Set in Stone: Provenance and Architectural Energetics for the Royal Charterhouse of Bourgfontaine

by

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Introduction

Introduction to the Site
The monastic site of Bourgfontaine was a Carthusian charterhouse founded between 1323 and 1325, by Charles of Valois and finished by his son King Philip IV. The Carthusian Order was and remains an ascetic monastic order that combines eremitism with community living. It was founded in the 11th century as a part of a wave of reformed monastic orders. Geographically, Bourgfontaine is located in the southern part of the modern Aisne department, deep in the Forest of Retz, one of the largest forests in France, about 80 kilometers northeast of Paris. This position, surrounded by forest and isolated from population centers, was ideal for the brothers who prioritize silence, isolation, and hard work to devote themselves to God. Geologically, the monastery sits above Oligocene era Lutetian Limestone bedrock, a 30-meter thick limestone deposit from which much of medieval and early modern northern France is built. Many smaller geological units make up this formation, each of which has different physical and chemical properties. Additionally, only some of these units posses good construction properties, mainly the Middle Lutetian limestone (Devos et al., 2010).

The close ties to the Valois family make Bourgfontaine a valuable example of royal patronage of monasteries but it has few written histories, and has had only limited excavations making any studies valuable to understanding how it functioned. Scholarship of Bourgfontaine that does exist is split between studies of Bourgfontaine’s historical documents and studies of Bourgfontaine
from the Valois perspective (Bonde & Maines, 2012). Most of the general information on the monastery comes from two major sources: a survey of Bourgfontaine’s history, site and holdings and original and copied historical documents. The historical documents describe the gifts that were made to the monastery and were catalogued and edited by Françoise Billotey and Lucien Marchand, both of whom analyze them from a monastic point of view (Billotey, 1948; Bonde & Maines, 2013; Marchand, 1953). In the late 19th century, abbé Poquet completed a broad study of the monastery, including the site’s history and description for the first time and lists and maps of the monastery’s holdings throughout France (Poquet, 1879). More recently, Sheila Bonde and Clark Maines completed a set of studies that focus on what made the site so unique, namely its royal patronage and robust water system (Bonde & Maines, 2012). To compliment historical records and further investigate their questions on the site, the two have led five field studies and surveys from 2006 to 2016.

Due to time and sacks during the Wars of Religion and the French Revolution most evidence of the Valois patronage at Bourgfontaine is found in historical texts. Those historical texts, however, show that the Charles, Philip VI, Jean le Bon, and the following kings truly treated Bourgfontaine in a manner typical of a royal foundation. Women in the Valois family also contributed. As the founder, Charles already invested a great deal of money into the monastery, gifting land and annual rents to the brothers. He additionally gifted his personal relics of St. Martin to the brothers. Charles’ son, King Philip VI, continued with his father’s generosity through re-gifting the monastery and the lands to the
brothers and finally giving his heart to be interred in a tomb inside the church (Bonde & Maines, 2013). Although the tomb does not survive today, its last location is assumed to have been to the east of the choir in an attached shrine after the original tomb and Philip VI’s heart were desecrated during the Wars of Religion. Evidence of this building can be seen in the cavalier view of the monastery painted by Louis Licherie. This eastern addition to the church was excavated and dated on the basis of material and written evidence to ca. 1570-1600 in 2015. Amateur excavations of the church interior have returned no evidence of the tomb. An important iconographic document is an eighteenth-century watercolor of a wall painting on the interior of the west façade that depicted Charles and Philip VI presenting a model of the church at Bourgfontaine to Saint Louis of Toulouse.

The excavations of Bourgfontaine focused on the remains of the Great Cloister and the monastery’s church. The church is a simple monastic church, with walls of dressed limestone masonry and a two-course foundation that consists of mortar and grès roussard, as revealed by excavation. Attached to northern side of the church between the nave and the choir is a large square tower and its associated stair turret both of which were built contemporaneously with the church. A later addition to the church was made during the Renaissance (between 1580-1600) in the form of a chapel which was discovered through excavation and whose date is secured on the basis of style

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and some documentation. For the purposes of this study, I will be focusing purely on the first phase of construction of the church and tower. The Great Cloister was the center of the monastery, containing the brothers’ cemetery and main fountain and ringed by the canons’ individual cells, an access alley, and finally the main fortification wall. All that survives above ground today is the fortification wall, although the toll of time and reuse is evident in the multiple breaks along its length and the stubby ruins of what were once fortified towers.

Excavations in this area focused on studying the layout of the cloister and the site-wide water system. The excavations approach the layout in both the general spatial associations between communal spaces and the specific design of a single cell to better understand how a brother moved through their spaces and, when allowed, interacted with one another. With the survey of Bourgfontaine’s water catchment and delivery system complete, Bonde and Maines continued their work by adding to what is known about the distribution of water within the great cloister during the summer of 2015.

The locations of the excavated trenches were planned on the basis of a radar survey, several test trenches, and crops marks recorded during a severe heat wave. These records were complemented by a rather unique document related the Bourgfontaine Charterhouse- a cavalier view of the site painted by Louis Licherie. The Carthusian Order commissioned the painting as a way of documenting the complete site and it shows the entire monastery. Although not painted to any scale, the painting offers the best information as to what scholars think the site looked like in the seventeenth century.
With such a small body of known historical documents, limited excavation results, and no certain plans for further excavations, it is vital to turn to alternative analyses to learn more. By completing this study of stone provenance and architectural energetics, I will be able to hypothesize about how the monastery was built and further the understanding of the areas in which we see the Valois patronage of Bourgfontaine.
Figure 1- View of Bourgfontaine Charterhouse painted 1686 by Louis Licherie.
Introduction of Provenance and Energetics
The role of modern archaeologists is no longer simply to excavate sites and collect artifacts, but to understand how each artifact, feature, and site fits into the past. To do this archaeologists have expanded their investigations beyond material culture and excavation into scientific analyses and broader site and region analyses to understand how the past was connected economically and culturally. Such investigations can use a variety of geological analyses to collect, quantify, and compare data to other sites and to historical narratives. Artifact spreads (scatters?) and, stable isotopes taken from freshwater sediment cores across Michigan were used to redevelop ideas of effects of massive climatic changes on Paleo-Indian groups in North America (Kleiven et al., 2008). The elemental compositions of Polynesian stone tools helped to map Pacific island voyaging networks and inter-island trading (Rolett, West, Sinton, & Iovita, 2015). In addition to geology, energetics, the study of energy under transformation, has been utilized in archaeology to quantify structures based on the amount of labor their construction required. When combined with architectural history, energetics becomes architectural energetics, which has been used internationally to study Roman baths (DeLaine, 1997) and Mayan cities (Abrams, 1994). This study is a combination of these analyses, using geology to determine samples compositions, comparing them to possible source quarries, and estimating the amount of time needed to construct the monastic church at Bourgfontaine.
Provenance

Provenance refers to the full record of ownership or location of a historical object or artifact. It is typically used to refer to the ownership of works of art, for example the National Gallery has the complete provenance for Titian’s ‘Diana and Actaeon,’ tracing the painting from its creation to the time when it was donated to them. In archaeology, provenance studies are created from research into the origin of an object or material and the implications of its deposition at its find location. This is typically done by determining the chemical, elemental, or isotopic composition of a sample and finding other samples with matching compositional fingerprints, which can be done with organic and inorganic samples (Pollard, 2008; Willmes et al., 2018). Archaeologists and anthropologists use the isotopic compositions of human bones to trace mass migrations and reconstruct human diets (Rasmussen, Bjerregaard, Gommesen, & Jensen, 2009). Art historians analyze the compositions of paintings and statues to authenticate their ages and help determine the material source (Meredith, 1994). Architectural historians research the provenance of the building stone of churches, castles and other buildings for two reasons: to find a suitable stone for restorations and repairs and to understand the economics of the building’s construction (De Kock et al., 2015; Lecuit et al., 2018; Malfilatre et al., 2012). Building on this foundational research, this study explores the provenance of the stones used at Bourgfontaine as a way to further examine the effects of royal patronage on site construction.
Architectural Energetics

The study of architectural energetics is the study of the quantification and transformation of energy as related to human construction. In this subfield, the study of the transformation of energy shifts focus away from joules, watts, and ergs and instead uses person/days, cubic meters and currency. These studies examine the time, materials, and compensation necessary to build the structures of the past and what these projects can tell us about the human societies that created them. In Mesoamerica, archaeologists used energetics to understand the labor necessary to build Mayan cities, how residence styles reflect socio-economic status, and what housing trends tell us about their society (Abrams, 1984). The study of Roman public works can evaluate the monetary and social costs, the approval that each project would yield, and how it may have changed the public’s view of emperor who commissioned it (DeLaine, 1997). As our understanding of the buildings and framework of society increases, we are better able to reconstruct narratives of the past that can be compared to those recorded in historical documents.

In order to study a structure’s energetic requirements, one must take into account a range of variables related to the construction and labor of different buildings. Values for these first variables are found away from the construction site as one accounts for the acquisition, transportation, and refinement of the raw materials such as stone, sand, timber, and water. The more “basic” variables, such as quarrying time and transport capacity, often have few associated historical records requiring archaeologists to use ethnographic parallels and experimental studies. These variables are highly dependent on the
contemporary tool technology, as the amount of energy a human can output in a
day remains constant while the efficiency of his tools changes. After learning
about the tool technology used in a study, it is crucial to convert the values based
on any differences in tool technology.

As the construction progresses and the supply variables are completed,
research focus returns to the site. Modern survey plans and excavation results
 supplement historical records of phasing and construction timing and associated
costs. Finally, the most human element, labor, is estimated using historical
calendars and building accounts, which are again supplemented by experimental
studies. Finally, the complete energy cost of the structure can be estimated and
compared to the cost of other structures, allowing archaeologists to infer the
wealth of the patrons and how such structures fit into past societies.
Provenance Analysis

Literature Review
Determining the provenance of stone construction materials is a vital part of rebuilding past trade networks (Rolett et al. 2015), understanding economic and social implications of supplying building materials (Antonelli et al., 2001; Fichera et al., 2015; Barba et al., 2009), and restoring buildings (Lecuit et al., 2018; Malfilatre et al., 2012). As archaeologists began to look into the movements of goods in the past, it became necessary to establish a way to match material sources, such as quarries, to the sites or artifacts wherein they were used. Currently, studies approach provenance questions through geochemistry, analyzing stone samples with neutron activation analysis (NAA), x-ray fluorescence (XRF), or laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) (Fichera et al., 2015; Holmes et al., 1986; Rolett et al., 2015). Geoarchaeologists also use petrography to find defining inclusions in the stone and this analysis is frequently paired with geochemical analyses to help provide more information on samples and support the geochemical findings (Lecuit et al., 2018).

Each scientific method offers its own challenges. XRF analysis is relatively fast and inexpensive but only determines concentrations to the parts per million; NAA gives concentrations in parts per billion, which requires takes weeks to complete and access to a nuclear reactor. Finally, LA-ICP-MS is able to rapidly measure elemental and isotopic concentrations but the cost of running the machine is very high. This study utilizes the wavelength dispersive XRF to determine the elemental composition of all collected samples. The XRF uses energy in the form of x-ray photons to excite
the electrons in the sample. The photon is released by the machine and hits an inner-orbital electron, knocking it anyway and triggering its replacement by an outer-orbital electron, which results in a release of energy. The energy released is equivalent to the difference in binding energy between the outer-orbital and the inner-orbital. Since the energy requirements of each orbital are known for each element, this emission, or *fluorescence*, acts as the fingerprint of an element and allows us to determine the composition of samples (Glascock, 2011; M. Steven Shackley, 2011). By using the XRF analysis, this study sacrifices some of the accuracy that could have been achieved in favor of faster, and cheaper, results. This choice was made considering other experiments that used the XRF to analyze limestone, which found that the elements analyzed are have observable concentrations in parts per million.

**Sample Analysis Methods**

The first step in this study was to collect samples. Over the summers of 2017 and 2018, Dr. Bonde and Dr. Maines collected small stone samples from the walls of the monastic church, the fortification wall surrounding the Great Cloister, and 2 architectural fragments. Both fragments belonged to the cloister arcade surrounding the Great Cloister- one fragment came from a capital block while the other was taken from a block of a pier. Dr. Maines and Dr. Bonde took these samples responsibly; using the backs of the blocks thus preserving the sculpted faces. To preserve the integrity of the stone from the church, samples were only taken from blocks that had fissures in them. These samples represent the entire assemblage taken from the Charterhouse of Bourgfontaine.

Dr. Bonde and Dr. Maines also collected three samples from regional quarries.
Two samples were taken from the quarry at Oigny-en-Valois, a hamlet located approximately 6 km away from Bourgfontaine. The last sample was taken from the Carrière de Noyent, sometimes called le carrière l’évêque, which is an active limestone quarry located in Septmonts, [distance between Septmonts and BF]. The samples were mailed from France to the United States before being transported to Wesleyan University.

After deposition at Wesleyan University, the samples were cleaned and examined for distinguishing characteristics. One sample from Oigny-en-Valois and one sample from the cloister fortification wall were slightly covered by a black weathering crust. This crust was removed using a rock saw and rock hammer. After cleaning, the samples were crushed in a two-step grinding process. The first step was to break the cobble-sized samples into smaller pieces using a small rock crusher. Second, the now pebble-sized sample was run through a shatter box. This machine uses oscillatory motion with weighted components to grind stone into a fine powder.

Next, 8 grams of the powder were measured using an electronic scale with 0.001-gram precision. Once a mass is properly measured in whole grams, the powder is transferred to mortar with a number of wax pellets equivalent to the mass in grams. Using the mortar and pestle, the mixture is homogenized into a fine powder of wax and stone dust. This powder is transferred into a small aluminum dish and pressed by a 15-ton hydraulic press into a compact briquette. The compact briquette is the sample’s final form; the compact stone and wax mixture is the perfect consistency for the XRF to analyze. Inconsistencies in surface texture, particle size, or homogeneity of the sample will result in inaccurate measurements (Glascock, 2011).
Finally, the briquettes are placed in the XRF machine and irradiated. This determines the elemental abundance by using the secondary x-rays that the elements fluoresce when irradiated. The Bruker WXRF software at Wesleyan University automatically measures the wavelengths and amplitudes and outputs a data table eliminating the error involved in human readings of the reflectance wavelengths.

After the analysis is complete, the XRF outputs a data table of the elemental values (Sc, TiO₂, V, Cr, MnO, Fe₂O₃, Co, Ni, Cu, Zn, Ga, As, Rb, Sr, Y, Zr, Nb, Mo, Sn, Sb, Cs, Ba, La, Ce, Pb, Th, U). These values are still in a raw form and must be converted in parts per million for easier comparison. Most values are output as elemental components, so the conversion is simple; however, the elements Fe, Mn, and Ti are output in a percent weight/oxide form. These elements require a more in-depth conversion to parts per million (PPM).

**Digital Data Collection Methods**

To check the findings of this study against other limestone studies, the elemental concentrations were compared to the quarry sample data at the Limestone Sculpture Provenance Project website. The LSPP uses neutron activation analysis to analyze the major elements (Rb₂O, Cs₂O, CeO₂Cr₂O₃, MnO, Fe₂O₃, CoO, UO₃, ZrO₂, SrO, …) in the limestone. Using the conversion methods from before, this data was added to comparison with the quarry data from Oigny-en-Valois and Septmonts. This data offers a good comparison between limestones from quarries potentially in use in the regions surrounding Bourgfontiane.
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<td>1.85</td>
<td>0</td>
<td>0.93</td>
<td>0.95</td>
<td>1.9</td>
<td>0.95</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Figure 2: This table shows all of the elemental compositions of each sample in PPM as calculated by the XRF. "C" = Church samples, "CLE" = Carrière de l’Évêque sample, "MF" = mur de fortif, "T" = Tour Valois, "OV" = Oigny en Valois, "BF" = misc. Bourgfontaine samples from the grand cloister. The red text sample numbers indicate samples from quarries, while blue represents samples from the monastery.
<table>
<thead>
<tr>
<th>Sample Site</th>
<th>Oigny 2A vs. BF R-Squared</th>
<th>Oigny 1B vs. BF R-Squared</th>
<th>Carrière de l’Évêque R-Squared</th>
</tr>
</thead>
<tbody>
<tr>
<td>Church 1C (C1C)</td>
<td>0.964</td>
<td>0.999</td>
<td>0.91</td>
</tr>
<tr>
<td>Church 2C (C2C)</td>
<td>0.959</td>
<td>0.996</td>
<td>0.929</td>
</tr>
<tr>
<td>Tour Valois (T1C)</td>
<td>0.985</td>
<td>0.996</td>
<td>0.907</td>
</tr>
<tr>
<td>MF1A</td>
<td>0.952</td>
<td>0.972</td>
<td>0.976</td>
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<tr>
<td>BF2A</td>
<td>0.956</td>
<td>0.973</td>
<td>0.974</td>
</tr>
<tr>
<td>BF3A</td>
<td><strong>0.994</strong></td>
<td>0.98</td>
<td>0.863</td>
</tr>
<tr>
<td>MF4A</td>
<td><strong>0.995</strong></td>
<td>0.985</td>
<td>0.874</td>
</tr>
<tr>
<td>MF5A</td>
<td><strong>0.986</strong></td>
<td>0.953</td>
<td>0.799</td>
</tr>
</tbody>
</table>

Figure 3: This table shows the R-Squared values of each site sample in relation to the quarry samples from Oigny en Valois and La Carrière de l’Évêque. Each sample has a fairly clear match with a quarry, the exceptions being BF2A and BF3A which correlate strongly to sample 1B from Oigny-en-Valois and the sample from the Carrière de l’Évêque.

**Results**

The results of each sample can be seen in Figure 2. Considering the range of elements that this analysis yields, I deemed it necessary to analyze the values on a broader platform than PPM fluctuation for each element. To do this, I used R-Squared values comparing the samples taken from Bourgfontaine to the samples taken from Oigny-en-Valois and the Carrière de l’Évêque. These values are calculated by graphing the site sample elemental concentrations against the quarry sample elemental concentrations. A trend line is then set to the graphed points and depending on how well the line fits the data (how far off the line each point is) the $R^2$ value will increase or decrease. If all of the points fall perfectly on the line, then $R^2 = 1$ so the closer to 1 the Bourgfontaine $R^2$ values are, the stronger the correlation between the site sample and the quarry sample. Strong correlations are indicative of a
connection between the samples, suggesting that they may be from the same quarry or the same formation. As seen on the table, the $R^2$ values for many of the Bourgfontaine samples show a close connection to the Oigny-en-Valois quarry. The graphs can be viewed in the appendix and the R-Squared values can be viewed in Figure 3.

The samples taken from the church walls and the wall of the Tour Valois [samples C1C, C2C, and T1C] show a very strong correlation (0.999, 0.996, 0.996) with the Oigny-en-Valois sample 1C [OV1C]. A sample taken from the fortification wall and the sample of the cloister arcade pier [MF1A, BF2A] both correlate most strongly (0.976, 0.974 respectively) to the quarry sample from the Carrière de l’Évêque [CLE]. These samples also have a slightly weaker correlation (0.972, 0.973) to the Oigny-en-Valois sample 1C [OV1C]. Finally, the samples taken from the cloister arcade capital, southeast fortification tower, and southeast fortification wall [BF3A, MF4A, MF5A] correlate strongly (.994, .995, .986) to the Oigny-en-Valois sample 2C [OV2C].

**Discussion**

During a cursory glance, the R-Squared values for samples MF1A and BF2A are somewhat confusing. They show that these samples match stone quarried 24 kilometers (15 miles) away from Bourgfontaine better than they match stone quarried 5 kilometers (3 miles) away. To better understand why the builders may have shipped stone from so much further away it is necessary to look at the context in which it was used, the context in which it was quarried.

The limestone of Bourgfontaine is a fine grain, soft, and friable limestone making it less than ideal for any building or sculpting project. An example of its
softness can be seen in the nave walls were wind and water have massively eroded the structure, which has received modern repairs to maintain structural integrity. The monks’ willingness to use this subpar stone as a main construction material likely speaks to their dedication to the Carthusian vows of poverty, which would dictate that they use the least expensive material available. During this time period, the cost of transporting stone over 12 miles from its source likely exceeds the cost of the stone itself, especially when transported by cart as opposed to riverboat (Bond, 2003).

Given the softness of the stone from Oigny-en-Valois any elaborate sculpting would require the brothers import better carving stone, which could justify the transportation cost from the Carrière de l’Évêque. Unfortunately, if the construction of Bourgfontaine follows the same layout seen at all other charterhouses, there would be no need for elaborate carving. Additionally, the brothers used the Carrière de l’Évêque stone as a general building material in the fortification wall and a pier of the great cloister rather than reserve its use for capitals or other more sculpted pieces. The general use suggests that the brothers did not have a choice and had no other alternative stone to use, possibly because all the stone from the quarry at Oigny-en-Valois had already been quarried. This hypothesis can also be disregarded as we seen use of stone from Oigny-en-Valois in the cloister arcade capitals and in other parts of the fortification wall. So unless workers worked to build the cloister and the fortification wall simultaneously it is unlikely that both structures would be built with both stone from Oigny-en-Valois and the Carrière de l’Évêque. In order to
better understand how seemingly random stones could be from different
 quarries, we must utilize the geological context of the stone.

The bedrock of the southern Aisne is limestone that formed during the
Eocene and Oligocene. As time went on, the sea that formed the limestone grew
and shrank, leaving younger bedrock on the surface as you travel to the south.
The plateaus and hills immediately surrounding Soissons, such as the one the
Carrière de l’Évêque sits atop, are made up of Lower and Middle Eocene
limestone. Travelling south towards Oigny-en-Valois, the limestone formed in
the Lower/Middle Eocene is buried by limestone formed in the Upper Eocene
and Lower Oligocene. When these deposits were first formed, the Principle of
Horizontality reigned supreme leaving each bed stacked one on top of the other.
As time past, tectonic uplift and erosion carved through these beds, exposing the
lower older beds in outcrops. The quarry at Oigny-en-Valois is a tunnel quarry,
meaning it tunnels into an outcrop following a bed of limestone. Using an
estimated location on a bedrock geology map of the Aisne, it seems the outcrop
at Oigny-en-Valois may have both Oligocene and Eocene limestone exposed. This
is in contrast with the Carrière de l’Évêque, which is an open pit quarry,
excavating stone from the top of the plateau on which it sits. On the same
bedrock geology map, the Carrière de l’Évêque likely sits on top of Middle
Eocene limestone. Therefore the stones that are excavated from Oigny-en-Valois
may be from the higher Oligocene bedrock or the buried Middle Eocene bedrock
while the stones from the Carrière de l’Évêque are from the Middle Eocene.
Because both sites sit on top of Middle Eocene bedrock it is possible that instead
of the Middle Eocene stone being quarried and transported from Carrière de l’Évêque, it is the same Middle Eocene stone quarried at Oigny-en-Valois. To provide more support for equivalent bedding hypothesis, I used the bedrock map and the Limestone Sculpture Provenance Project quarry database to hopefully find more Middle Eocene samples from the Aisne.

The LSPP collected and analyzed 41 total samples from 6 quarries in the Aisne region (see Appendix V: Map I). The closest of these quarries is the Carrière de l’Évêque, which, as discussed above, makes it unlikely that any of them acted as a source quarry for Bourgfontaine. The samples from these quarries can however, be used to support the equivalent bedding hypothesis stated above. Using the same Aisne bedrock map, I compared the bedrock age at each LSPP sample quarry to the quarry at Oigny-en-Valois to see if which quarries utilized the same formations. This comparison showed that 3 quarries in the Aisne likely mined the same formations: la Carrière de Vassens, la Carrière de Berny-Rivière, and have course, la Carrière de Noyant (la Carrière de l’Évêque). The quarries at Vassens and Noyant-Septmonts both sit on the Middle Eocene formation, while the quarry at Berny-Rivière sits on the Middle Eocene/Lower Eocene formation border (see Appendix V: Map II, Map III).

This quarry positioning becomes even more apparent when the compositions are plotted against each other using the same R-squared comparison methods I used for the monastery samples. The first plot had to be the values from the Carrière de l’Évêque (CLE) and the four samples from Noyant-Septmonts that the LSPP had composition values for. Before analyzing
the data, I thought the samples should match well since they were both taken from the same quarry and the same formation. When analyzed the R-Squared values were very high- 0.94638 was the lowest value of the four LSPP samples [LHA316a, LHA419, LHA420, LHA421]. The samples LHA419 and LHA421 correlated strongly (see Figure 4), which is indicative of a match, a theory supported by the sampling site descriptions the LSPP provides. LHA419 was taken from the “top of the banc franc” (“Frankish Bank”), which is a type of young Lutetian Limestone (Vázquez, Menéndez, Denecker, & Thomachot-Schneider, 2015), while LHA421 was taken from a loose block. Since the stone are such a close match, it seems likely that the loose block was taken from the top of the banc franc and placing the origin of both stones at the top of the quarry in what is marked Middle Eocene Limestone.

<p>| Carrière de l'Evêque vs LSPP Carrière de Noyent-Septmonts R-Squared Values |
|-----------------------------|-----------------------------|</p>
<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Carrière de l'Evêque R-Squared</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHA420</td>
<td>0.94638</td>
</tr>
<tr>
<td>LHA316a</td>
<td>0.95893</td>
</tr>
<tr>
<td>LHA419</td>
<td>0.99629</td>
</tr>
<tr>
<td>LHA421</td>
<td>0.99568</td>
</tr>
</tbody>
</table>

Figure 4- Comparison between sample from Carrière de l’Évêque and Carrière de Noyent. The R-Squared values help determine which Lutetian layer the Carrière sample is from and indirectly which Lutetian layers are seen at Bourgfontaine.

The next plot compared CLE and the five samples from Vassens quarry. The lowest R² value from the graphed trend line was 0.9965 (see Appendix IV),
again showing a very strong match between the two sample locations. The sample site description of the Vassens quarry is straightforward but vague; the researchers sampled five blocks outside of the quarry. These blocks are from unspecified depths in the quarry, however the strong correlations between the samples suggest that they below to the same formation. The Aisne bedrock map places the quarry on Middle Eocene limestone and the bedrock map from (Devos et al., 2010) places the quarry on Lutetian course limestone supporting the hypothesis of equivalent bedding.

The samples taken from the quarry at Berny-Rivière, more specifically the quarry at ferme Confrecourt, show the amount of variation that occurs in these limestone formations. Of the twelve samples taken from this site, only two had $R^2$ values above 0.99, with the majority of the other being in the low 0.90’s and as low as 0.79. According to the sample site description given by the LSPP, the two samples with $R^2$ values greater than 0.99 were both taken from the banc royal or “royal bank” which is an older Lutetian formation than the banc franc (Gély, 2009). On both bedrock maps, this site is located on, or close to, the border between Middle Eocene and Lower Eocene formations. Indeed the LSPP has multiple sample location on two different formations, banc royal and calc coquillier, showing that the quarry straddles the border and workers extracted stone from both layers. The $R^2$ differences seen in these samples provide evidence that not all of the limestone is so nicely correlated as those samples from Noyant-Septmonts and Vassens.
The final quarry comparison quantified the correlation between CLE and stone from the quarry at Courville. This comparison once again showed the variation that can occur in these limestone formations. The Aisne bedrock map did not extend far enough to provide information on the Courville quarry and the map from Davos et. Al., 2010 shows it as Lutetian Limestone. The broadness of “Lutetian Limestone” is shown by the LSPP sample site descriptions of Courville where three different strata (petite banc, Liais, and “roche.”) are described. These strata intersperse the previously stated banc franc and banc royal offering a more complete view at the composition of Lutetian limestone. Despite being closely related stratigraphically, the R² values show them as rather distinct, all of the R² averages of the strata are less than 0.88, the lowest of any of the analyzed quarries. The differences between these R² values and the R² values from other quarries shows how different each strata making it even more likely that the samples from Vassens and Noyant-Septmonts were extracted from the same layer as CLE. It should also be noted that because of the different compositional analysis methods used by the Limestone Sculpture Provenance Project, comparisons made with LSPP samples have half of the data points of purely Bourgfontaine sample comparisons.

While the R² values of MF1A and BF2A originally suggested that the stone’s origin could be the Carrière de Noyant (Carrière de l’Évêque), when taken in full context this idea falls apart. The architectural context for the samples was that of a common ashlar block, with no intricate carving or specialty function aside from bearing weight. The geographical context places
Oigny-en-Valois a fourth of the distance from Noyant-Septmonts to Bourgfontaine, making it the far less expensive source. Finally, the geological shows that there are many strong correlations between different quarries in the Aisne, meaning there is a continuous limestone formation that both Oigny-en-Valois and Noyant-Septmonts use. If the same quality stone is extracted from quarries 6 km away, 24 km away, or 29 km away the stone will be taken from the nearest- Oigny-en-Valois. Now that we have established the location of the quarry the brothers used, we can determine how long it would have taken to transport the limestone from quarry to site.
Architectural Energetics

Building the charterhouse of Bourgfontaine, like the building of Rome, did not happen in a day. It likely took years of dedicated effort, and time, from quarrymen, carters, freemasons, rough-masons and other laborers to transport, work, and finally place the stones that make up Bourgfontaine. Using architectural energetics, it is possible to understand how much effort went into constructing the monastery. This study will focus on the church, a simple, unvaulted hall terminating in a polygonal apse.

Background and Methodology

Source of Power

The first variable that must be valued concerns the provision of power for transportation of stone. Primarily, which of the two draught animals available, horses and oxen did the carters use? In the 14th century choosing between horses and oxen is difficult: the horse has superior endurance and draught, while the ox requires much less maintenance and food (Engels, 1978; Langdon, 1982). An ox only requires straw and pasture to be fed properly while to feed a cart horse properly one must grow or buy oats which will cost more than 3 times the money needed to feed an ox (Langdon, 1982). The oxen yoke is a very basic device that causes few problems for the animal and allows carters full access to the power of the beast. When fitted with the same or similar yoke, a horse loses power because as the horse tries to pull a load, the yoke presses on its trachea and jugular, straggling and severely limiting the power output from the animal.
(White, 1962). Instead, horses must be fitted with horse collars that wrap around the shoulders and waist. In addition to needing more expensive food and more specialized harnesses, horse hooves grow weak when faced with soggy conditions, such as those seen in northern Europe, increasing wear and risk of damage (White, 1962). Such conditions create a need for horseshoes that increase still further the cost of using horses as draft animals.

Unlike horses, oxen are low maintenance and have always been used as draught animals. During his lifetime, the medieval chronicler Guibert of Nogent recorded use of oxen as draught animals in the 12th century construction of Laon Cathedral. The record is of a miraculous event where an exhausted ox collapsed, stranding a cart of stone on the climb to the cathedral when from nowhere an ox appears and helped pull the cart to the cathedral site. Afterward, the ox was unyoked and walked back from whence it came. After this miraculous event, its likeness is preserved in sculpture in the towers of the cathedral it helped build (Guibert, 1970). In the rural countryside, draught animals are an investment from the beginning to the end it is important that their owners are able to make money using them. In the 14th century, a horse at the end of its life is useless while an oxen can be set to pasture and slaughtered for meat making even its death something that can be profited from, which is why they were a much more popular rural draught animal (Langdon, 1982). Looking ethnographically at modern day rural societies, oxen continue to be used as draught animals in areas such as rural forests and small-scale farms, because of their strong, steady, and hardy nature (E. Otavo Rodriguez, 1986; Tess Taylor, 2011). Lower costs, lower
maintenance, and a wider spread use all make it seem plausible that teams of oxen instead of horses were used to haul the stone from Oigny-en-Valois to Bourgfontaine.

There are no known documents recording the weight of adult oxen in France of the 14th century. To address this problem, I created an estimated weight compared to modern oxen, which weigh between 400-900 kg depending on the breed. The estimate of the medieval ox must take into account the dramatic increases in weight caused by selective breeding and better diet during the agricultural revolution. Taking these increases into account I estimate the weight as 350 kg, or somewhat less than half the weight of today’s largest breeds. The draft capacity of an animal is decided by how much weight it is able to drag behind it at a walking speed. Full-grown oxen have a draft capacity of 10-14% of their body weight, which for a 350 kg ox means 35-49 kg of draught. Using this estimated weight, the calculated draft power for a team of two animals is on 81 kg, less than expected due to the fact that as you harness more animals together the individual power of each animal decreases (Peter R. Watson, n.d.). Estimating the speed of the oxen over rolling hills with varying road conditions is difficult so for the purposes of this “dirty model” those factors are ignored. The speed I used comes from a work that describes the energetics of logging with oxen, wherein the author estimates that an ox hauling a load 12% of its body weight will move 3.5 kilometers per hour over flat ground (E. Otavo Rodriguez, 1986). Using these variables we have estimated that the oxen used in the construction of Bourgfontaine weighed 350 kilograms, had a pair draught
capacity of 81 kilograms and could move, fully loaded, at a speed of 3.5 kilometers per hour.

**Vehicles for Transport**

The second variable is the vehicle used to transport the stone. Luckily, there are sources contemporary with Bourgfontaine’s construction that show building materials being transported in carts (Binding, 2004; Camille, 1998). These images depict the use of large two-wheeled carts and four-wheeled wagons in even numbers, making it difficult to draw any conclusions about the specific cart used at Bourgfontaine. Instead, we must think of the context in which these vehicles would be used and the design of the two vehicles. The four large wheels of a wagon provide a steady platform to load and carry goods but require a larger, and therefore heavier, frame for proper support. Similar large wheels and a set back axle characterize the typical two-wheeled cart, also called a tumbrel or bullock cart. The set back axle in a tumbrel allows for easy unloading of the cart since the draught animal can be unhooked and the load can slide from the back. Examples of these carts can be seen in historic and modern agricultural use, as well as images from the French Revolution as tumbrels were frequently used to transport prisoners to execution. The large wheels of both vehicles would allow them to roll over holes or ditches, while the compact design of the tumbrel decreases the weight of the cart allowing for more cargo per load. If transporting a large amount of goods over a great distance, a wagon’s steady platform and larger bed makes it the best option, as seen during the Western Expansion of the United States. But, to transport stone short distances
on rural dirt roads, a two-wheeled cart’s lighter design and set back axle make it the most efficient option.

A second issue concerning the stone transport vehicle is size. While trying to calculate the weight and draft of our two-wheeled wooden cart, I once again ran into the problem of documentation. It seems during the Middle Ages no one thought to stop, measure, weigh, and record their two-wheeled carts so once again I turned to historical and modern parallels for assistance. Historically, two-wheeled carts have been seen since the Middle Bronze Age and have traditionally been made out of wood or other plant materials. In the modern world, two-wheeled carts are used internationally in agriculture. In most places they are called “bullock carts” instead of tumbrels, so named after the draft animal that power most of them, bullock is, of course, another name for an oxen. Presently, these carts’ frames and wheels are made of some combination wood and metal, the former of which can be used as a parallel to the medieval purely wooden carts. In India, farmers still rely on bullock carts to transport the majority of their goods, which drove a Masters engineering student to write a dissertation on what improvements can be made to the design of the carts. In the dissertation, “Status of Bullock Carts and Comparative Evaluation of Different Types of Cart Available in Chhattisgarh Plains,” the author weighed different carts and calculated their draught. The measurements for the wood-wheeled wood-frame cart can be seen in Figure 5.
The table shows that at tare weight, meaning when the cart has no added weight, the cart has a draught of 22.45 kg. By subtracting this draught from the estimated draught capacity of the oxen, I found that the oxen had 58.55 kg of draught capacity left for the payload. Using this data, and the rest of the draughts from the table, I created plotted payload vs. average draft and calculated the trend line equation, which I then used to calculate the payload size for a draft of 81 kg (see Figure 6). In total, using a wooden framed, wooden wheeled cart the oxen can carry a maximum of 1815 kg per trip.

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Payload, kg</th>
<th>Average Draft, kg</th>
<th>Average Speed km/h</th>
<th>Average Power requirement, kW</th>
<th>Average wheel slippage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tare (350+60)</td>
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<td>3.67</td>
<td>0.23</td>
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<tr>
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<tr>
<td>CV</td>
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<td>5.89</td>
<td>2.43</td>
<td>-</td>
<td>4.52</td>
</tr>
</tbody>
</table>

Figure 5 - Table showing the measured values of a wood frame, wood wheels cart (Patre, 2016).
This figure shows the correlation between payload size (kg) and average draft (kg). The data comes from (Patre, 2016) measurements with wooden framed, wooden wheeled carts. After plotting the data and formatting the trend line, The R² value of the trend line showed such a strong correlation that I used the trend line function to calculate the payload for a draft of 81 kg and I have confidence that the calculated value accurately reflects what the actual value would be.

**Transportation Time**

With the transportation method and capacity fully realized, the next step was to assign values to transportation time. To start, we must know the position of the quarry at Oigny-en-Valois in relation to Bourgfontaine. I used Google “My Maps” to map the location of Bourgfontaine and the quarry of Oigny-en-Valois and used the “Add Directions” tool to measure the travelling distance on modern roads, which came out to 6.16 km. This calculation assumes error by using modern roads instead of historical routes or routes based entirely in terrain. I minimized the error in my map through a series of edits that were made to cut out small turns and to follow the contours of the land more closely. The edited route had a length of 5.77 km. Using the edited route distance of 5.77 km and 3.5
km/h as the approximate speed of the oxen cart (Rodriguez, 1986), it would take 1.65 hours to travel from Oigny-en-Valois to Bourgfontaine. I estimated it would take an hour to load or unload the cart, bringing the total one-way trip time to 2.65 hours and the round trip time to 5.3 hours. So, if each round trip journey from the quarry to the site took 5.3 hours, how many trips could be completed in one workday?

**Daily and Weekly Hours**

To answer this question it is no longer feasible to draw parallels between the modern and the historic worlds. Luckily, working hours in the Middle Ages were more widely recorded than oxen and cart weights which makes historical comparisons possible. The best comparisons in England come from chronicles of religious house, building accounts, and building contracts (Hislop, 2000). Each of these sources has benefits and drawbacks, for example chronicles focused more on the mason than the masonry he produced. The majority of building accounts from this period describe construction that was completed for the Crown and can provide detailed accounts of costs, including specific materials and laborers wages. Other documents, such as the Fabric Rolls of York Minster, provide the information of a chronicle, building account, and building contract in a series of documents and fabric rolls. These rolls provide the first system of fixed working hours in the 1370 *Masons’ Ordinances*, which I used as a basis to estimate the daily hours at Bourgfontaine (Knoop, 1967).
## Artois Work Accounts

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<tr>
<th>Seasonal Average</th>
<th>April 7th</th>
<th>June 21st</th>
<th>November 1st</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunrise</td>
<td>7:14</td>
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<td>7:35</td>
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<tr>
<td>Sunset</td>
<td>20:26</td>
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</table>

## Winter Daily Hours

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</tr>
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<tbody>
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<td>7:37</td>
</tr>
<tr>
<td>Sunset</td>
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<td>16:50</td>
<td>17:24</td>
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<tr>
<td>Total working hours</td>
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<td>7</td>
<td>8</td>
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## Masons’ Ordinances

<table>
<thead>
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**Figure 7:** This figure shows the sunrise and sunset times for the starting and ending dates of each work season according to the *Masons’ Ordinances* and the Artois work accounts (Knoop, 1967; Small, 1989). The sunrise/sunset times are provided by sunrise-and-sunset.com
The *Masons’ Ordinances* separates the year into two seasons, summer and winter, which each have a different set of working times associated with them. During the summer months, from the first Sunday of Lent to Michaelmas, workers had to be working from sunrise to 30 minutes before sunset with about 2 hours of breaks throughout the day for eating, drinking, and resting. In order to figure out the average hours of a summer workday, I looked up the sunrise and sunset times for the village of Villers-Cotterêts for the first Sunday of Lent in 1325 (February 24th), the longest day of the year (June 21st), and Michaelmas (September 29th) (Cheney & Jones, 2000). Using these times I calculated the working hours of those three days and averaged them to get an average summer workday length of about 11 hours. The *Masons’ Ordinances* sets the length of the winter workday to be from sunrise to sunset with 1.25 hours of breaks for eating, drinking, and rest. Based on this rule, I calculated the workday length using sunrise and sunset times from the day after Michaelmas (September 30th) the shortest day of the year (December 21st) and the day before the first Sunday of Lent (February 23rd). The calculation came out to be around 9 hours. This means that during the summer a single ox cart can make two trips, while in the winter a single ox cart can make 1.7 trips, which I rounded down to 1.5 trips.

Earlier I calculated the average seasonal workday hours based on the dates from the *Masons’ Ordinances* to be about 11 hours in the summer and 9 hours in the winter. I then used the Artois account rolls and the Vale Royal building account to estimate how many workdays there would be in each year. I then combine these calculations, using the hours from the *Masons’ Ordinances* to
make estimates about the hours worked during the seasons dictated by the Artois account. The *Masons’ Ordinances* and the Artois work accounts use seasons that are separated by about a month, which may cause a noticeable difference in daily hours, and eventually the amount of work that can be completed in a season. I wanted to quantify this difference in hours so I calculated the average seasonal daily hours using the Artois season shifts (Easter to Toussaint) and the *Masons’ Ordinances* season shifts (First Sunday of Lent to Michaelmas). The differences in sunrise and sunset times between two calendars do not make a difference; both calendars have an 11-hour workday in the summer and a 9-hour workday in the winter.

To properly approximate the length of the workweek we can again turn to historical employment and expenditure accounts for historical parallels. Documents similar to English building accounts exist in northern France where bailiffs, or *baillis*, were employed by the local aristocrat as chief local administrative officers charged with accounting for the expenditures of their area (Small, 1989). As such, the bailiffs recorded building expenditures and their records have become a great source of information on the conditions of labor in the region. The bailiffs recorded all of this on account rolls, which are still held by some regional archives. In her 1989 paper, “The Builders of Artois in the Early Fourteenth Century,” Carola Small studied the account rolls of the county of Artois from the reign of the Countess Mahaut (1302-1329) (Small, 1989). The breadth of this study allowed her to write about patterns of employment, including total working days and wages, for the approximate time period of...
Bourgfontaine’s construction. To provide some workweek comparison, I also used lengths recorded in construction records from Vale Royal and Beaumaris in England (Knoop, 1967).

The workweeks discussed in these sources all agree that workers had a five and a half day (5.5) workweek. There were some exceptions, at Thilloy in 1323 the master mason worked six days while the unskilled laborers worked only 4, but payment records indicate that 5.5 days was standard (Small, 1989). The differences between regions and sites arouse around the observance of feast days. These days were intended to be observances of certain saints’ days but may have simply been days off, either way there was no labor on performed. In Artois during 1312 workers observed 45 feast days (25 in the summer and 16 in the winter) during the working week which was the typical work calendar at the time (Small, 1989). Meanwhile, in England, during the construction of Vale Royal in the years of 1279 and 1280 workers had only 5 feast days with other time off around Christmas, Easter, and Whitsun averaging to 25 days total (Knoop, 1967). When calculating the number of working days per season and per year, I created two estimates from these records: one followed the Artois 1312 working year, and one that followed the Vale Royal 1279-1280 working years. During my research of the period contemporary with Bourgfontaine’s construction, these two records were the highest and lowest numbers of observances respectively.

Finally bringing the daily hour and workweek estimates together, I calculated both the amount of stone transported per season, in m³ and kilograms and the amount of time necessary to transport all of the stone used to build the
church to the site itself. I created two estimates for this time frame, one using the 1312 Artois feast day calendar (Small, 1989), and one using the 1279-1280 Vale Royal working calendar (Knoop, 1967). The 1312 Artois calendar is split into 33 weeks of summer with 29 holidays and 19 weeks of winter with 16 holidays, or a total of 241 workdays per year, 152.5 per summer and 88.5 per summer. During the summer months, using the estimate that a cart can complete 2 trips per day and carry 1815 kg (or 2.31 m³) of stone per trip, a single cart can transport 352 m³ of limestone per summer. In the winter, assuming that the cart makes 1.5 trips a day and carries the same amount of stone per trip, a single cart can transport 154 m³ of stone, leading to a yearly total of 506 m³ of limestone. Using the Vale Royal calendar, keeping the number of trips per day and amount of stone per trip constant, a single cart would be able to carry 359 m³ per summer and 186 m³ per winter, or 545 m³ per year in total. 

After completing the seasonal estimates, I moved on to calculating the total amount of stone in the church itself. I began by using a measured plan of the building. I calculated the total area of all walls, windows, portals, embrasures, and buttresses before trying to extrude these values into the third dimension and estimate the total volume of the church. To calculate volume I worked with site photographs and a height measurement from a south nave embrasure to the ground using coursing lines to approximate other heights. The total wall volume is approximately 1428 m³.

Of course, the church walls are not purely masonry and contain a rubble core in the middle making the total volume a combination of masonry and
rubble core. Considering the thickness of the walls averages out to 1.1 m, the assumed proportion of face-to-rubble would be about 2:1. To test this, I wanted to look at the broken parts of the church walls and determine the ratio of rubble vs. ashlar by calculating the area of each part and dividing it by the total. Unfortunately, modern restorations have covered the broken sections of the original wall to prevent further degradation, making any ruined sections unusable for my purposes. Instead I made the assumption that Bourgfontaine walls of the same thickness would have the same proportion of face stone vs. rubble I looked at photographs from around the site that show cross-sections of the fortification walls that surrounded the monastery and used ArcMap to outline the total area, the area of face stone, and the area of rubble core. By using ArcMap I could also retrieve the areas to calculate the ratios of face stone vs. total area and rubble vs. total area. I averaged all of these ratios to determine the most likely percentages of face stone and rubble that made up the walls, which came out to be 62.6% face stone and 37.4% rubble core. Applying these averages to the volume of the church I calculate that about there are 893 m$^3$ of face stone and 534 m$^3$ of rubble fill. Now that the composition and volume of the wall are known, we can start estimating how long it would take to dress the stone, create the fill, and finally build the walls.
Construction Begins

Measuring the Masonry
Before the walls can be erected, the stones must first be dressed; meaning at least 5 of the 6 sides must be squared off to create regular planes the regular planes needed for dressed masonry walls. This process requires a mason to handle each individual stone used in the church, and is likely the most time consuming step of construction; luckily, the stone from Oigny-en-Valois is soft which will speed the carving process. The majority of the dressing for masonry likely would have taken place at Bourgfontaine itself, with the stones being transported in a rough-cut form from the quarry. On the bumpy road from Oigny-en-Valois to Bourgfontaine, it is extremely likely that any pre-dressed stone would experience some sort of jostling that may render it unusable as wall masonry. This is supported by documentary evidence in the form of drawings and sketches that depict the construction of both religious and secular structures. Multiple images from Medieval Building Techniques, show block dressing being preformed at the site and a few depict rough cut stones being brought to construction sites. Specifically, an image from the “History of Schönau monastery” depicts masons dressing stone for the monastery wall on site, oxen pulling a wagon loaded with rough-cut stones, and quarriers quarrying and shaping stones in the quarry (Binding, 2004). Additionally, construction records of the Vale Royal Abbey indicated that the quarrymen only cut and trimmed the stone before sending it to the site leaving the shaping to the masons (Colvin, 1963). As one may expect, these onsite limestone workshops produce a lot of waste, which can be preserved in the archaeological record. Excavations at the
Abbey of Saint-Jean-Des-Vignes in Soissons uncovered in a series of test trenches thick layers of limestone dust and small debris that seemed to make up a large area by the Gothic choir (Bonde & Maines, 2003). After completing some ethnographic investigation of modern architectural restoration workshops, Dr. Bonde and Dr. Maines interpreted this layer as an indication that during construction the area was the site of similar stone dressing. If the majority of the dressing took place on site and the stones transported by cart were purely rough cut, then it is necessary to recalculate the total volume of stone that must be carried by the cart.

When I estimated the volume of the church, I used a height of 9.55 m over 35 courses to calculate the height of each course to be 0.27 m high. Using this value, and side facing and straight on photographs of the north nave buttress, I estimated the size of each block to be .27 m tall, .61 m long, and .27 m wide. In rough-cut, it seems most likely that the quarriers would leave a decent amount of extra stone on each block making the dimension somewhat larger. When calculating the costs of building the Mayan city of Copan, (Abrams, 1994) estimates that Mayan masons lost almost half of the original stone when dressing masonry made from volcanic tuff (45%). This situation differs from my own in that Oigny-en-Valois is a chalk quarry instead of tuff quarry and Mayan workers only used stone tools as opposed to the iron chisels that French masons still use today. The geological attributes of the stone definitely makes a large difference, as the chalk is less crystalline, softer, and will fracture much less than the Mayan tuff especially when worked with a sharp iron chisel. As such, I
propose that the quarriers worked to rough-cut stones with an added 3 cm on each face. This increases the dimensions to .33 m tall, .67 m long, and .33 m wide, which increases the volume of the stone by a factor 1.64. In order to use this factor to recalculate the volume of stone that must be transported I used the volume of face stone in the church walls, 894 m³, and multiplied it by 1.64, which brings the new stone volume to 1466 m³. It can be assumed that some of the waste from the dressing process will be reused in the rubble fill. The predicted volume of waste stone is 570 m³, which if it could be completely saved and turned into rubble fill would be enough for the entire church. Unfortunately, the waste cannot be perfectly converted into since some portion of it will be limestone dust and pebbles as seen at Saint-Jean-des-Vignes. I estimate that half of the Bourgfontaine limestone waste, 285 m³, can be reused as rubble, which raises the predicted total transported volume to 1,751 m³.

Other Construction Materials

Grès Roussard

In addition to limestone, three other materials are necessary for construction at Bourgfontaine: grès roussard, lime, and sand. The name grès roussard, or “russet sandstone,” is indicative of the earthy reddish ochre and reddish brown colors that are typical of it. Two courses of grès roussard, together with a lot of mortar, make up the shallow foundations of the church at Bourgfontaine. This foundation has a total volume of 105 m³, 56 m³ of which are comprised of large rough-cut grès roussard blocks. More specifically grès roussard is a type of ferruginous sandstone that is frequently used in
foundations due to its high density and low porosity, limiting the capillary effect of groundwater leaching into the lower courses of limestone walls. This practice can be seen in other French churches and cathedrals sometimes with sandstone, sometimes with dense limestone or chalk (Bonde, Maines, & Mark, 1989; Vázquez, 2015). The density of the grès roussard used at Bourgfontaine would make it incredibly difficult and expensive to transport over long distances.

Luckily, about 500 meters to the northeast of the church site, there is an outcrop of this russet sandstone, and just as importantly, sand. The quarry site is on the top of a wooded ridge that also has outcrops of grès and sand. The quarrying occurred in a few different locations along the ridge, although the principle operations took place along the outcrops there is a number of shallow pits that suggest some minor pit quarrying occurred as well. Fig. 8 shows an image of one of the grès outcrops. Transporting materials from this quarry would have been quick since the part with the fully loaded cart is almost entirely downhill. Transporting grès is an important part of foundation building, but transporting sand is a vital part of construction for the entire church.
Figure 8- Photograph of one grès roussard outcrop that is northeast of Bourgfontaine. Courtesy of Dr. Clark Maines

Sand and Lime

Lime and sand are the two parts of the medieval mortar recipe typically mixed in a ratio of 1:3, lime to sand (Lynch, 1998). This mortar is used in the rubble fill as cement, securing all of the stone rubble in place between the facing stone used on the inner and outer sides of the church walls and in between the courses of the walls to help secure and evenly distribute the weight of the stone above. Upon looking at the cross sections of the fortification walls and comparing the amount of stone to mortar in the rubble fill, I estimate that about 75 percent of the fill is stone, while the other 25 percent is mortar and assume that this is normative. It follows, using the 1:3 ratio, that of the 531 m$^3$ of rubble fill in the church, 133 m$^3$ of it is lime mortar, meaning approximately 33 m$^3$ of lime and 100 m$^3$ of sand.

The ubiquity of mortar in medieval construction makes sand and lime essential construction materials throughout Europe. At Bourgfontaine, the
proximity of the sand quarry to the site decreases the amount of work associated with transportation; the lime would still have to be manufactured. To create lime, one must burn limestone in a kiln for a length of time that varies between 1-7 days. For the lime manufacturing purposes of Bourgfontaine, it seems safe to assume that a small kiln (~15 m³) would be loaded with 10 m³ of limestone and produce 9 m³ of lime after 2 days of firing and cooling. After this cooling, the quicklime must be soaked with water to create slurry. The slurry must first be sieved to separate the resultant putty from the water; then set aside covered in water and allowed to mature to improve its “workability.” During Roman construction projects, slacked lime matured for 3 months before being mixed with sand for use as mortar (DeLaine, 1997). Based on English building accounts, which mention purchasing quicklime and slaked lime, it seems that medieval mortar did not mature for as long, perhaps one month instead of three (Hislop, 2000). After maturing, the putty is mixed with sand, and beaten before being used as mortar (Lynch, 1998). Each kiln firing would produce 9 m³ of lime, which would have to be mixed with 27 m³ of sand to create 36 m³ of mortar.

Using the total site-wide mortar volume, 182 m³, and the ratio of limestone to mortar, I calculated that manufacturing all of the mortar would require that 51 m³ of limestone be brought from Oigny-en-Valois. However, the production of lime in relation to the construction timeline is not that simple and needs further explanation. In order to begin construction with mortar, lime must be manufactured well in advance. Historically, freemasons also worked during

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2 The differences in firing time seem to reflect differences in fuel type, size of fired pieces, type of stone, and the design of the kiln (DeLaine, 1997).
the winters carving stone meaning there would be masonry waste to use in lime production before construction began (Colvin, 1963; Knoop, 1967).

Considering half of the waste stone is used as rubble fill, I assume that a tenth of the masonry waste, 57 m$^3$, can be gathered from the freemasons and converted into lime. As the first constructed feature, mortar needed for the foundation would have to be created before anything else. Therefore I assume that to produce this mortar some limestone rubble, 10 m$^3$ for every 36 m$^3$ of mortar, still had to be transported from Oigny-en-Valois. If the site strictly reused masonry waste, the carters only needed to transport only an extra 14 m$^3$ of limestone to create mortar for the foundations increasing the total amount of transported limestone to 1766 m$^3$. Given the proximity of the sand quarry and consistent water sources at the church site, I will ignore the transportation times for these components in this study.

**Timber**

In medieval construction, wood is used for fuel, building scaffolding, constructing temporary workshops for masons, roofing the church, and more, likely making it and limestone the most used resources. At the time, giving timber from nearby proprietary forests was a common practice among noble patrons in England (Colvin, 1963). So it stands to reason that despite the formal gifting of the monastery and the surrounding lands not occurring until 1329, the construction of the monastery must have utilized the area’s resources. Lacking documentary evidence it is impossible to be sure, but it is the most logical and efficient way to work. Since Bourgfontaine is surrounded by forest to this day
and is represented as surrounded by forest in Licherie’s seventeenth-century, cavalier view of the site, I assume that it was surrounded by forest during the construction phases of the charterhouse as well. As a result, I do not take timber transport into account.

**Estimating Construction Timing**

**Surveying and Constructing Foundations**

Construction began, as it does today, with surveying the site and laying out the church plan. The person in charge of this survey would be whomever was in charge of building the church, which in most cases was a master mason. Master mason was a designation used to describe an individual who had a firm understanding of both dressing stone and planning a building. Typically, there was no detailed draft of the building if any sketch at all, as the master mason could keep it all in his head, especially for a simple building like the church at Bourgfontaine (Knoop, 1967). This plan would be brought to fruition through setting out the site, a task akin to the modern staking of sites before construction. Unlike modern sites, however, there were no theodolites, dumpy levels, or graduated measuring tapes. Instead, the master mason used a series of rods and ropes, with knots at different lengths, to string out the outline of a site. Using a 3, 4, 5 right triangle, a square, and proportionally knotted rope the master mason could check the angles of the plan as laid out to make sure everything was aligned (Harvey, 1971).

At Bourgfontaine, the survey likely started at the west façade, the simplest section of the plan, and moved to the east towards the 3 facets of the choir. To
plan the choir, the survey stayed flush with the nave walls until reaching the angles of the apse. The mason then strung a line across the width of the church and marked the center point. Because the apse is half a regular hexagon, he divided the area of the three facets into three equilateral triangles that share the marked center as a common vertex. Then using three other pieces of rope, whose lengths were equal to the earlier marked midpoint, he set out the two other sides of the equilateral triangle to create one side of the apse and flipped the triangle to mark the other two facets. Using the setting out of trenches at a modern archaeological excavation as a parallel, it likely took a day of work for the master mason and a few rough-masons or their laborers to complete this process. After laying out the plan, laborers could begin digging out the foundation trenches marking the first part of the church’s physical construction.

The foundations of the church at Bourgfontaine are 1.1 meters wide and only three-quarters of a meter deep making the total volume 105 m³. Foundation trenches are sometimes a bit larger than the foundations themselves so that laborers can easily set the necessary stones and rubble fill. Based on photographs of the excavated church foundations at Bourgfontaine, I do not believe this to be the case. In the photographs, it is clear that there is a layer of mortar set down before the first course of grès roussard is laid in place, and that both the vertical faces of the mortar and the courses of grès roussard are about flush with one another. Because the foundations were dug into clay and are fairly shallow, it is unlikely that they would be shored at all, decreasing the labor required for excavating. Using an estimate of 0.14 person/days per m³ the
foundations require 14.7 people/days total to be excavated (Pegoretti, 1843). Once the foundations were excavated, the next step is to lay down the actual foundation itself. Pegoretti also calculated the time it takes to lay a foundation, including mixing mortar, which for Bourgfontaine equates to 36.8 people/days. I combined these values to calculate how long it would take to finish the foundation, which is approximately 51.5 people/days in total based on summer working hours.

**Dressed Walls**

The act of laying two lines stones and mortar in courses then filling the cavity between them with rubble fill is fairly universal in medieval building practice. Through observation of a series of restoration project undertaken at Copan, Honduras, Elliot Abrams provided figures for dressed wall construction and placing fill behind a dressed wall that I use here. He calculated that one person could construct 0.1 m³/hr of dressed masonry wall and fill 0.6 m³/hr of rubble. These times included the time taken for planning At Bourgfontaine, this means that in one day a single person could construct 1.1 m³ of wall or 6.6 m³ of fill in the summer, 0.9 m³ of wall or 5.4 m³ of rubble fill in the winter. Following the Artois work calendar, this means a single builder could construct 168 m³ of wall or 1,007 m³ of rubble fill during the summer, and 80 m³ or wall or 478 m³ of rubble fill during the winter. The *Masons’ Ordinances* give 171 m³ of wall or 1,028 m³ of rubble fill per builder during summer and 96 m³ of wall or 575 m³ of rubble fill per builder during winter. The dressed walls, 893 m³, require 813 summer days, or 993 winter days, to complete while the filling the rubble core,
534 m³, requires 81 summer days, or 99 winter days, to complete. In total the church and Tour Valois would require 894 summer person-days, or 1092 winter person-days, to complete. Following the Artois calendar, a team of 10 builders would completely finish the church and tower in one season.

Scaffolding and Roofing
As the walls of the church are built up and become taller, there would have been a need for timber scaffolding, which creates four more labor costs: sawing timbers, planting the uprights, erecting the scaffold, and raising the stone and rubble. For Bourgfontaine considering the nave height of ~10.5 meters, I estimate that there would be a need for a total of 7 levels of scaffolding with platforms every 1.5 meters. Each scaffold level is a face made with four uprights that support the standing platform. The faces are calculated as the length of the boards times the height of the uprights; in this case, I will use board dimensions of 2 meters by 0.2 meters and the previously stated upright height of 1.5 meters. Using skilled carpenters, carving these uprights would take 0.25 days per upright, erecting the scaffolding required 0.021 days per m² face and sawing the wood required 0.06 person days per m² (Pegoretti, 1843). A single 2-meter long 1-meter wide section of scaffolding required 0.12 days of cutting for five planks across, 1 day to cut the four uprights per section, and 0.063 days to erect the section. The total time to build the scaffolding to the top of the wall comes out to 0.84 days of cutting planks, 7 days of cutting uprights, and 0.44 days of erecting, totaling to 8.28 days per 10.5-meter tall section.
Although it is unlikely that the entire building would be surrounded at once, with no reuse of uprights or planks, I completed this calculation to estimate the maximum possible time cost. The rough perimeter of the church and tower is 124 meters, for a total of 434 sections of scaffolding and 514 person/days. Pegoretti uses the constant of 12 hours days, so when modified to the Bourgfontaine 11 hour summer workday, the total days jump to 560. The minimum cost, would be to have a 2-meter long section of scaffold on either side of the wall that is broken down and moved as necessary. Using the interior perimeter of 107 meters, the exterior perimeter of 124 meters, I calculated the total cost of sawing and erecting the scaffolding to be 67 days. The dramatic drop in time is caused by the decreased amount of sawing both planks and uprights.

In addition to the labor required for building the scaffolding, there is also labor required for raising construction materials to the proper height, which is quantified as 0.012(h-1) days per m³ (Pegoretti, 1843). If a team of 10 rough-masons are on the scaffold building, they will used 14.3 on scaffolding shorter than 7.5 meters, one laborer can raise the necessary amount of material to keep pace with their building. Once the building progresses to scaffolding 7.5 meters high and above, 2 laborers are needed to keep pace with the building.

The final part of the church to be built was the roof. Today, the only remaining physical evidence that the church had a roof is the slight roof cut and the putlog holes in the interior of the west façade. Based on roof styles of the time, the roof would have been symmetrical across the centerline, which shows
in the mirrored putlog holes towards the top of the face of the façade (Mark, 1993). Without physical remains of the roof (i.e. anchor points, wall-plate, etc.) we can turn to documentary evidence for some information. The Louis Licherie painting shows the church as having a triangular roof that curved around the apse. Unfortunately, of the Romanesque church roofs that survive today, all have triangular roofs. The stylistic differences between them are shown in the ways that each church uses interior supports a little differently and the type of wall-plate that supports the roof (Hewett, 1974). So without more physical evidence, or a documentary source describing the style of the roof, it is impossible to know what it looked like originally.
Conclusions

Transportation

The total time cost of transporting materials for the church at Bourgfontaine has been calculated to be 850 person-days, which is shown in greater detail in Figure 9. Although it may seem quite high, this figure represents the total time needed for a single cart to haul all of the stone from Oigny-en-Valois to Bourgfontaine. In order to show the total time transportation may have actually taken, I will recalculate it with more reasonable numbers of working carts. Historically, the number of carts used per site varied quite a bit as each site accounted for transportation.

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Figure 9- Person/Day and Work Year Cost of Transporting Stone to Bourgfontaine

During construction at Vale Royal Abbey and Sandgate Castle, carters were hired per day leading to frequent changes in carters; Vale Royal employed 261 carters in 36 months while Sandgate Castle used more than 110 different carts in 4 weeks (Knoop, 1967; Rutton, 1893). Contrasting the high turnover of those accounts, while carrying out repairs on Rochester Castle in 1368, the site
employed only 8 carters, 4 were hired for 176 days, and 4 were hired for 125.5 days ("Fabric Roll of Rochester Castle," 1859). A less well recorded style of royal employment was the conscription of carts, seen in 1446 at Sheffield Castle, where “60 waggons" worked for “bread, beer, and other victuals” and no pay (Knoop, 1967). Without documentary evidence it is difficult to support any one estimate of how many carts the master mason at Bourgfontaine used, and whether employment was short-term, long-term, or conscripted. Later construction supported by Philip VI could have also used royally owned carts that had been sent to Bourgfontaine instead of hiring peasants from the surrounding areas. If carters were hired, it seems likely that due to its isolated location, the master mason at Bourgfontaine could only hire a few carts as the peasants of the surrounding region needed to tend fields or otherwise work the land.

For that reason, I chose to calculate the time needed to cart limestone using 2 and 5 carts. Although these estimates are moderate when compared to the previously mentioned royal foundations, Bourgfontaine’s moderate size means that 5 carts dramatically decrease the amount of time needed to transport the limestone. As shown in the table below, using one cart to transport limestone requires 3.5 years for the Artois calendar and 3.2 years following the Mason Ordinances’ calendar. With two carts, this time is halved to 1.75 and 1.6 respectively, while five carts reduce the time to 0.7 and 0.64 years (8.4 and 7.7 months) respectively. In order to prevent delays once construction began, carting probably started before construction so that mortar could be prepared,
and freemasons could begin dressing stone. If 5 carts began at the start of the New Year, to build reserves and provide materials for site preparation, by late July or early September all of the church’s limestone would be on site, meaning it could be finished in one summer work season.

**Quarrying and Dressing**

In the quarry, labor was separated into three different categories: master quarriers, cutters, and trimmers. These laborers were organized into gangs under a master mason and likely worked year round to quarry and roughly shape stone before sending it to the site for the freemasons to fine-cut each block to the required size and shape (Colvin, 1963). Since estimates of quarrying speed are rare to find, I created my own estimate that 2 quarriers could provide enough stone for one cart by using quarry records from the construction of Vale Royal Abbey.³

Once the stone is on the site, the next factor to consider is the number of masons working on dressing the stone. There are two main types of medieval mason: the freemason and the rough-mason.⁴ The freemason is a skilled stoneworker, able to fine dress the highest quality stone in any pattern needed

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³ Estimate made using Vale Royal accounts from 1278-1280 where an average of 15 quarriers and 31 carters are simultaneously employed and the quarry is “four to five” miles from the site (Knoop, 1967). For reference, Oigny-en-Valois is about 4 miles from Bourgfontaine.

⁴ These distinctions come from later Medieval English building accounts that refer to rough-masons, or row masons, as being in charge of laying stone and brick. The distinction between freemason and rough-mason is connected to the freestone, high-quality stone that can be worked “freely” in any way, which was saved for the more skilled masons (Knoop, 1967). The English accounts use the term *cubatore* and *cubitore* to describe the position of layer and rough-mason. Accounts from Caernarvon in the 14th century describe layers (*cubitores*) being employed as “scrapplers” in the quarry during the winter months, while later accounts never describe *cubatores* and *lathom*’ rough ever dressing stone (Colvin, 1963; Knoop, 1967).
whether decorated, geometric, or rough-cut. With the limited fine stonework that exists at Bourgfontaine today, the employed freemasons likely cut all of the wall stone used at the site. Rough-masons on the other hand acted as the stone layers and dressers on site and would be the main building workforce employed. With each rough-mason came a few laborers who would carry materials, do some rough dressing and laying, and otherwise helped the rough-mason in any way necessary (Knoop, 1967). For this study, I assume each rough-mason had 1 laborer working for him.

The medieval freemason worked with a mallet, an iron chisel, and an axe. Roman quarriers working with similar tools could quarry 1 m$^3$ of dense Apennine limestone per day, suggesting that medieval freemasons dressing 2 m$^3$ of a softer, easier to carve, limestone is a reasonable estimate (DeLaine, 1997). To estimate the number of freemasons working at the site, I assume that there are enough freemasons dressing 2 m$^3$ of stone per day to keep up with the stone being carted to the site. A single cart would require only 3 freemasons in the summer for and 1 freemason in the winter to keep up with the limited amount of stone delivered. Using 2 carts requires 5 freemasons in the summer and 3 in the winter. Finally, 5 carts can transport 11.6 m$^3$ of stone/day, requiring 6 freemasons to be on site in the summer while in the winter 5 carts transport only 8.7 m$^3$/day lowering the employment to 5 freemasons\(^5\). Once the carts had

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\(^5\) Many of the calculated values were not whole numbers but came out with decimals. Because the values represent the number of days needed to dress a specified volume, when I calculated the number of freemasons needed, I always rounded up when faced with a decimal. This catchall method skewed the ratios of seasonal stone transport and mason employment.
transported the stone, and the freemasons had cut it, it was the role of the rough-masons and their laborers to assemble the blocks into walls.

With 5 carts transporting limestone in the summer, the freemasons cut 7 m³ of dressed stone per day and 4.6 m³ of waste stone per day, working enough stone to employ 8 rough-masons full-time. Assuming construction began at Easter with 8 rough-masons dedicated to building the walls, by the end of the summer the church would be complete.

**Site Preparation**

Before the dressed walls are raised, however, the foundations of the church must be dug and brought to ground level. As calculated earlier, the cost of excavating of the foundation trench and laying the foundation is 51.5 person/days. If the rough-masons and their laborers worked together to excavate the trench, mix the mortar and lay down the foundation stones the 16 of them would finish it in 3.5 days, barely changing the estimated summer construction timeline.

The site was busy with workers long before construction officially began to gather and process the materials needed for construction. In order to build the foundation and the walls during summer, mortar needed to be ready for use; meaning the lime preparation and maturation must have been completed in the winter. To do this, the lime makers likely had some of the carts bringing the rough-cut stone to the site, switch to bringing quarry rubble. This pre-construction preparation would have let the lime makers process the limestone and would have allowed the slacked mortar mature, increasing its quality while
not sacrificing construction time (Lynch, 1998). The other building necessities that needed to be prepared are sand and blocks of grès roussard. Natural deposits of both are located just several hundred meters from the church site and are thus close enough to neglect transport time. The labor needed to collect both resources is, however, a cost that must be taken into account. The total sand volume used in the foundation mortar and the rubble fill is 136.5 m$^3$. Using the quarrying rate of pozzolana, volcanic ash, as a parallel to the quarrying rate of sand I determined quarrying sand required 12.3 person-days (DeLaine, 1997). The total volume of grès for the church is 56 m$^3$. Quarrying the dense grès roussard requires 1 day per m$^3$, so the total volume of grès required a total of 56 person/days, for a combined total of 68.3 person/days to quarry both sand and grès. During the winter, a somewhat common practice, seen at Caernarvon, is to employ rough-masons in the quarries (Colvin, 1963). If the 8 rough-masons needed at Bourgfontaine in the summer were also employed as quarriers in the winter, they would complete the quarrying of both grès and sand in 8.5 days.

**Historical Context**

These calculations with moderate numbers of laborers make it clear that the construction timeline for the church at Bourgfontaine is short, likely 8-10 months. The starting date on construction at the site is a little more difficult to pin down and ranges from 1323-1325 based on letters between the papacy and Charles. Charles sought to found this monastery in the final years of his life, during which time he had been a greedy and power-hungry man, something that
would have weighed heavily on his soul.\(^6\) During this part of the middle ages, the idea of Purgatory was widespread and fully developed (Bonde & Maines, 2013). It also was a factor in shaping the importance of living a pious life. Charles of Valois completed a number of charitable works toward the end of his life, including paying to feed paupers in exchange for their prayers, so it is clear he feared for his immortal soul (Bonde & Maines, 2013 p. 7). Likely, founding Bourgfontaine and establishing a dynamic of reciprocal prayers was meant to help him avoid Purgatory and guide his soul toward heaven. As such, it seems likely that he would want church construction to begin at Bourgfontaine as quickly as possible.

Letters sent from the prior-general of the Carthusian Order in 1323 indicate that Charles was quickly building the funds necessary to construct the monastery (Bonde & Maines, 2013). This implies that construction had yet to begin but it is possible that this time was also used to plan the monastery. In his last will and testament, written in 1325, Charles admits that the monastery is still unfinished but says nothing about how much was already built (Bonde & Maines, 2013). Taking into account both of these documents and the planning that must be done before building, it seems the earliest construction could begin is January of 1324. This would provide almost a year and a half to collect more funds and plan, and if carters, freemasons, and lime makers began to work right after the New Year, the church would be complete by the winter. Additionally,

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\(^6\) During his lifetime, Charles pursued the crowns of Aragon and Constantinople. While pursuing power in the French court of his nephew Louis X, Charles found himself at odds with a royal chamberlain and was involved in his trial and later execution (Bonde & Maines, 2013).
English monastic building accounts record that brothers frequently moved to the site of the monastery before its full completion to begin their lives on the new site (Colvin, 1963). Bourgfontaine’s community of brothers began to form when Pope Jean XXII sent a letter to the Carthusian prior general in February 1324 requesting that 4 brothers be sent to Charles of Valois (Bonde & Maines, 2013). From these 4 brothers the count would pick Bourgfontaine’s new prior and after the prior being chosen, the brothers presumably moved to Bourgfontaine to live in wooden cells while construction occurred. Although the lack of defined documentary evidence makes the timeline of construction impossible to know for sure, but using my energetic calculations I can say with certainty that the church and tower could be completed in one year. Meaning if construction began in 1324 or even 1325, then construction of the church was completed and the community of brothers was started before Charles died.

The stone used to build the church walls and almost certainly the rest of the monastery speaks to the priorities of construction and offers support to the idea that time was of the essence. Compositional analysis of the stones supports the hypothesis that the monastery is built using stone from Oigny-en-Valois. This stone is from a soft, light chalk that is likely from either the banc franc or banc royal formations of Lutetian limestone. Although the stone is easy to weather⁷, using the quarry at Oigny-en-Valois makes sense when comparing stone and transportation costs, but perhaps more importantly, it makes sense when

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⁷ If the church walls had been plastered and painted, as is seen at other medieval churches and cathedrals, the weathering rate of the stone would have much lower than it is today. Therefore it is possible that durability was less of a concern to medieval builders.
comparing construction speed. If the brothers had used other quarries, such as le Carrière de l'Évêque in Septmonts or a quarry in Paris, the rate of construction would have slowed considerably while dramatically increasing the cost. So in keeping with the hypothesis that the church was to be completed as quickly as possible, the stones of the church were taken from the most time-efficient source- Oigny-en-Valois.
Appendix I: Energetics Equations

<table>
<thead>
<tr>
<th>For 2 Oxen Team</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Mass (oxen)</td>
<td>700 kg</td>
</tr>
<tr>
<td>Draft Power (From “Animal Traction”)</td>
<td>81 kg</td>
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<tr>
<td>Speed on Flat (From “Wood Extraction with Oxen”)</td>
<td>3.5 km/h</td>
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<tr>
<td>Cart Draught</td>
<td>22.45 kg</td>
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<tr>
<td>Available Draught Capacity for stone</td>
<td>58.55 kg</td>
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<tr>
<td>Limestone density</td>
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<tr>
<td>Distance from Oigny to BF</td>
<td>5.77 km</td>
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<tr>
<td>Time for one trip</td>
<td>1.65 hours/trip</td>
</tr>
<tr>
<td>Time to load/unload the cart</td>
<td>1 hour/trip</td>
</tr>
</tbody>
</table>

Mass of stone per cartload (equation modified from “Status of Bullock Carts” data)

\[ y(x) = \text{Available draft capacity (kg)}, x = \text{load weight (kg)} \]

\[ y(x) = 0.0315x + 10.906 \]

When \( y(x) = 81 \text{ kg}, x = 2225 \text{ kg} \)

2225 kg = gross weight (tare+payload)
Gross weight – tare weight = payload
2225 kg – 410 kg = 1815 kg of payload
1815 kg of limestone per trip

Loaded vs. Unloaded Cart Velocities (equation modified from “Status of Bullock Carts” data)

\[ y(x) = \text{cart speed (km/h)}, x = \text{gross weight (kg)} \]

\[ y(x) = -0.0013x + 4.1972 \]

When \( x = 2225 \text{ kg}, y(x) = 1.3 \text{ km/h} \)
Daily, Weekly, and Yearly Hours

Length of summer workday: Following hours as set by the Masons’ Ordinances (will look into Artois rules)

- Summer defined from 1st Sunday of Lent through Michaelmas (Mason Ordinance)
- **Summer defined from Easter to Toussaint (Artois)**
- Sunrise → 30 minutes before sunset, 2 hours of total breaks
- Average working hours based on 2019 sunrise/sunset times in Villeres-Cotteres
  - February 24th, 2019- 07:41 → 18:21, work day ~8 hours
  - June 21st, 2019- 05:43 → 21:55, work day ~14 hours
  - September 29th, 2019- 07:44 → 19:30, work day ~10 hours
  - Summer Average ~11 (10.7 hours)
  - April 7th, 2019- 07:14 → 20:26, work day ~11
  - June 21st, 2019- 05:43 → 21:55, work day ~14 hours
  - November 1st, 2019- 07:35 → 17:26, work day ~7 hours
  - Summer Average ~11 (10.7 hours)

- Trips per day = work day hrs/(one trip + loading time) * 2
  - 11.16 hrs/((1.65 hours/trip + 1 hour) * 2) = 2.1 trips
  - 2 trips per day in the summer

- Summer Average of stone mass per day
  - Stone per trip * trips per day = stone mass per day
  - 1815 kg/trip * 2 trips/day = 3630 kg/day

- Summer average of stone volume per day
  - Stone mass per day / density of limestone
  - (3630 kg/day) / (1570 kg/m³) = 2.31 m³ per day

Length of winter workday:

- Winter continues from Michaelmas to First Sunday of Lent (Mason Ordinance)
- **Winter continues from Toussaint to Easter (Artois)**
- Sunrise → Sunset, 1.25 hours of total breaks
- Average working hours based on 2019 sunrise/sunset times in Villeres-Cotteres
  - September 30th, 2019- 07:46 → 19:28 workday ~10 hours
  - December 21st, 2019- 08:40 → 16:50 workday ~7 hours
  - February 23rd, 2019- 07:43 → 18:19 workday ~9 hours
  - Average winter workday ~ 9 (8.6) hours
  - November 2nd, 2019- 07:37 → 17:24 workday ~ 8 hours
  - December 21st, 2019- 08:40 → 16:50 workday ~ 7 hours
  - April 6th, 2019- 07:16 → 20:24 workday ~12 hours
  - Average Winter workday ~ 9 (9) hours

- Average stone per day (winter) = Winter workday/road trip time
  - 9 hrs/((1.65 hours/trip + 1 hour) * 2 = 1.7 trips

- 1.7 trips cannot be accurate; we have to round to either 2 trips or possibly 1.5 trips. If the quarrymen live at Oigny-en-Valois, they would
have to return to the quarry at night rounding the trip number up to 2. If the quarrymen do not live in Oigny then it may be reasonable that each day workers would only do 1.5 trips.

**Working week:** Estimates vary but we can compile/compare

- **Assumptions-** 365 day/year
- **2 seasons-** (winter: Michaelmas → first day of lent) (Summer: Lent → Michaelmas)
- **Artois:** 45 holidays on the year; 5.5 day work week
- **Mediaeval Mason:**
  - **Vale Royal:** 27 holidays in 1279, 22 holidays in 1280; Beaumaris Castle - Oct. 1319-Feb. 1320 20 days off; Eaton - 1444-1445, 1445-6
    - 46 holiday, 38 weekdays off in 1444-5, 43 weekdays in 1445-6

**Working Year (Small, 1989):**

- Following the Artois workbooks we can assume that the workers at Bourgfontaine celebrated around 45 holidays.
  - **Artois 1312-** 29 holidays between Easter and Toussaint (33 weeks) and 16 holidays in the winter (19 weeks)
- **Rough Estimates of Stone movement per day (One Oxen team)**
  - **33 weeks of Summer (Lent to Toussaint)**
    - 33 weeks * 5.5 workdays/week = 181.5 work days
    - 181.5 work days - 29 holidays = 152.5 work days
    - 2.31 m³ of stone per day → 352 m³ of stone per summer
  - **19 weeks of winter** (Assuming 1.5 trips a day)
    - 19 weeks * 5.5 workdays/week = 104.5 work days
    - 104.5 workdays - 16 holidays = 88.5 workdays
    - 88.5 workdays * 1.5 trips/workday= 133 trips
    - 1.16 m³/trip → 154 m³ of stone per winter
  - **Yearly stone total = 506 m³ of stone transported per year**
- **1428 m³ of limestone in BF**
  - **1428 m³/(506 m³/year)= 2.8 years to transport all necessary limestone to BF**

**Working Year (Knoop, 1967):**

- **Average of 25 days off at Vale Royal (1279 and 1280) per year**
  - 5 feasts days off during the year
  - Additional days off around on Christmas, Easter, and Whitson (Pentecost) therefore focused in summer months
    - Estimation of 3 summer feasts, 2 winter feasts
    - 7 days at Christmas
    - 6 days at Easter
    - 6 days at Pentecost
    - (15 days in the summer, 9 days in the winter)
  - **31 weeks of Summer (Lent to Michaelmas)**
    - 31 weeks * 5.5 workdays/week = 170.5 work days
- 170.5 works days - 15 holidays = 155.5 work days
- 2.31 m³ of stone per day → 359 m³ of stone per summer
  - 21 weeks of winter (Assuming 1.5 trips a day)
    - 21 weeks * 5.5 workdays/week = 115.5 work days
    - 115.5 workdays - 9 holidays = 106.5 workdays
    - 1.5 trips/day * 106.5 days = 160 trips
    - 1.16 m³ stone per trip → 186 m³ of stone per winter
  - Yearly Stone = 545 m³
- 1428 m³ of limestone in BF
  - 1428 m³/(545 m³/year) = 2.6 years to transport stone
Estimates of Dressed Wall Composition

Masonry Estimates
- ArcMap estimates of face stone vs. rubble core
  - West and South Fortification Wall Junction
    - West Wall [courses 3-14 from top to bottom]
      - Total area (pix²) = 339,296
      - Face stone (pix²) = 225,778/339,296 * 100% = 66.5%
      - Rubble core (pix²) = 113,541/339,296 * 100% = 33.5%
    - South Wall [courses 4-13 from top to bottom]
      - Total area (pix²) = 358,491
      - Face stone (pix²) = 240,367/358,491 * 100% = 67%
      - Rubble core (pix²) = 118,124/358,491 * 100% = 33%
  - West Wall, view from North to South [courses 16-20 from top to bottom]
    - Total area (pix²) = 944,119
    - Face stone (pix²) = 559,151/944,119 * 100% = 59.2%
    - Rubble core (pix²) = 384,885/944,119 * 100% = 40.8%
  - North Wall, view from Southwest [courses 5-20]
    - Total Area (pix²) = 408,836
    - Face stone (pix²) = 261,054/408,836 * 100% = 64%
    - Rubble core (pix²) = 147,805/408,836 * 100% = 36%
  - BF South Nave wall, exterior view Sside view
    - Total Area (pix²) = 7888.3
    - Face stone (pix²) = 4436.5/7888.3 * 100% = 56.2%
    - Rubble core (pix²) = 3451.9/7888.3 * 100% = 43.7%
- Means:
  - Rubble Core % = 35.8%
  - Face stone % = 64.2%
- Total Church Face stone
  - 1428 m³ * 0.642 = 894 m³
- Total Church Rubble Fill
  - 1428 m³ * 0.358 = 534 m³
- Construction Rates (How the Maya...)
  - Dressed stone wall- 0.1 m³/hr, 1.0 m³/day (yearly average)
    - 1.1 m³/day (Summer) [1.1 m³/0.642 = 1.7 m³ of BF thickness/ratio wall]
    - 0.9 m³/day (Winter)
  - Rubble fill- 0.6 m³/hr, 6.2 m³/day (yearly average)
    - 6.6 m³/day (Summer) [6.6 m³/0.358 = 18.4 m³ of BF thickness/ratio wall]
    - 5.4 m³/day (Winter)
  - Total face stone and rubble fill construction time-
    - 894 m³ / (1 m³/day) = 894 person days to construct
    - 534 m³ / (6.2 m³/day) = 86 person days to construct
Appendix II: Correlation Graphs

Oigny 1B vs. BF

Oigny 2A vs. BF Samples

BF Sample Composition Values (PPM)

Oigny 1B Composition Values (PPM)

BF Sample Composition Values (PPM)

Oigny 2A Compositional Values (PPM)

Oigny 2A Composition Values (PPM)
Carriere de l'eveque vs. Bourgfontaine
Site Samples

Carriere de l'eveque Compositional Values (PPM)

BF Sample Composition Values (PPM)

Church 1C
Church 2C
1A (Mur de Fortif)
2A Tambour
3A Chapiteau
4A Tour de fortife
5A Mur de Fortif
Tower
### Appendix III: Limestone Sculpture Provenance Project and Bourgfontaine Sample Compositions

<table>
<thead>
<tr>
<th></th>
<th>Rb (PPM)</th>
<th>Cs (PPM)</th>
<th>Ce (PPM)</th>
<th>Cr (PPM)</th>
<th>Mn (PPM)</th>
<th>Fe (PPM)</th>
<th>Co (PPM)</th>
<th>U (PPM)</th>
<th>Zr (PPM)</th>
<th>Sr (PPM)</th>
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## Appendix IV: The Carrière de L’Évêque vs. Limestone
### Sculpture Provenance Project: Aisne Quarry Samples

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## Carriere l’éveque vs. Aisne: Vassens (R-Squared)

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**Carriere l’êveque vs. Ainse:**
Berny-Riviere (R-Squared)

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Appendix V: Maps

Map 1- Study Sample Collection Locations
Map 2- Bedrock Map of the Aisne Region
Map 3- Bedrock Map of Quarry Sample Sites
Bibliography


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