410.	12.7	171.	0.028	1.89	0.157	7.9	55.	0.203	0.50	3.15	3.50	0.277	0.059	0.239	38.6	-	0.199	-
B243	59.4	460.	13.7	159.	0.027	2.99	0.196	6.4	51.	0.226	0.49	2.10	2.20	0.70	0.066	0.211	42.	0.044	0.184	-
B244	55.3	470.	12.1	174.	0.028	2.29	0.188	6.5	39.	0.161	0.46	2.01	2.01	0.51	0.060	0.211	41.	0.033	0.172	-
B245	55.0	470.	16.8	156.	0.029	1.30	0.121	6.1	40.	0.150	0.45	2.01	2.02	0.66	0.067	0.232	45.	-	0.153	-
B246	56.8	380.	-	158.	0.025	-	0.139	7.0	84.	0.150	0.389	2.46	2.17	0.48	0.079	0.247	50.	-	0.195	-
B247	55.5	360.	21.1	307.	0.070	3.9	0.269	5.7	47.	0.240	0.51	1.94	2.76	0.53	0.065	0.125	24.8	0.063	0.262	-
B248	57.4	420.	14.9	134.	0.022	1.86	0.120	6.9	39.	0.126	0.44	2.83	2.24	0.75	0.071	0.296	52.	0.024	0.148	-
B249	55.5	450.	-	147.	0.023	-	0.209	7.7	43.	0.246	0.337	2.26	2.17	0.42	0.070	0.208	36.6	-	0.134	-
B250	38.6	1060.	30.5	208.	0.028	0.61	0.066	2.6	21.7	0.34	0.210	0.63	0.90	0.320	0.026	0.063	11.2	0.038	0.111	-
B251	53.5	640.	24.7	199.	0.029	2.56	0.138	7.3	48.	0.253	0.43	2.28	2.14	0.318	0.069	0.249	44.	0.053	0.163	-
B252	55.7	370.	8.3	178.	0.023	3.02	0.113	7.2	73.	0.230	0.45	2.70	2.13	0.331	0.082	0.283	51.	-	0.184	-
B253	57.7	490.	29.2	190.	0.059	2.31	0.211	8.1	88.	0.293	0.49	1.97	2.16	0.54	0.057	0.200	38.2	-	0.200	-
B254	55.7	370.	16.8	211.	0.050	2.33	0.265	6.4	72.	0.251	0.52	1.98	1.97	0.299	0.072	0.194	37.2	0.057	0.227	-
B255	57.4	325.	8.0	119.	0.017	1.35	0.137	6.7	50.	0.259	0.393	2.55	2.30	0.354	0.074	0.240	46.	0.026	0.155	-
B256	55.2	316.	10.7	116.	0.031	1.44	0.170	8.5	57.	0.299	0.51	3.14	2.27	0.80	0.097	0.310	58.	-	0.184	-
P207	56.1	410.	10.3	143.	0.020	2.07	0.181	5.6	48.	0.202	0.40	1.77	1.08	0.348	0.038	0.189	32.5	-	0.143	-
E. Cluny: Sculpture Fragments																				
C122	52.4	490.	19.4	-	-	5.2	0.76	13.6	-	0.67	1.87	15.6	12.3	-	0.56	1.00	154.	0.045	0.71	-
C123	53.7	440.	-	355.	0.105	6.0	0.81	15.8	125.	0.68	2.30	18.3	14.3	-	0.65	1.19	178.	0.039	0.99	-
C141	34.9	-	81.	640.	0.55	23.5	6.0	32.2	152.	0.96	3.84	19.0	23.6	3.67	0.61	1.16	153.	1.32	3.02	-
C142	34.2	-	82.	500.	0.55	25.2	6.4	32.9	145.	1.01	3.87	19.1	24.6	3.83	0.67	0.93	162.	1.54	3.27	-
C215A	44.5	392.	31.0	303.	0.327	13.6	2.27	22.9	104.	0.69	2.39	17.6	17.9	2.66	0.60	0.90	138.	0.90	2.20	-
C215B	44.7	380.	33.2	328.	0.345	13.6	2.33	22.6	113.	0.69	2.43	18.0	19.0	2.66	0.56	0.91	152.	0.92	2.29	-
C216A	48.3	450.	44.	279.	0.241	11.1	1.50	17.1	100.	0.51	2.05	17.5	17.0	2.52	0.61	0.88	135.	0.94	1.71	-
C216B	46.1	390.	41.	284.	0.254	10.4	1.53	18.7	92.	0.51	1.96	16.8	16.0	2.42	0.57	0.87	124.	0.81	1.63	-
C217A	41.0	360.	43.	387.	0.380	14.5	2.56	26.1	121.	0.69	2.47	16.5	17.2	2.51	0.58	0.91	147.	1.21	2.28	-
C217B	41.6	310.	49.	420.	0.372	14.4	2.46	22.8	118.	0.69	2.52	16.7	17.6	2.53	0.53	0.89	136.	1.20	2.36	-
C218A	43.1	390.	35.6	352.	0.46	17.9	2.86	27.6	124.	0.76	2.79	19.5	21.5	3.17	0.70	0.93	143.	1.21	2.87	-
C218B	42.8	340.	55.	349.	0.42	16.0	3.01	29.1	86.	0.77	2.75	20.0	21.8	3.30	0.78	0.96	144.	1.07	3.04	-
C219A	44.6	350.	41.	326.	0.302	11.0	2.14	21.2	105.	0.61	2.17	16.7	22.5	2.45	0.56	0.83	132.	0.92	1.82	-
C219B	44.1	360.	37.9	322.	0.307	10.2	2.07	22.4	108.	0.60	2.15	16.9	22.0	2.49	0.53	0.86	130.	0.95	1.91	-
P220	53.7	420.	22.2	430.	0.151	6.9	1.30	22.3	168.	0.90	2.54	19.5	16.0	3.13	0.79	1.29	186.	-	1.41	-
P221	55.6	470.	17.8	690.	0.134	6.3	0.84	18.0	154.	0.67	2.54	19.1	15.3	2.87	0.75	1.34	194.	-	1.08	-
F. Musée Carnavalet: Sculpture Fragments																				
F193	-	380.	19.7	500.	0.110	2.57	0.120	10.9	71.	0.191	0.45	2.77	5.1	0.72	0.117	0.191	30.2	0.44	0.55	-
F194	-	880.	23.9	980.	0.114	3.83	0.154	8.7	39.	0.206	0.41	2.97	5.6	0.75	0.124	0.161	25.1	0.158	0.77	-
F195	-	420.	19.9	550.	0.127	4.1	0.243	11.1	53.	0.184	0.57	2.83	5.0	0.68	0.128	0.183	27.6	0.44	0.71	-
F196	-	530.	13.7	560.	0.120	5.7	0.186	9.1	-	0.216	0.51	3.21	5.9	0.80	0.129	0.171	27.0	0.311	0.70	-
F197A	-	370.	25.7	460.	0.109	4.0	0.242	10.1	51.	0.189	0.58	2.83	5.2	0.72	0.126	0.183	29.5	0.258	0.71	-
F197B	-	430.	25.4	610.	0.126	4.3	0.229	12.1	54.	0.184	0.60	2.97	5.4	0.79	0.117	0.188	30.3	0.364	0.68	-
F197C	-	400.	28.6	540.	0.162	6.2	0.300	18.3	56.	0.220	0.73	3.24	6.0	0.82	0.141	0.184	34.8	0.311	0.76	-
F198A	-	650.	21.1	590.	0.138	4.3	0.245	10.6	38.	0.155	0.52	3.46	6.4	0.78	0.155	0.179	32.1	0.42	0.69	-
F198B	-	410.	23.8	460.	0.126	4.8	0.243	12.5	53.	0.233	0.72	3.20	5.9	0.79	0.126	0.207	33.1	0.43	0.89	-
F198C	-	380.	22.2	470.	0.103	3.4	0.196	9.5	53.	0.150	0.50	2.75	5.2	0.70	0.115	0.171	26.4	0.200	0.74	-
F199	-	740.	38.5	550.	0.141	6.2	0.126	28.0	33.	0.39	0.74	3.02	5.1	0.83	0.142	0.250	48.	0.71	0.50	-

Table 2. (cont.)

Sample ID	*CaO pct*	*SrO ppm*	*BaO ppm*	*Na_2O ppm*	*K_2O pct*	*Rb_2O ppm*	*Cs_2O ppm*	*Cr_2O_3 ppm*	*MnO ppm*	*Fe_2O_3 pct*	*Sc_2O_3 ppm*	*La_2O_3 ppm*	*CeO_2 ppm*	*Sm_2O_3 ppm*	*Eu_2O_3 ppm*	*Yb_2O_3 ppm*	*Lu_2O_3 ppb*	*HfO_2 ppm*	*ThO_2 ppm*	*MgO pct*
F. Musée Carnavalet: Sculpture Fragments (cont.)																				
F200	-	680.	31.1	710.	0.115	4.0	0.091	23.6	37.	0.267	0.69	3.23	5.8	0.90	0.130	0.218	44.	0.44	0.66	-
F201	-	550.	23.5	730.	0.187	6.2	0.336	15.1	88.	0.296	0.76	3.45	6.6	0.90	0.122	0.200	37.8	0.44	0.68	-
F202A	-	470.	15.0	395.	0.060	3.4	0.234	17.5	23.7	0.37	0.72	2.47	3.80	0.84	0.145	0.250	39.2	0.307	0.53	-
F202B	-	570.	12.9	650.	0.111	6.7	0.273	29.4	24.8	0.46	0.86	3.17	4.4	1.05	0.179	0.188	29.1	0.168	0.68	-
G. Nôtre-Dame Cathedral, Paris: Sculpture Fragments																				
M01	46.9	370.	17.2	440.	0.067	-	0.090	7.1	82.	0.138	0.395	2.09	3.86	0.59	0.080	0.134	26.3	0.137	0.42	-
F51	44.3	390.	23.6	460.	0.056	1.25	0.086	7.2	83.	0.142	0.382	2.11	3.84	0.70	0.073	0.129	23.2	0.146	0.42	-
H. Abbey of Saint-Denis: Sculpture Fragments																				
M74	53.5	660.	28.4	580.	0.125	4.4	0.228	25.3	24.9	0.305	1.03	3.58	6.3	0.90	0.152	0.276	54.	0.376	0.81	-
C125	50.1	820.	30.3	530.	0.112	5.5	0.205	24.3	23.2	0.326	0.96	3.67	6.7	-	0.142	0.271	43.	0.363	0.71	-
P06	39.2	490.	159.	880.	0.347	9.4	0.201	21.6	47.	0.115	0.70	2.88	5.5	0.77	0.103	0.254	43.2	1.00	0.77	-
P20	40.1	510.	78.	830.	0.296	8.6	0.189	23.5	36.	0.119	0.75	4.1	8.0	0.96	0.145	0.320	51.	0.85	0.83	-
M51X	52.5	490.	25.9	940.	0.101	3.2	0.140	8.8	28.	0.186	0.45	2.22	3.75	0.66	0.069	0.123	23.3	0.153	0.50	-
I. Mantes: Heads of Kings																				
M280	56.4	510.	30.6	610.	0.117	5.7	0.254	10.9	99.	0.204	0.60	2.60	4.3	0.91	0.096	0.149	26.5	0.170	0.55	-
F283	56.0	490.	24.2	640.	0.114	2.97	0.291	11.5	100.	0.197	0.60	2.42	4.8	0.81	0.092	0.158	28.9	0.273	0.52	-
J. Vézelay: Sculpture Fragments																				
P10	26.5	304.	97.	720.	0.60	32.5	2.07	36.2	129.	1.13	4.4	18.2	21.1	2.51	0.54	1.18	199.	2.51	3.11	-
P23X	30.9	280.	68.	680.	0.360	20.3	1.45	21.2	159.	1.10	2.97	16.4	17.8	2.10	0.43	0.75	114.	1.04	1.85	-
P23Y	35.3	400.	73.	680.	0.395	21.0	1.19	25.2	140.	1.45	3.25	17.3	18.6	2.16	0.50	0.90	145.	1.72	2.24	-
B261	51.3	520.	54.	660.	0.54	31.3	4.8	26.4	199.	1.48	3.80	14.3	17.2	2.20	0.48	0.91	144.	0.78	1.85	-
B265	49.5	480.	83.	1050.	0.62	36.2	6.7	31.9	209.	3.01	4.5	17.2	20.6	2.64	0.56	1.08	159.	0.90	2.44	-
K. Glencairn Museum: Head																				
P16	43.3	940.	65.	690.	0.133	6.6	0.276	17.9	33.	0.212	0.80	4.8	9.2	1.03	0.154	0.227	44.	0.387	0.96	-
L. The Cloisters: Fragment of an Angel																				
C68	57.9	285.	-	225.	0.049	1.94	0.390	12.9	151.	0.59	2.02	16.7	14.8	2.56	0.62	1.08	187.	0.044	0.79	-

Grâce quarry to that from the Port Mahon gallery is also evident in Figure 5. There are, however, statistically significant differences in the concentrations of manganese and, to a lesser extent, calcium. A comparison of manganese oxide concentrations for the three stone sources shows that they are divided into two quite distinct compositional groups, although there is a small degree of overlap. The manganese oxide concentrations for the two Val-de-Grâce galleries are lower than those for the Port Mahon gallery, as are the calcium oxide concentrations (TABLE 2C). Calculations based on these data show stone from the Port Mahon site to be relatively pure calcium carbonate.

To identify the missing major component in the less pure Val-de-Grâce stone, six samples (Q153, Q160, Q171, Q180, Q183, Q184) were tested for magnesium content by atomic absorption spectrophotometry. The stone proved to be a combination of calcium carbonate (mean concentration by weight: 87% ± 3%) and magnesium carbonate (mean concentration by weight: 11% ± 2%).

To determine the crystal structure (i.e. minerals) of the Val-de-Grâce limestone, three of the same specimens (Q153, Q180, Q184) were analyzed by X-ray diffraction. The stone was found to be primarily the mineral calcite with minor amounts of quartz. Although calcite is nominally calcium carbonate, magnesium ions are often substituted for calcium ions within the crystal lattice. Since the analysis described in the previous paragraph showed these representative samples to contain both calcium carbonate and magnesium carbonate, it may be inferred that Paris stone is essentially pure calcite in which about 13% of the calcium ions have been replaced by magnesium ions.

Several quarry fragments were also analyzed by X-ray fluorescence spectroscopy to identify constituents not detected by neutron activation analysis. The following elements were found: silicon (4–5%), probably present as quartz; sulfur; titanium; copper; and traces of aluminum and tin.

Data for the three quarry galleries can be combined to form one Paris quarry reference group that is consis-

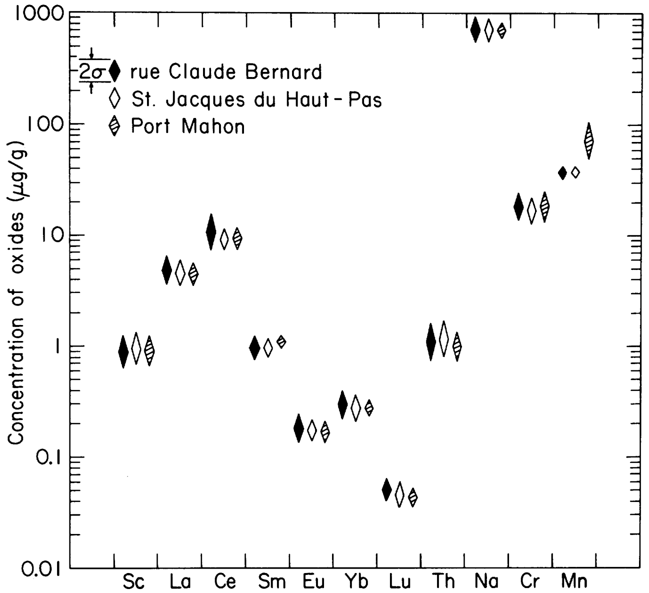

Figure 5. Comparison of compositional profiles of three Parisian quarry galleries. Symbols indicate the standard deviation ranges for the component oxides that best characterize the stone formation.

tent in composition and representative of the Paris limestone formation. By calculating multivariate statistical probabilities based on nine elements, it can be shown that 39 of the 51 quarry specimens belong to this compositional reference group. The average probability of group membership is 65 ± 20%. This compositional group exhibits low concentrations of manganese, iron, and rare earth elements when compared with limestone from other French deposits.

The 12 samples excluded from the Paris quarry reference group on the basis of multivariate probability calculations differ from the group not only in composition but in other respects as well. Four aberrant specimens (Q152, Q176, Q187, and Q279) represent fragments from the highest or lowest levels of their respective galleries. Q165, which was obtained from a thin layer of calcareous marl containing pockets of fossil-bearing material, does not match the elemental profile of the reference group. Q165 has the highest calcium concentration of any quarry specimen analyzed and correspondingly lower trace element concentrations; its strontium content is high but barium and rubidium content is below detection limits. The fragment from which Q161 was taken has a large number of fossilized remains. The hard, particulate stone from which Q269 was drilled has many dark inclusions in a tan matrix and is honeycombed with holes; it is exceptionally low in chromium and in alkali and rare earth elements. The fragments represented by Q273 and Q275 each came from a layer less than eight cm thick and harder than all others from the Port Mahon gallery. In the case of Q186 and Q188, from layers near the bottom of the Saint-Jacques du Haut-Pas gallery, somewhat less than one g of powder was removed from small fragments of beige and brown clay-bearing stone. These specimens, which have a very low probability of group membership, exhibit exceptionally high concentrations of iron and rare earth elements.

It should be noted that the deviant samples discussed above are not truly representative of the deviance to be expected in the limestone formation. Some specimens from the Port Mahon gallery were, in fact, included for analysis primarily because they represent atypical depositional layers.

Characterization of the Parisian limestone formation requires not only information on the composition of a statistically significant number of samples, but also an estimate of the variability in the composition. The variability depends mainly on the sampling technique and homogeneity of the stone, and to a smaller degree on the errors inherent in the analytical procedure. These factors are summarized by the percentage spread in the data (i.e., the group standard deviation expressed as a percentage of the mean concentration of the oxide).

To obtain a measure of the reproducibility of the sampling and analytical procedures, specimens of powder from four different locations on a single stone fragment were tested. For these four specimens the spread of the elemental concentrations ranges from 2–26% (TABLE 3). Homogeneity of that portion of the Paris limestone formation under study may be estimated from the data for the Parisian quarry reference group as a whole. These data show a spread approximately three times greater than the spread for multiple analyses of one hand sample.

If sculptured fragments are to be related to the Parisian rock source on the basis of composition, two conditions must be met: the composition of stone from other sources must differ significantly from that of Parisian stone, and variations within the Paris formation must be small compared with variations among geologically different sources. Comparison of Parisian stone with that from Burgundian sources is instructive. Because no quarry material was availablé for analysis, Burgundian stone cannot be characterized with the same confidence as Parisian rock. Data are available, however, for a number of museum objects known with reasonable certainty to have come from the abbeys of Moutiers-Saint-Jean and Cluny (TABLES 2D,E). Correlation diagrams of concentration data for these disparate locations show that stone from the Paris region is clearly different from that used for Burgundian Romanesque sculpture. The difference, most apparent in the rare earth element concentrations,

Table 3. Range of variability in Parisian limestone formation.

Element determined	Percent Spread* in Single Hand Sample (4 analyses)	Percent Spread* in Paris Quarry Reference† Group (39 analyses)	
		Unadjusted concentrations	Least-square fit concentrations‡
Calcium	7	8	8
Sodium	12	24	14
Chromium**	12	35	22
Manganese	10	33	33
Iron	19	59	44
Scandium**	14	39	19
Lanthanum**	12	30	10
Cerium**	24	29	16
Samarium**	7	25	10
Europium**	11	27	14
Ytterbium**	2	25	9
Lutetium**	26	25	10
Thorium	18	38	16
Average % Spread	13	31	17

*Group standard deviation as percent of mean concentration.

†Group membership was determined by multivariate statistical techniques, using the program ADCORR.

‡Best least-square fit to concentrations of elements marked ** using the program ADSTAT.

is illustrated by a plot of europium oxide versus cerium oxide (FIG. 6).

Applications to Sculpture from the Paris Basin and Burgundy

Medieval, Merovingian, and Gallo-Roman Sculpture from the Musée Carnavalet

Samples of Romanesque, Merovingian, and Gallo-Roman sculpture in the collection of the Musée Carnavalet, Paris (TABLE 1), were analyzed to determine whether they originated in the Parisian stone source under investigation (TABLE 2F). Calculation of multivariate probability shows that six fragments taken from Romanesque pier and foundation bases (accession no. AP315 [F197A-F197C, F198A-F198C]) and three fragments from a Romanesque basin and wall niche (acc. no. AP147 [F193, F195, F196]) have compositions consistent with the Paris quarry reference group. Specimens from a Merovingian sarcophagus (acc. no. AP650 [F199, F200]) and Gallo-Roman pilasters (acc. no. AP19 [F202A, F202B]), on the other hand, are excluded from group membership, as are the twelve quarry samples discussed previously. One sample from a Gallo-Roman stela (acc. no. AP14 [F201]) has a low probability of belonging to the group. It is likely that the pre-Romanesque fragments were extracted from quarries in the valley of the Bièvres River further east than those under investigation, quarries having somewhat different compositional profiles.[9]

Statue Fragments Attributed to Nôtre-Dame Cathedral

Neutron activation data have helped to confirm the relationship deduced from other techniques between sculptural fragments that were originally part of one ensemble. A magnificent head of a king (FIG. 7A) in The Metropolitan Museum of Art (acc. no. 38.180 [M01]) is known to be that of King David from the Saint-Anne portal of Nôtre-Dame Cathedral, Paris, because it is represented in a 1729 engraving of the portal made before the column statues were removed during the French Revolution (FIG. 7C). In 1977, a series of sculpture fragments from Nôtre-Dame was discovered at the Hôtel Moreau during excavations for a building foundation. Among the finds was a fragment that, according to the 1729 engraving, was certainly the lower portion of the figure of King David [F51] (FIG. 7B). Samples from the head and the body fragment match sufficiently closely in composition to confirm that they are indeed from the same sculpture (TABLE 2G). Their compositions do not, however, correspond as closely to the Paris quarry reference group as might be expected of stone from that source.

The sources of limestone for sculptural decoration

9. C. Lorenz, private communication.

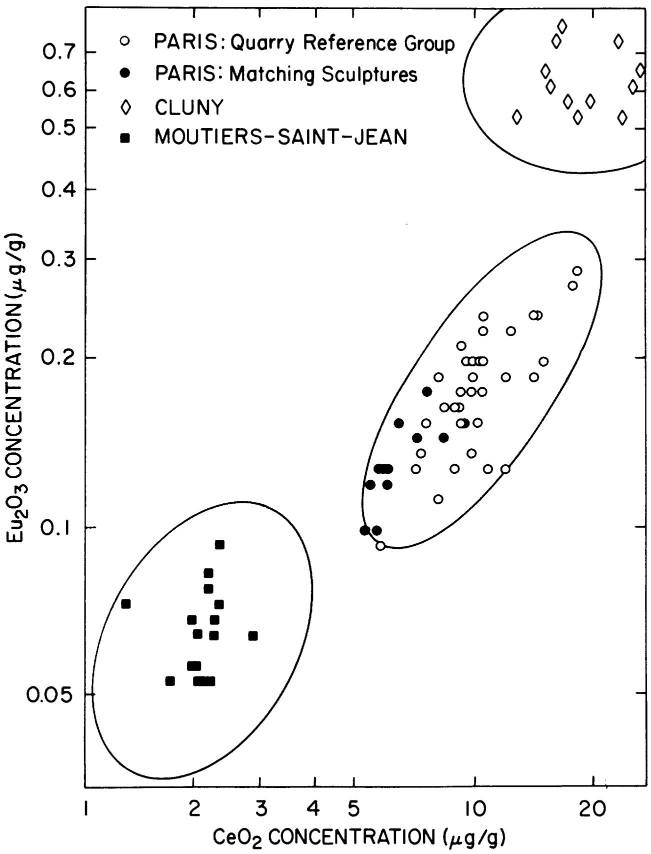

Figure 6. Europium oxide-cerium oxide correlation diagram for three geographically and geologically different sources of Romanesque limestone sculpture: Paris (quarry reference group and matching museum objects), Cluny (Burgundy), and Moutiers-Saint-Jean (Burgundy). Ellipses enclose probability range that includes 95% of group members. All concentrations are expressed as micrograms per g.

were selected for the color, grain, and physical characteristics for carving. The important quarries in use during the Middle Ages each probably provided stone for a number of building sites; today the locations of only some of these quarries are known. The very dense, fine-grained, grayish-white limestone of the sculptures may have come from another quarry site in the Paris basin that produced much of the material for the decoration of the facade. To establish more precisely the relationship of the sculpture to such a quarry requires systematic sampling of likely stone sources and comparison of the analytical results with those from the Nôtre-Dame fragments.

The recent research of Marc Viré[10] indicates that a large number of quarrying sites in Paris and its environs may have furnished material in the 12th and 13th centuries for public buildings and for the sculpture adorning them. Viré, Ellenberger and his co-workers,[11] and John James[12] suggest that the decorative stone for the Paris cathedral may have come from as far away as the open-cut quarries of Saint-Leu-d'Esserent in the Oise Valley, some 40 miles NW of Paris. Unfortunately we have no analytical data on the stone of this region against which to test these suggestions. The hypothesis that limestone for sculptural decoration of a major cathedral was selected from quarries other than those nearby is significant in several respects. From a practical point of view, transportation of the stone along waterways instead of overland would have cost far less. It is known, for instance, that the building material for old Saint Paul's Cathedral in London and for Canterbury Cathedral was brought from as far away as Normandy. Thus, distance was not necessarily the critical factor. It must be remembered that the physical characteristics required of stone for sculpture are different from those of stone for architectural fabric. The quality of the stone was therefore the most important consideration, regardless of the distance the stone had to be transported.

Sculpture Attributed to Saint-Denis

An impost capital with acanthus leaf decoration now in The Metropolitan Museum (acc. no. 13.152.1 [M74, C125]) is said to have come from the Royal Abbey of Saint-Denis, just north of Paris. The capital is closely related in size and design to another impost capital in The Metropolitan Museum (acc. no. 1982.226) and two capitals in the Glencairn Museum (acc. nos. 09.SP.271 [P06]; 09.SP.12 [P20]). This stylistically homogeneous group may have come from a portion of the abbey constructed in the mid-12th century. Unfortunately, full documentation for this origin is lacking. A column figure (MMA acc. no. 20.157 [M51]) is securely linked, however, to the old cloister of the abbey by an 18-century engraving that shows it still *in situ*. Close correspondence of the compositional characteristics between the impost capitals and the column figure known to have been made for the abbey would fortify the reputed Saint-Denis origin of the capitals.

The samples from the three tested capitals and the column figure are reasonably similar in composition when their concentrations are adjusted to compensate for relatively large variations of calcium oxide concentration.[13] What is more, the adjusted compositions of the

10. Viré, loc. cit. (in note 6).

11. Ellenberger, Marvy, and Viré, loc. cit. (in note 5).

12. John James, "Investigation into the Uneven Distribution of Early Gothic Churches in the Paris Basin, 1140–1240," *The Art Bulletin* 66 (1984) 24.

13. E. V. Sayre, *Brookhaven Procedures for Analysis of Multivariate Archaeometric Data. Brookhaven National Laboratory Report BNL–*

A

B

C

Figure 7. A. Head of King David, Metropolitan Museum of Art (acc. no. 38.10); B. Body fragment found in 1977 at Hôtel Moreau, Paris, now in the collection of the Banque Française du Commerce Extérieure. Musée de Cluny, inv. cl. 22896; C. Engraving by Dom Bernard de Montfauçon in 1729.

Figure 8. Head of a King, Metropolitan Museum of Art (acc. no. 29.100.29).

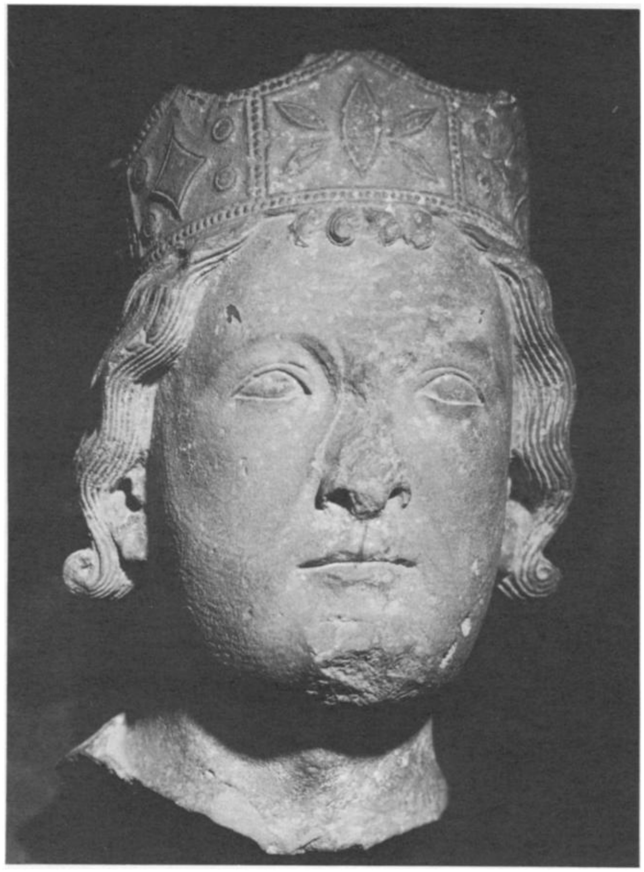

Figure 9. Head of a King, Louvre (acc. no. R. F. 203).

four samples are consistent with an origin for stone in the Paris region (TABLE 2H). But it is not possible to determine whether they are, in fact, from Saint-Denis because no statistically-valid group of samples from the abbey is available for comparison. Nor do we know the location of the medieval quarries that produced the building material and sculptural decoration for Saint-Denis, despite the considerable body of historical information available concerning the construction of the abbey. Again, it should be noted that the proximity of the Seine River to the abbey permitted the transportation of quarried stone along the river's course. Indeed the stone used for these sculptures of reputed Saint-Denis origin forms a loose compositional group with the samples from Nôtre-Dame Cathedral.

21693 (revised 1984); *Program ADSTAT* (Chemistry Department, Brookhaven National Laboratory, 1973; revised 1984). The computer program ADSTAT adjusts one set of data to another by multiplying concentrations in one set by a factor chosen to achieve the best least-squares matching between log-concentration values for the two sets.

Heads of Kings Attributed to Mantes

Similarity in composition of limestone samples can add to the understanding of specific sculptures that seem to be related by style and general appearance or physical size, but cannot otherwise be associated. Sometimes the traditional stylistic analysis leads to reservations about the authenticity of sculptures that appear to be identical to one another.

The relationship between two very similar heads of kings, one in The Metropolitan Museum (acc. no. 29. 100.29 [M280]) and the other in the Louvre (acc. no. R.F.203 [F283]), represents a classic case. The heads have been the subject of repeated claims that only one can be the original; the other is said to be a later copy (FIGS. 8, 9). In 1973, Leon Pressouyre convincingly demonstrated that the head in the Louvre came from the collegiate church at Mantes and was carved around 1230–1240.[14]

14. Leon Pressouyre, "Une tête gothique et son 'double,'" *Revue de l'Art* 21 (1973) 32–40.

Figure 10. Heads of Kings, South Porch at Chartres Cathedral.

The Louvre sculpture actually appears in a 1908 photograph of the Depôt Lapidaire at Mantes. The torso to which it belongs still exists at Mantes; the breaks at the neck fit exactly. The New York head, on the other hand, does not have a known provenance. It is more damaged and was at one time restored by a dealer who added a new nose and chin, which were later removed. Originally both heads had short stubble beards, but all evidence of a beard has been scraped from the New York head except under the chin. Because the New York head was apparently not in the Depôt in 1908, it has been called a copy that was first damaged to look authentic and then restored. But could not the New York head have been removed from Mantes before 1908? A third, possibly related head that was not previously reported exists at the Depôt. It is quite likely that all three heads were once part of a series of nearly identical kings like those on the South Porch of Chartres Cathedral (FIG. 10). Kings in such series were rather mechanically produced, one nearly duplicating the next.

To resolve these issues of original and copy and, by extension, establish or deny the common provenance of the carvings, samples of stone from the New York and Louvre heads were analyzed. Comparison of the nine most significant trace element concentrations shows close correspondence between the two heads, suggesting that their stone comes from the same quarry. If the New York head were indeed a recent copy of the Louvre head, it would be highly coincidental for it to be carved in stone from the same quarry. Thus the stone analysis testifies to the authenticity of both heads.

Stylistic and art historical studies of the heads assert that only one head can be original, indicating an inherent ambivalence toward accepting two very similar works as genuine. The analysis of the stone helps to resolve this debate (TABLE 2I). Sculptures made in series present exceedingly complex problems once the carvings are removed from their original context. With a Mantes origin established for both heads, the question of their original purpose within the sculptural decoration can be properly addressed.

A Head Attributed to Vézelay

Trace element composition of stone can contribute to solving questions of authenticity. A large head of Christ (FIG. 11) in the Glencairn Museum (acc. no. 09.SP.117 [P16]) is directly related to the monumental Christ on the tympanum of the narthex portal of the church at Vézelay (FIG. 12). Neil Stratford[15] recently demonstrated that the Glencairn head is smaller than that on the narthex. He suggests that the Glencairn head was probably made as a fake based upon a plaster cast of the tympanum sculpture. It is now suspected that the head was carved in Paris in the early part of the 20th century. A comparison of the compositional profile of the head with the profiles of the Paris quarry reference group and a small group comprising specimens from four sculptures attributed to Vézelay shows that the head closely resem-

15. L. Saulnier and N. Stratford, *La Sculpture oubliée de Vézelay. Bibliothèque de la Société Française d'Archeologie* 17 (Droz: Geneva 1984) 77, fig. 33.

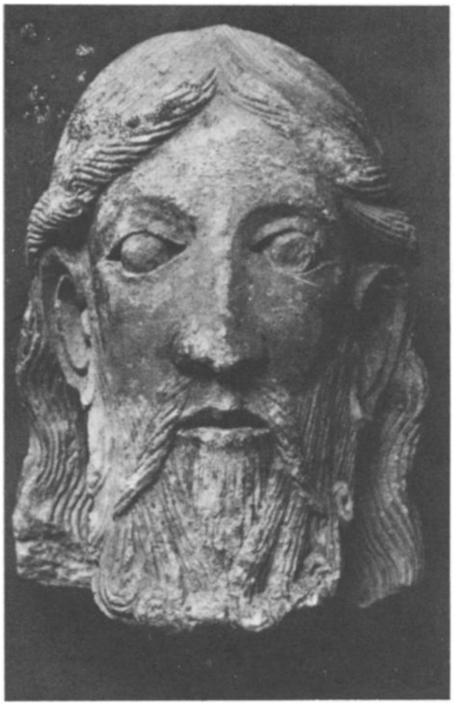

Figure 11. Head of Christ, Glencairn Museum, Bryn Athyn, Pennsylvania (acc. no. 09.SP.117).

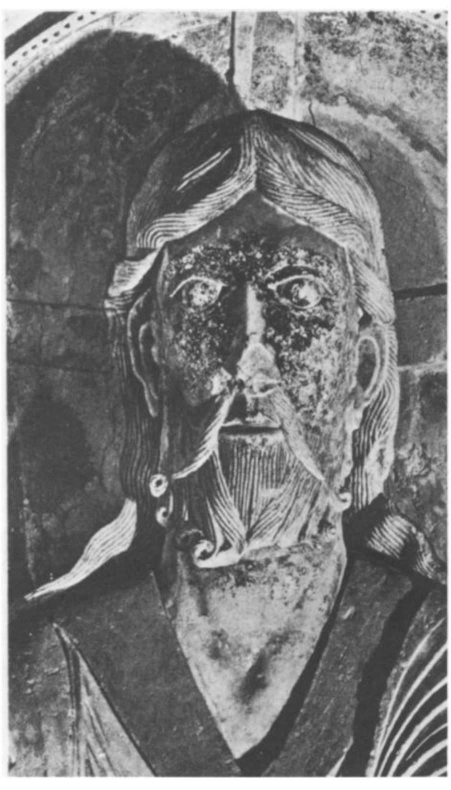

Figure 12. Vézelay head.

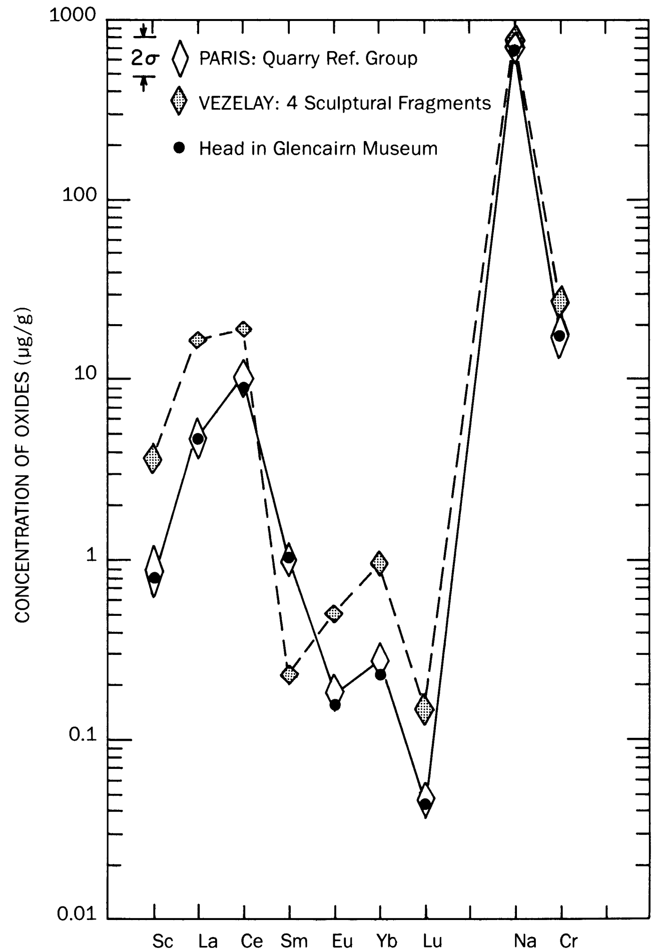

Figure 13. Compositional profiles of Paris quarry reference group and a group of four sculptures attributed to Vézelay compared with that of a head in the Glencairn Museum. Symbols represent standard deviation ranges for the trace component oxides that best characterize the stone.

bles stone from the Parisian quarries under investigation (FIG. 13). In all probability the head was produced for the Parisian dealer Lucien Demotte, using locally quarried stone.

Sculpture from Cluny and Moutiers-Saint-Jean

The venerated Burgundian abbeys of Cluny (Saône-et-Loire) and Moutiers-Saint-Jean (Côte d'Or) have been almost totally destroyed and their sculptural decorations scattered. The identification of many pieces now in museum collections is based upon their known provenance, but the close stylistic relationships among works from Moutiers-Saint-Jean and Cluny can impede definitive attribution for the remainder. For example, a small fragment of an angel (FIG. 14) in The Cloisters (acc. no. 47.101.20 [C68]) has been assigned to Moutiers-Saint-

Figure 14. Fragment of a relief: angel, Metropolitan Museum of Art, The Cloisters Collection (acc. no. 47.101.20).

Jean but it also displays many stylistic characteristics of Cluny sculpture.[16] The Moutiers attribution rests on the fragment's striking parallels to capitals now in the Fogg Art Museum known to have come from Moutiers: the distinctively modelled oval face with deeply-drilled eyes and the schematic elliptical folds of drapery, each defined by a double edge, repeating across the torso. Although the form of the head can be found at Cluny, none of the pieces now there displays the double-edged separation between the bands of drapery, a feature common to all the Moutiers sculptures. Nevertheless a Cluniac origin cannot be categorically rejected. The history of the angel fragment can be traced to Cluny. Although it was sold to the Museum by the dealer Joseph Brummer, he acquired it from Joseph Altounian of Mâcon. All the Cluny fragments Altounian possessed came from his wife who was born in Cluny and acquired them there in her youth.[17]

A comparison of the composition of stone from the angel with that from each abbey confirms a likely Cluniac origin for the angel fragment. Even though both abbeys lie within the Burgundy region, definable differences exist between the limestones used for architectural decoration at Cluny and Moutiers-Saint-Jean. Samples from portions of the Cluny choir screen (Metropolitan Museum of Art acc. no. 47.101.23 [C122, C123]), the window frame from a house at Cluny (MMA acc. no. 47.84 [C141, C142]), and architectural friezes from the abbey (Glencairn acc. no. 09.SP.144 [P220, P221]); MMA acc. no. 1980.263.1 [C215–C219]) form a compositional group characterizing the Cluny stone (TABLE 2E). It is significant that samples taken from a variety of structures dating over several centuries have highly similar compositions. This suggests that a single quarry, or quarries with closely related compositional characteristics, provided the stone for ecclesiastical and secular buildings.

A different compositional profile emerges from samples of the Moutiers-Saint-Jean capitals at the Fogg Art Museum (acc. nos. 1922.17–1922.27 [B243–B254]), and the Gothic portal at The Cloisters (acc. nos. 40.51.1, 40.51.2 [C133–C135, C212–C214]). The compositions of the angel fragment (TABLE 2L) so closely resembles that of the Cluny group and bears so little resemblance to the stone used at Moutiers-Saint-Jean that the angel was most likely carved of the same limestone as other sculptures from Cluny (FIG. 15).

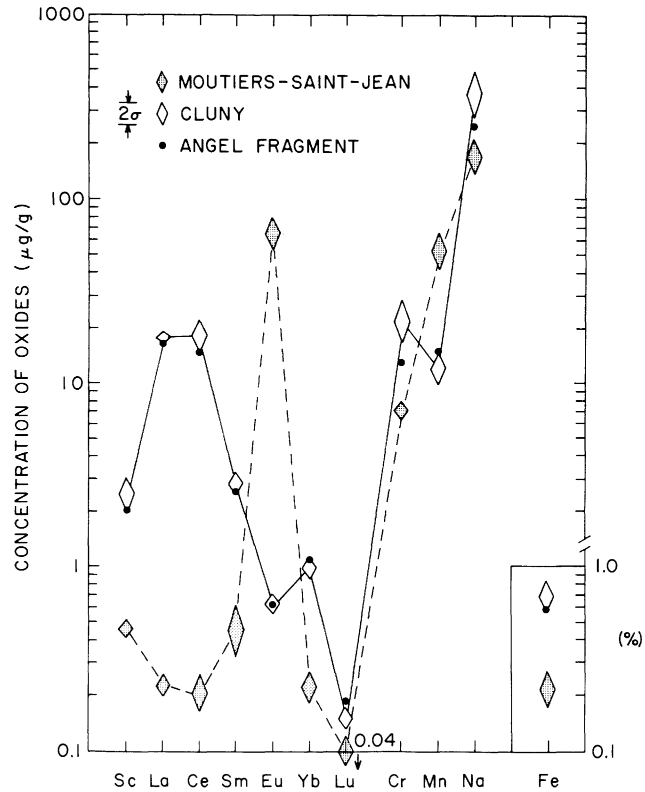

Figure 15. Compositional profiles of limestone sculptures from Cluny and Moutiers-Saint-Jean compared with that of the angel fragment in The Cloisters. Symbols indicate the standard deviation ranges for the trace and minor component oxides that best characterize the stone.

The stylistic implications of the scientific results help distinguish different Burgundian sculptors, each of whom worked at more than one building site. According to George Zarnecki[18] and the more recent work by Edson Armi,[19] Giselbertus of Autun was trained at Cluny and at Vézelay before arriving at Autun. His career can then be charted at the main Burgundian churches. A similar development is likely for the Moutiers Master. Having worked first at Cluny before carving the capitals at Moutiers, his carving technique and general stylistic orientation show revealing parallels to the sculpture known to have come from the west facade at Cluny. For instance, the thick, banded drapery on the arm of the Saint Peter figure, now in the Rhode Island School of Design, Providence, is nearly identical to the arm of the angel. The known fragments from the west facade show only

16. Stephen K. Scher, *The Renaissance of the Twelfth Century, Exhibition Catalogue* (Museum of Art, The Rhode Island School of Design: Providence 1969) catalogue entry no. 4.

17. Information kindly provided by Neil Stratford, The British Museum.

18. D. Grivot and G. Zarnecki, *Giselbertus, Sculptor of Autun* (Trianon: London 1961) 161–162.

19. C. E. Armi, *Masons and Sculptors of Romanesque Burgundy: the New Aesthetic of Cluny III* (The Pennsylvania University Press: University Park 1983) 109–114.

limited stylistic homogeneity. It is therefore not surprising to find in the figure of the angel the double separation between bands of drapery that usually distinguishes the figural sculpture at Moutiers. The angel fragment thus offers a compelling link between the sculptural decoration of Cluny and Moutiers. The evidence of neutron activation analysis offers reasons for associating the angel fragment with Cluny and helps to explain the development of a sculptor who was active at both Cluny and Moutiers-Saint-Jean.

Similarities in compositional profiles permit yet another sculpture to be securely associated with Moutiers-Saint-Jean. A capital in the Glencairn Museum (acc. no. 09.SP.94 [P207]), portraying the story of Lazarus and Dives (Luke 16:19–25), is stylistically more advanced than the Fogg Art Museum capitals, but its dimensions are nearly identical.[20] Since work at Moutiers continued until after the middle of the 12th century, the capital could be from a later phase of construction. The close correspondence between the elemental profiles of the Lazarus capital and the group of limestone objects known to be from Moutiers confirms the suspected Moutiers-Saint-Jean origin of the Glencairn capital.

Appendix: Analytical Procedures

The elemental concentrations of the limestone were measured by thermal neutron activation analysis. This technique has been used extensively to investigate archaeological material and has been described in detail by Bishop, Harbottle, and Sayre.[21]

To prepare samples for irradiation, surface impurities were removed from fragments by drilling a shallow depression in the stone with a tungsten carbide drill bit and discarding the first powder produced. Powdered limestone (at least 1 g) was then collected and mixed well to ensure a homogeneous sample.[22] The samples were oven dried overnight at 100°C before accurately weighed portions of powder (approximately 100 mg each) were sealed in ultra-high purity quartz ampules. Standards[23] were weighed accurately and packaged in the same manner as the limestone, and included with each set of approximately 30 samples to share the irradiation history of that set.

The neutron activation of the samples was accomplished in two steps. Sets of ampules were irradiated for two minutes in the Brookhaven High Flux Beam Reactor at a location where the thermal flux was approximately 1×10^{14} neutrons/cm²/sec to produce short-lived isotopes of manganese, sodium, and potassium. After suitable measurements were all completed, a second bombardment of the same ampules (at a thermal flux of approximately 2.6×10^{14} neutrons/cm²/sec) for seven hours activated the longer-lived isotopes of 20 other potentially useful elements. These isotopes were permitted to decay for a 9–10 day period before processing.

The gamma-ray spectra of the elements present in the limestone and in the standard samples were measured using a 40-ml lithium-drifted germanium semiconductor detector linked to a 4096-channel pulse-height analyzer. The data were recorded on magnetic tape for computer processing, and the elemental concentrations were calculated for each sample by comparing integrated peak areas in samples and standards. These concentrations were measured with an analytical precision of 10% or better, depending on the elements concerned.[24]

Identification of stone constituents other than those determined by neutron activation analysis was accomplished by subjecting several Parisian quarry fragments to dispersive X-ray fluorescence spectrophotometry.

The magnesium oxide concentration was determined by atomic absorption spectrophotometry for six Val-de-Grâce quarry specimens, three from the rue Claude Bernard gallery, and three from the gallery beneath the Church of Saint-Jacques du Haut-Pas.

To identify the crystal structure (i.e., minerals) of the limestone from the Val-de-Grâce quarries, X-ray diffraction analysis was carried out on one fragment from the rue Claude Bernard gallery and two from the gallery below the Church of Saint-Jacques.

Acknowledgments

The authors would like to thank Dr. Pieter Meyers for suggesting this project and participating in its initial stages.

We are indebted to the persons and institutions who

20. *Radiance and Reflection: Medieval Art from the Raymond Pitcairn Collection [in the Glencairn Museum]. Exhibition Catalogue* (The Metropolitan Museum of Art: New York 1982) catalogue entry no. 22.

21. R. L. Bishop, G. Harbottle, and E. V. Sayre, *Chemical and Mathematical Procedures Employed in the Maya Fine Orange-Fine Grey Ceramic Project. Peabody Museum Memoir* 15, No. 2 (Harvard University: Cambridge, Massachusetts, 1980).

22. Sayre, op. cit. (in note 1).

23. Approximately 30 mg of each of the following standards were used: United States Geological Survey rock standards PCC-1, GSP-1, DTS-1, BCR-1, AGV-1, G-2, and National Bureau of Standards Argillaceous Limestone No. 1A. The strontium oxide concentration in argillaceous limestone, determined by atomic absorption spectrophotometry by E. N. Norton at Brookhaven National Laboratory, is 0.220%.

24. Garman Harbottle, "Provenience Studies Using Neutron Activation Analysis: the Role of Standardization," *Seminar on Ceramics as Archaeological Material, Sept. 29-Oct. 1, 1981* (Smithsonian Institution Press: Washington, D.C. 1982).

so generously provided stone fragments or permitted the sampling of objects in their care: Mr. Marc Diré and Mr. C. Lorenz of the Equipe d'Histoire des Sciences et des Mouvements Intellectuels of the Université de Paris I, Panthéon-Sorbonne, who provided the fragments of Parisian quarry stone that formed the nucleus of this study; Rev. Martin Pryke of the Glencairn Museum, Bryn Athyn, Pennsylvania, who gave permission to sample Romanesque sculpture in its collection; Mr. Eugene Farrell, Chief Conservator of the Fogg Art Museum, Harvard University, who sent specimens of stone from the museum's Moutiers-Saint-Jean columns; and Mr. Jack Soultanian, Chief Conservator of the Isabella Stuart Gardner Museum, Boston, who provided several samples.

Special thanks are due to Dr. Ronald L. Bishop for helpful discussions at every stage of the analytical work, and to Messrs. Neil Stratford, Michael Hughes, and Andrew Middleton of the British Museum.

This work was carried out at Brookhaven National Laboratory under contract DE-AC02-76CH00016 with the United States Department of Energy.

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