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ÉPURES D'ARCHITECTURE: GEOMETRIC CONSTRUCTIONS FOR VAULT BUILDING IN PHILIBERT DE L'ORME'S *PREMIER TOME DE L'ARCHITECTURE* (1567)

This paper focuses on the representation of épures*—the 1:1-scale geometric drawings necessary for the production of stereotomic works—in Philibert de L'Orme's* Premier tome de l'architecture *(Paris 1567).* Épures *are technical drawings that medieval and early modern practitioners developed in order to solve the geometric challenges posed by stereotomy.* Épures *are traced on site and have functions similar to those of modern blueprints: they are produced by the* appareilleur *(setter) to communicate the geometry of the vault and its components (the voussoirs) to all the craftsmen involved in its making—those who prepare the templates, the carpenters who produce the centering, and the stonecutters who shape the voussoirs—and they are referred to throughout the execution process. Reading* épures *is a complex task for non-practitioners, and one that architectural historians have largely shunned, thus leaving a core aspect of de L'Orme's theory of architecture unexplored. In this paper, I use the case study of the entrance to a* descente de cave *(inclined barrel vault), the simplest of stereotomic works illustrated by de L'Orme, to demonstrate how* épures *are produced and read.*

Stereotomy is the art of cutting stones into particular shapes for the construction of vaulted structures. The size, shape, and assembling technique of their components (the voussoirs) is what distinguishes stereotomic vaults, such as the annular vault covering the lower portico in the courtyard of Charles V's Palace in Granada, from the broader family of stone vaults, such as those covering the nave of the Church of Saint Séverin in Paris (figs. 2-3). In Granada, the large voussoirs (compared to the overall dimensions of the vault) were individually cut to fit each other precisely and then assembled like the pieces of a three-dimensional jigsaw puzzle. In Saint Séverin, instead, the vaults' bays (the compartments comprised between the ribs) were built using smaller stones of standard shape and size which, like bricks, are held together by the mortar that fills the joints. The shape and stability of the Granada vault result from the accurate carving of its voussoirs, while those of the Saint Séverin vaults result from the wedge-like shaping of its mortar fillings[1].

Geometric complexity further distinguishes stereotomic vaults from the category of *voûtes clavées,* vaults built with dressed stones. Such a distinction is evident, for instance, when comparing the stereotomic dome covering the caldarium of the West Bath in Jerash with the barrel *voûte clavée* of the Temple of Diana in Nîmes (figs. 4-5). In Nîmes, the plan and elevation of the vault provided the stonecutters with all the information necessary to shape its voussoirs because a barrel vault is, from the standpoint of geometry, the horizontal extrusion of a linear element, the arch. Stereotomic vaults, instead, are characterised by geometries complex enough that their defining orthographic views – plans, elevations, and cross-sections – do not fully describe the shape of their components. The Jerash dome features voussoirs whose faces lie neither on the vertical or the horizontal plane and, therefore, appear skewed in both plan and cross section. Thus, its production requires a further step in order to define the real shapes and sizes of the voussoirs, either through geometry and drawing – as in late medieval and early modern practice – or through empirical cutting techniques, as it was most likely the case at Jerash.

Stereotomy is an ancient art that has been practiced over a wide chronological span, from Hellenistic Greece to present-day Apulia, and across a broad geographical area, centered in the Mediterranean Basin but reaching far beyond – from Cairo to Gloucester, from Yerevan to Braga, and to colonial Latin America[2]. The art is best known for the variety of acrobatic masterpieces produced in early modern France and Spain, such as the composite vaults supporting the floating staircases of the Rohan Palace in Bordeaux and the Lonja de Mar in Barcelona (figs. 6-7)[3]. It is also known for a substantial body of theory that started with the books of architects such as Philibert de L'Orme (1514-1570) and Alonso de Vandelvira (1544-ca. 1625) and engaged practitioners and mathematicians alike in a heated debate that continued through the eighteenth century[4]. By focusing on the geometry of solids, this body of theory also crucially contributed to the definition of Gaspard Monge's 1798 theory of descriptive geometry, the branch of mathematics concerned with the two-dimensional representation of three-dimensional objects[5]. As historian of mathematics Joël Sakarovitch has shown, the modern theory of solid geometry derives from the practice of stereotomy and owes a substantial debt to the experiments in complex vaulting conducted by generations of architects, *appareilleurs* (setters), and stonecutters[6].

The execution of a stereotomic vault poses a fundamental geometric challenge which consists in the fact that a vault's defining orthographic views – the plans, elevations, and cross-sections that are the traditional instruments of architectural representation – do not provide all the information necessary to define the shapes of its voussoirs. To illustrate this problem, let us examine the case of the entrance to a *descente de cave*, the simplest of stereotomic works illustrated by de L'Orme[7].

A *descente de cave* (literally, a descent to a basement) is an inclined barrel vault that covers a flight of stairs or a ramp which provides access to a vaulted space, typically a basement. This work

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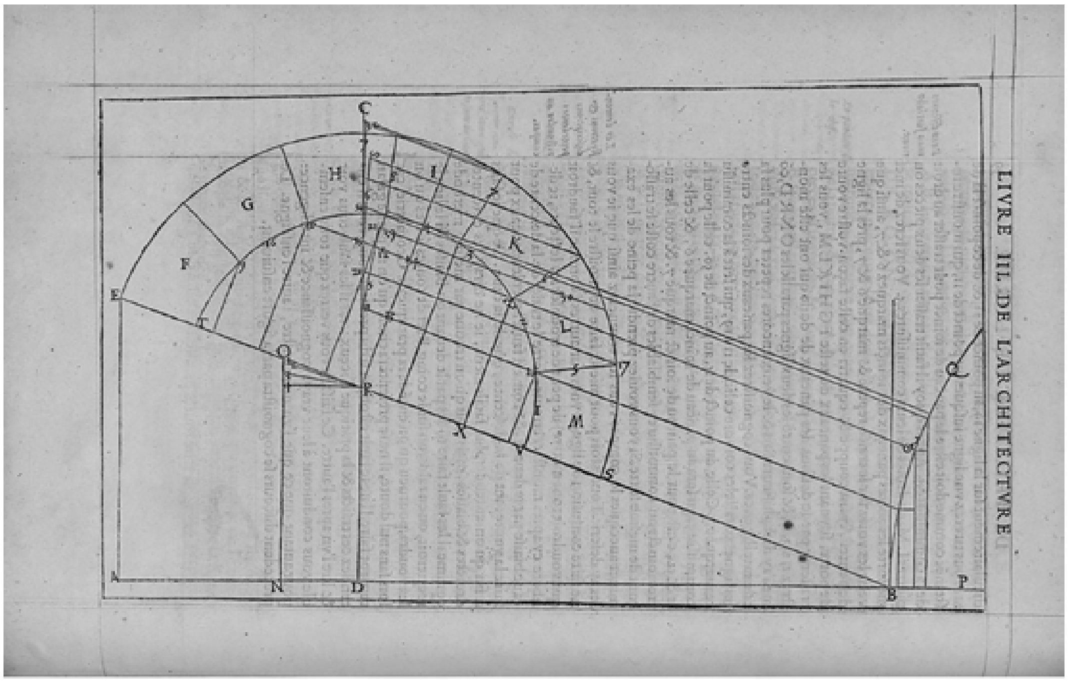
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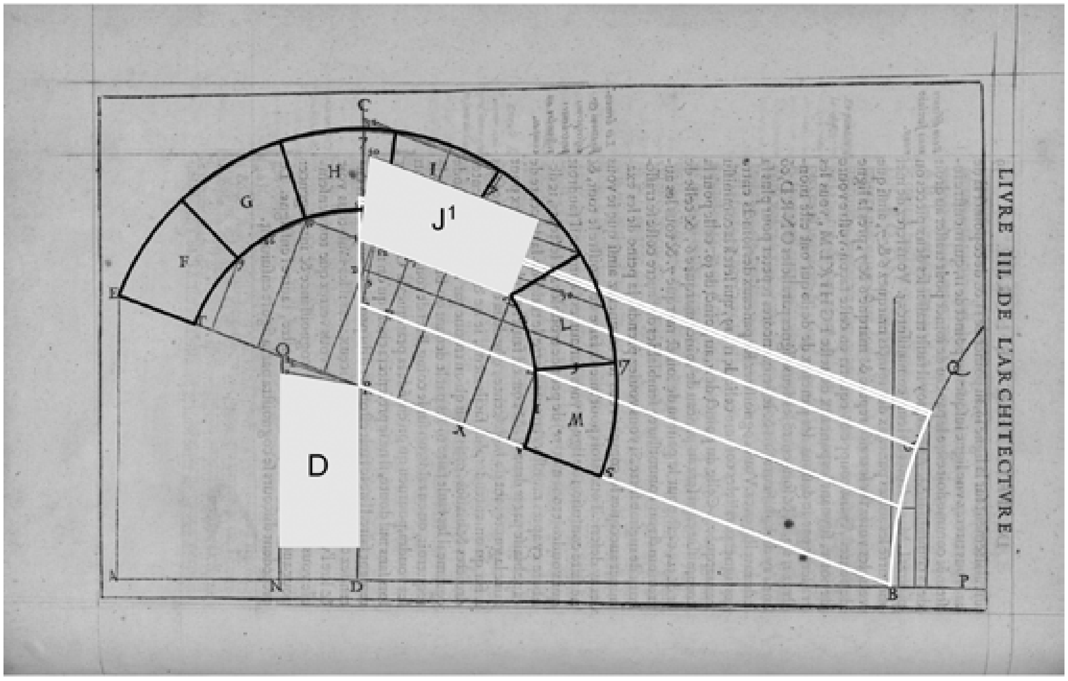
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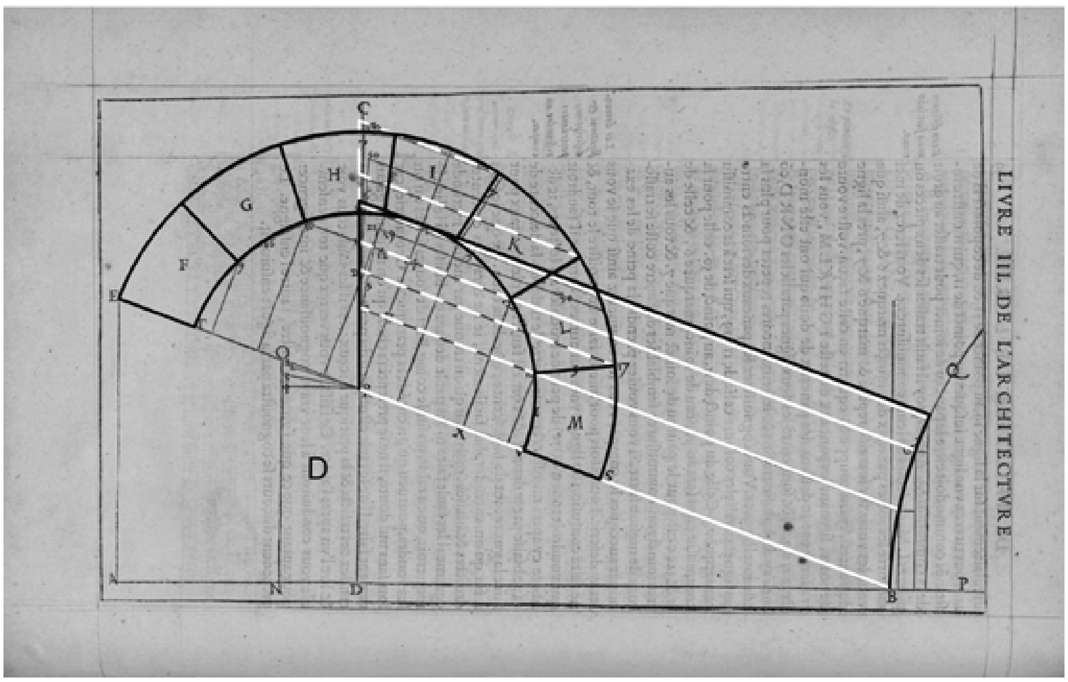
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comprises two separate stereotomic problems: a solid-plane intersection on the upper end – where the semi-cylindrical inclined barrel vault meets the entrance vertical wall – and an interpenetration of solids on the lower end, where the barrel vault that covers the staircase/ramp meets a second vault covering the basement[8]. Here, the discussion will be limited to the entrance, upper end, of this vault (fig. 8). The geometric challenge in the execution of this work lies in the fact that the vertical plane of the entrance wall cuts the inclined semi-cylinder of the barrel vault at an angle, thus producing a semi-elliptical arch on the entrance front that is not defined by the vault's longitudinal and transversal cross-sections – the orthographic views that define the shape and size of this work (fig. 9, in which the transversal cross-section of the vault is highlighted in grey; the frontal voussoirs of the finished work are outlined with dashed lines; and F labels the frontal face of the voussoirs on the transversal cross-section). In fact, of the six faces that compose each of the front voussoirs of this work, only one is defined in its true shape and size by these drawings: the face *F* shown on the transversal cross-section. The remaining faces of these voussoirs – the frontal faces lying on the entrance wall, the intrados and extrados faces, and the lateral faces which will constitute joints once the vault mounted – are all inclined with respect to the planes of the vault's longitudinal and transversal cross-sections and, therefore, their true shapes and sizes are not provided by these orthographic views.

Stereotomic vaults like the entrance to a *descente de cave* can be executed with three different cutting methods which require varying degrees of geometric knowledge[9]. The first method, called *ravalement* (reduction), allows the stonecutter to circumvent altogether the geometric problem posed by this vault by cutting the voussoirs' faces after mounting them. When applying this

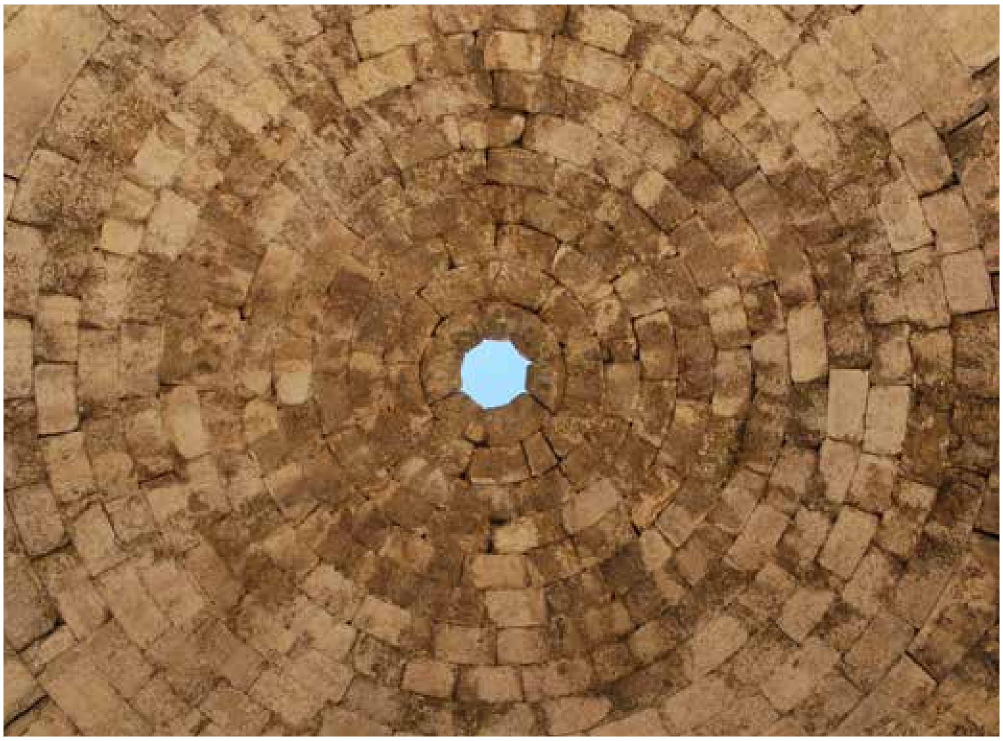
* The title of this article is a homage to the work of Joël Sakarovitch (1949-2014), architect and historian of science, whose *Épures d'architecture: de la coupe des pierres à la géométrie descriptive, XVI^e-XIX^e siècles* (Basel 1998) is the most important modern contribution to the understanding of stereotomy and its history.

[1] Stereotomy is an ill-defined term which has been employed to signify a range of stonecutting practices many of which require no stereotomic expertise. I have attempted at establishing an operative definition of the term in S. Galletti, *Stereotomy and the Mediterranean: Notes Toward an Architectural History*, "Mediterranea: International Journal on the Transfer of Knowledge", II, 2017, pp. 73-120, https://doi.org/10.21071/mijtk.v0i2.6716, last accessed on 22 May 2019. In the interest of consistency, I repeat here that definition and use the same examples from Granada and Paris to highlight the difference between stereotomic and non-stereotomic works.

[2] Galletti, *Stereotomy and the Mediterranean*… cit.

[3] The most comprehensive works on the history of late medieval and early-modern stereotomy in France and Spain are J.M. Pérouse de Montclos, *L'architecture à la française: du milieu du XV^e à la fin du XVIII^e siècle*, Paris 1982 and J.C. Palacios, *Trazas y cortes de cantería en el Renacimiento español*, Madrid 1990. While there is no comprehensive work for the history of the practice in Italy, the works of Marco Rosario Nobile provide a rich panorama of case studies focused on Sicily, southern Italy, and the Mediterranean.

[4] Ph. De L'Orme, *Le Premier tome de l'architecture*… , Paris 1567; A. de Vandelvira, *Libro de traças de cortes de piedras compuesto par Alonso Van de Elvira, arquitecto Maestro de Canterîa compônese de todo género de cartes, diferencias de capillas, escaleras, caracoles, templos y otras dificultades muy curiosas* [ca. 1585], ms R10, Biblioteca de la Escuela Técnica Superior de Arquitectura de Madrid, in *El tratado de ar-*



pagina 77
Fig. 1 *Philibert de L'Orme's épure of the entrance to a descente de cave (in* De L'orme, *Premier tome… cit., f. 59v; drawing S. Galletti).*

Fig. 2 *Pedro and Luis Machuca, Palace of Charles V, Granada, 1562-1569. Annular stereotomic vault covering the portico (photo S. Galletti).*

Fig. 3 *Church of Saint Séverin, Paris, second half of the fifteenth century. Non-stereotomic vaults covering the nave of the church (photo Romanceor, Wikimedia Commons, CC BY-SA 3.0).*

Fig. 4 *West Bath, Jerash, second century CE. Stereotomic dome covering the caldarium (photo Erics, Wikimedia Commons, CC BY-SA 4.0).*

Fig. 5 *Temple of Diana, Nîmes, first century CE (photo Ji-Elle, Wikimedia Commons).*

method, the stonecutter shapes the front voussoirs of this work exactly as those of a regular barrel vault, then mounts them, and finally cuts off the excess material by following the vertical surface of the actual entrance wall (fig. 10, in the left column of which the voussoirs are shaped and mounted like those of regular barrel vault, whereas in the right column they are cut in situ following the vertical surface of the entrance wall). The procedure – which has been employed to build stereotomic vaults across the pre-modern world – requires no geometric constructions but implies a substantial loss of material. The loss of material also implies higher transportation costs – one of the items of highest expenditure in pre-modern building construction – since blocks much larger than those required by the final work need to be transported for on-site processing.

The second cutting method, called squaring (*taille par équarissement/dérobement* in French and *labra por robos* in Spanish), requires the stonecutter to transfer the orthographic projections of each voussoir as shown on the cross-sections of the vault onto the stone blocks for cut-

quitectura de Alonso de Vandelvira, edición G. Barbé-Coquelin, Madrid 1977.

[5] G. Monge, *Géométrie descriptive: leçons données aux Écoles normales l'an 3 de la République*, Paris 1798.

[6] Sakarovitch, *Épures d'architecture*… cit.

[7] The case study of the entrance to a *descente de cave* has been previously analyzed in Sakarovitch, *Épures d'architecture*… cit., pp. 149-170, and in A. Calandriello, *De l'Orme's Graphics Language: Between Stereotomy and Orthogonal Pro-to-Projection*, in ICGG 2018. *Proceedings of the 18th International Conference on Geometry and Graphics* (Milan, 3-7 August 2018), edited by L. Cocchiarella, Cham 2019, pp. 1859-1869. Both authors focus on the overall geometry of the vault and its representation and make no attempt at delving into the practical steps necessary for the development of the templates and the execution of the work on which I focus in the present paper. For a more general approach to stereotomy's graphic methods, see S.L. Sanabria, *From Gothic to Renaissance Stereotomy: The Design Methods of Philibert de l'Orme and Alonso de Vandelvira*, "Technology and Culture", XXX, 1989, pp. 266-299 and F. Camerota, *Renaissance Descriptive Geometry: The Codification of Drawing Methods*, in *Picturing Machines 1400-1700*, edited by W. Lefèvre, Cambridge 2004, pp. 175-208.

[8] A degree of confusion about this vault is generated by the fact that, in both early modern and modern literature, the term *descente de cave* is used interchangeably to indicate the upper end (entrance) or the lower end (basement) of the inclined barrel vault. For instance, de L'Orme applies the term to his discussion of the upper end of a *descente de cave* (De L'Orme, *Premier tome*… cit., ff. 58r-59v), whereas in the *Encyclopédie* published by the Association ouvrière des compagnons du devoir the term is only employed for the lunette on the lower end of the vault (*Encyclopédie des métiers. La maçonnerie et la taille de pierre*, Paris 1991-2010, III, pp. 248-256).

[9] For a detailed description of these methods, see Sakarovitch, *Épures d'architecture*… cit., pp. 111-121.

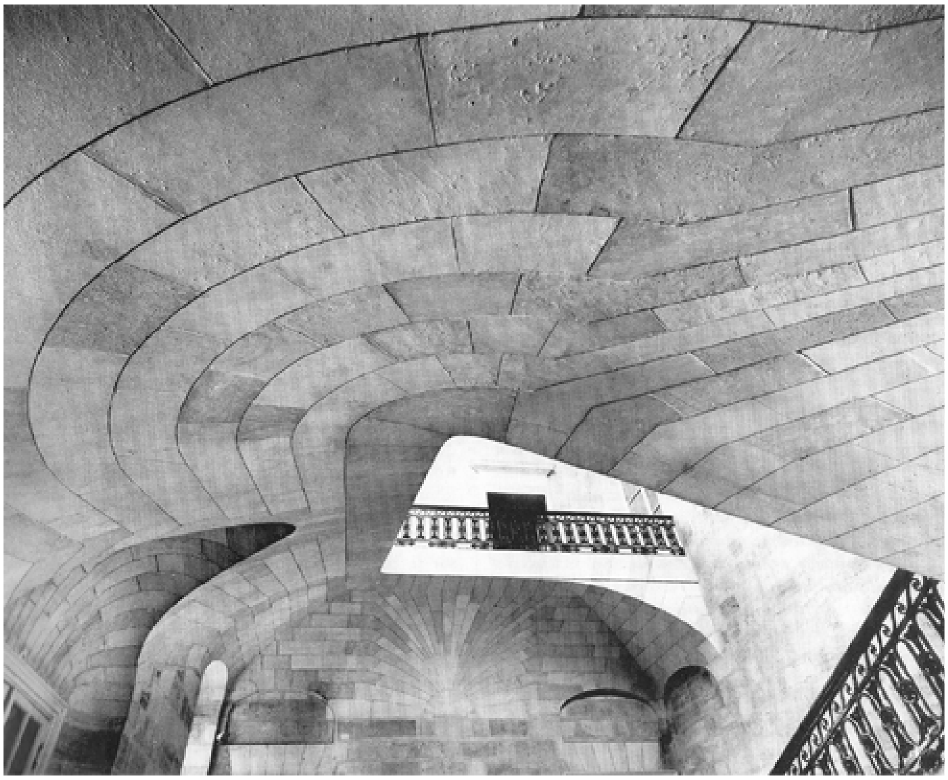


Fig. 6 *Joseph Étienne, Rohan Palace, Bordeaux, 1772-1778. Composite vault supporting the floating staircase (in* Pérouse De Montclos, *L'architecture à la française… cit.; photo M. Dubau).*

Fig. 7 *Joan Soler i Faneca, Lonja de Mar, Barcelona, 1774-1802. Composite vault supporting the floating staircase (photo Baldiri, Wikimedia Commons, CC BY-SA 3.0).*

ting. The voussoir's final shape is then progressively carved out of the stone block through a series of intermediate cuts and surfaces, "as if stripping the imagined figure of its clothing" in the words of eighteenth-century theoretician Amédée-François Frézier[10] (fig. 11, which illustrates how the orthographic projections of the chosen voussoir, shown at the top, are transferred to the sides of a stone block, shown at the bottom, which is then shaped through a series of intermediate cuts). The procedure requires the mastery of double orthographic projections but significantly reduces the loss of material when compared to the *ravalement* method – in order to obtain the same voussoir shown in figure 11, the *ravalement* method requires a stone block at least twenty percent larger in volume. On the other hand, cutting by squaring implies a significant waste of stonecutters' labor because a number of intermediary surfaces – i.e. surfaces that belong neither to the initial stone block nor to the final voussoir – need to be cut and then destroyed in the process of 'stripping' each block.

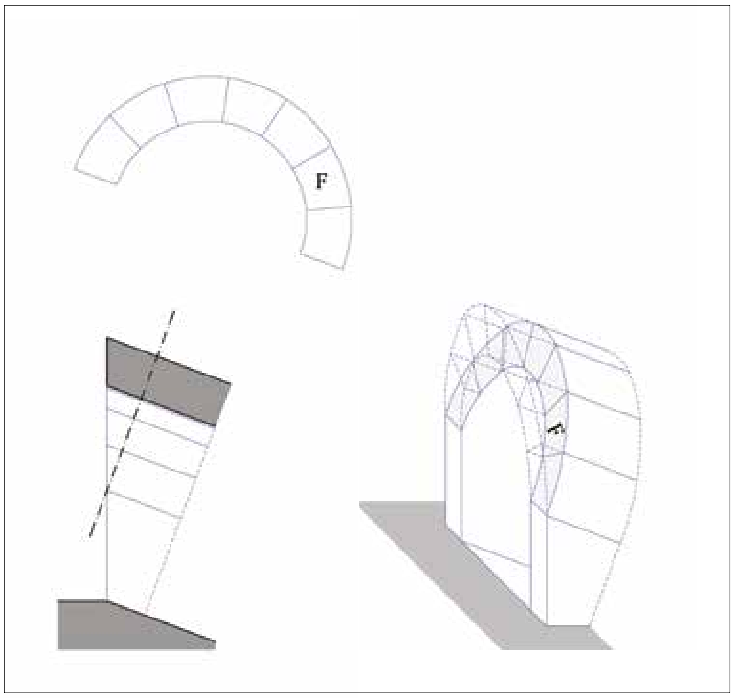
The third cutting method, called templates method (*taille par panneaux* in French and *labra por plantas* in Spanish), requires an *appareilleur* to produce paper or wooden models (templates) that replicate the true shapes and sizes of the voussoirs' faces, which the stonecutter will then apply to the blocks for carving (fig. 13). In the case of the entrance to a *descente de cave*, in which the template of the frontal face *F* is provided by the transversal cross-section, it will be sufficient for the *appareilleur* to produce either the template of the intrados face *D*, or *face de doile*, or those of the lateral (or joint) faces J^1 and J^2, for the stonecutters to be able to proceed with the shaping of the voussoirs (fig. 12, which shows two methods for obtaining the voussoir: via the templates of frontal face *F* and joint faces J^1 and J^2, at the top, and via the templates of frontal face *F* and intrados face *D*, at the bottom). The templates method is by far the most efficient of stereotomy's cutting methods from the standpoint of economy of labor and material supply and transportation – in order to produce the same voussoir shown in figure 12, the squaring method requires a stone block about twice as large in volume (cf. fig. 11). Yet, it is also the most challenging of them because it implies the mastery of solid geometry's fundamentals, such as plane rotations and surface developments. In order to obtain the true shapes and sizes of joint faces J^1 and J^2 shown above, for instance, the *appareilleur* needs to rotate the inclined planes onto which those faces lie onto the vertical plane of the vault's longitudinal cross-section (fig. 14). Similarly, in order to obtain the true shape and size of intrados face *D*, one needs to first translate horizontally and then rotate the inclined plane onto which D lies onto the vertical plane of the vault's lon-

[10] A.F. Frézier, *La théorie et la pratique de la coupe des pierres et des bois, ou traité de stéréotomie à l'usage de l'architecture*, Strasbourg 1737-1739, II, p. 12.

Fig. 8 *Château d'Écouen, staircase, mid-sixteenth century. Entrance to a descente de cave (photo D. Lemel, http://www.lemel.gallery/ ; last accessed on 23 September 2020).*

gitudinal cross-section (fig. 15). The technical drawings generated by the *appareilleur* to obtain a vault's templates are called *épures* (see fig. 1). The choice of cutting method for a stereotomic vault depends on a variety of factors. Feasibility is the first. In most cases, the *ravalement*, squaring, and templates methods are interchangeable and can be applied to execute the same vault, as is the case with the entrance to a *descente de cave*. A few vaults constitute exceptions, such as cloister vaults, which cannot be executed with the templates method, and the helical barrel vault of the Vis de Saint Gilles type, which can be cut with the squaring and templates methods but not with the *ravalement* one[11]. In many instances, vaults are realized with hybrid methods that involve combinations of tools and approaches from the three categories described above. The rate of wages for specialized workmanship and the costs of material and transportation also play a crucial role in the choice of cutting method. For instance, while choosing the templates method may be wise for a building site located far from quarries and waterways because it allows for saving a substantial amount of material and lower transportation costs, squaring may be preferable in a building site located near the quarry even if this cutting method drives up the labor

[11] On the morphology of these vaults, and how it prevents from applying certain cutting methods to execute them, see *Encyclopédie des métiers*… cit., III, pp. 226-228 and 381-385.



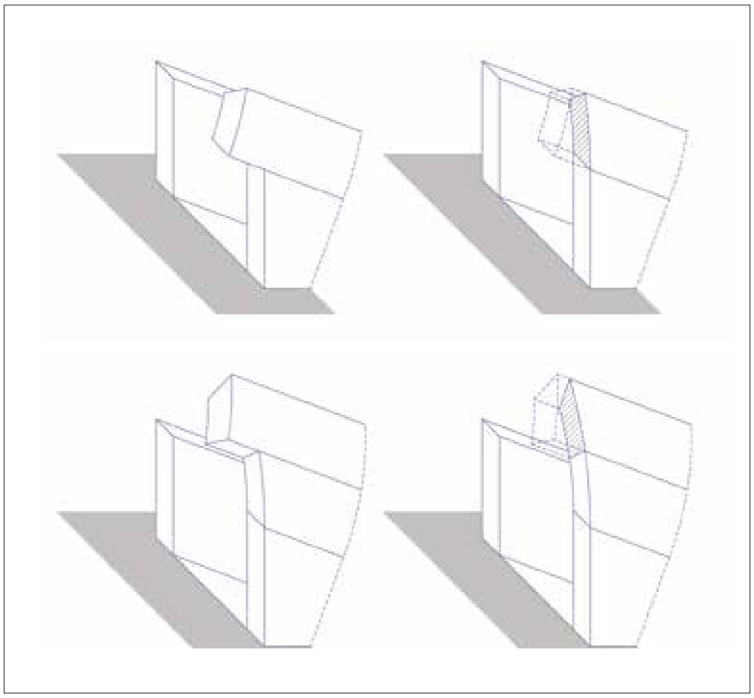


Fig. 9 *Longitudinal cross-section, transversal cross-section and axonometric view of the entrance to a descente de cave (drawing S. Galletti).*

Fig. 10 *Ravalement cutting method applied to the entrance to a descente de cave (drawing S. Galletti).*

costs by extending the cutting process. Depending on time, place, and the size of the building site, it may be a better choice to place the bulk of the workload on the stonecutters rather than on the highly specialized and high-earning *appareilleurs*, as one should keep in mind that, in the pre-modern world, expert *appareilleurs* were among the highest paid members of the building trades[12]. The type of contractual agreement between patron, designer(s), and workers also matters in this regard since, as Frézier explains, in cases where *appareilleurs* and stonecutters are paid a flat rate on the finished work but are not responsible for the provision of stone, they have no incentive in investing time in the production of *épures* and templates in order to avoid the waste of material[13]. Yet, costs and building site management do not account for what may be the most relevant factor in determining the cutting method for the execution of a stereotomic vault: the pride *appareilleurs* and stonecutters take in executing a vault with what they view as the most elegant – i.e. skillful, streamlined, and waste-less – of the methods they master. The choice of using *épures* and templates is often the way in which such pride manifests. Stereotomy is indeed a virtuoso art, first and foremost in the eyes of those who practice it.

Épures are a subset of technical drawings specifically produced to solve the geometric challenges posed by stereotomic vaults. They integrate a vault's defining orthographic views, the geometric constructions necessary to define the shape of its components, such as plane rotations and surface developments, and the templates that will be passed onto the stonecutters for the execution of the voussoirs. The combination of these elements – orthographic views, geometric constructions, and final templates – into a single graphic product distinguishes *épures* from other, less complex forms of technical drawings used in pre-modern building sites, such as *modani*. *Épures* are the direct predecessors of the drawings utilized in modern descriptive geometry, for they feature the plane rotations and surface developments that are at the very core of Monge's theory about the two-dimensional representation of three-dimensional objects.

Typically, *épures* are traced on site at full scale and have functions similar to those of modern blueprints: they are produced by the *appareilleur* to communicate the geometry of the vault and its voussoirs to all the craftsmen involved in its making – the stonecutters, the carpenters who produce the centering, and those who, where needed, prepare the templates – and they are used to control the shape of the vault and its components throughout the execution process. The *épures* that illustrate early modern stereotomy books such as de L'Orme's and Vandelvira's are small-scale renditions of the full-scale tracings used in building sites.

Vestiges of pre-modern *épures* are a rare find because they were often traced on provisional surfaces such as the wooden planks of a vault's scaffolding or the plaster beds covering the pave-

[12] Data on building-trade wages in fifteenth- and sixteenth-century France is found in C. Grodecki, *Documents du minutier central des notaires de Paris: histoire de l'art au XVI[e] siècle* (1540-1600), Paris 1985 and É. Hamon, *Documents du minutier central des notaires de Paris: art et architecture avant 1515*, Paris 2008.

[13] Frézier, *La théorie et la pratique de la coupe des pierres…* cit., pp. 14-15.

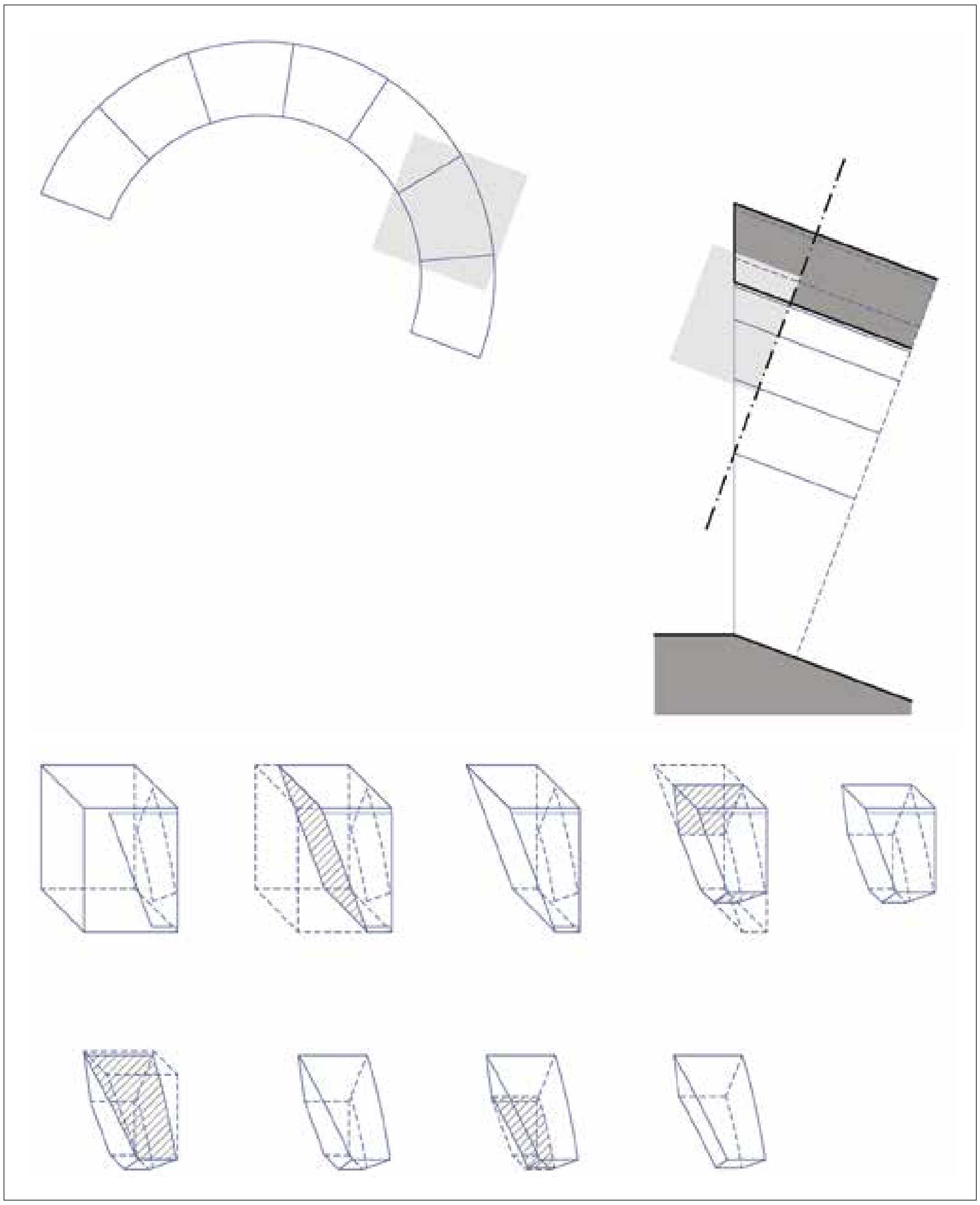


Fig. 11 *Squaring cutting method applied to the entrance to a descente de cave (drawing S. Galletti).*

ment of a tracing house[14]. Those that have been preserved are the *épures* that were drawn directly on the walls and floors of buildings, according to a practice of drawing on stone that dates back at least to ancient Egypt and which was still in use in early modern Europe[15]. With regard to stereotomy, an early example of *épure* traced on stone is found in the vestry of Murcia Cathedral[16]. Yet, the oldest stereotomic *épures* preserved are not full-scale, construction-site tracings but the small-scale renditions included in the thirteenth-century sketchbook of Villard de Honnecourt[17]. Villard's drawings show that the practice of transferring stereotomic knowledge through books – as opposed to oral transmission in the building site – largely predates the treatises of de L'Orme, Vandelvira, and their peers.

The emergence of *épures* in the medieval and early modern era is associated with a renewed interest in geometry and with the development of the templates cutting method, which, as mentioned above, requires a higher mastery of solid geometry compared to other cutting techniques in exchange for a reduction in material and transportation costs. Sixteenth-century authors of stereotomy books show a clear preference for the templates cutting method and, therefore, for the production of small-scale *épures* on paper. These circulated in manuscript form through the works of practitioners such as Pedro de Alviz (?-ca. 1545), Hernán Ruiz the Younger (ca. 1514-1569), and Vandelvira among others, as well as, starting with the publication of de L'Orme's *Premier tome* in 1567, in printed works whose intended audience was much wider than the circles of initiated professionals to whom earlier manuscripts were addressed[18]. The popularity of *épures* and templates at this point in

14 On the various tracing techniques used in medieval and early modern construction sites, see especially R. Bechmann, *Villard de Honnecourt: la pensée technique au XIII^e siècle et sa communication*, Paris 1993, pp. 52-58; M.Á. Cajigal Vera *et al.*, *The Full-Scale Tracings of the Parish Church of Nogueira Do Miño*, in *I tracciati di cantiere: disegni esecutivi per la trasmissione e diffusione delle conoscenze tecniche*, a cura di A. Pizzo, C. Inglese, Roma 2016, pp. 108-117; and I. Camiruaga *et al.*, *Conservation of Early Modern Architectural Large-Scale Tracings: Challenges and Approaches*, ivi, pp. 118-126.

15 For a history of tracings on stone in particular, see C. Inglese, *Progetti sulla pietra*, Roma 2000.

16 J. Calvo López *et al.*, *The Tracing for the Sail Vault at the Murcia Cathedral Vestry: Surveying a 16th-Century Full-Scale Working Drawing*, "International Journal of Architectural Heritage: Conservation, Analysis, and Restoration," VII, 2013, 3, pp. 275-302. Further examples are found in M.J. Freire Tellado, *Los trazados de montea de factura renacentista del edificio de los escolapios de Monforte de Lemos (Lugo)*, in *Actas del Segundo Congreso Nacional de Historia de la Construcción* (A Coruña, 22-24 octubre 1998), edición F. Bores Gamundi, Madrid 1998, pp. 173-180; M. Taín Guzmán, *La utilización de monteas en la construcción en piedra: el caso gallego*, in *El arte de la piedra: teoría y práctica de la cantería*, edición J. Roldán Martín, Madrid 2009, pp. 173-204; and J. Calvo López *et al.*, *Métodos de documentación, análisis y conservación de trazados arquitectónicos a tamaño natural*, "Arqueología de la Arquitectura," XII, 2015, http://dx.doi.org/10.3989/arq.arqt.2015.024, last accessed on 22 May 2019.

17 C. Lalbat, G. Marguerite, J. Martin, *De la stéréotomie médiévale: la coupe des pierres chez Villard de Honnecourt, I*, "Bulletin monumental", 145, 1987, pp. 387-406 and C. Lalbat, G. Marguerite, J. Martin, *De la stéréotomie médiévale: la coupe des pierres chez Villard de Honnecourt, II*, "Bulletin monumental", 147, 1989, pp. 11-34.

18 P. de Alviz, *Dibujos de trazados arquitectónicos*, ms. 12686, Biblioteca Nacional de España, 12686; H. Ruiz el Joven, *El Libro de arquitectura*, ms R16, Biblioteca de la Escuela Técnica Superior de Arquitectura de Madrid, in *El Libro de arquitectura de Hernán Ruiz, el joven*, edición P. Navascués Palacio, Madrid 1974; De L'Orme, *Premier tome*… cit.; Vandelvira, *Libro de traças*… cit.

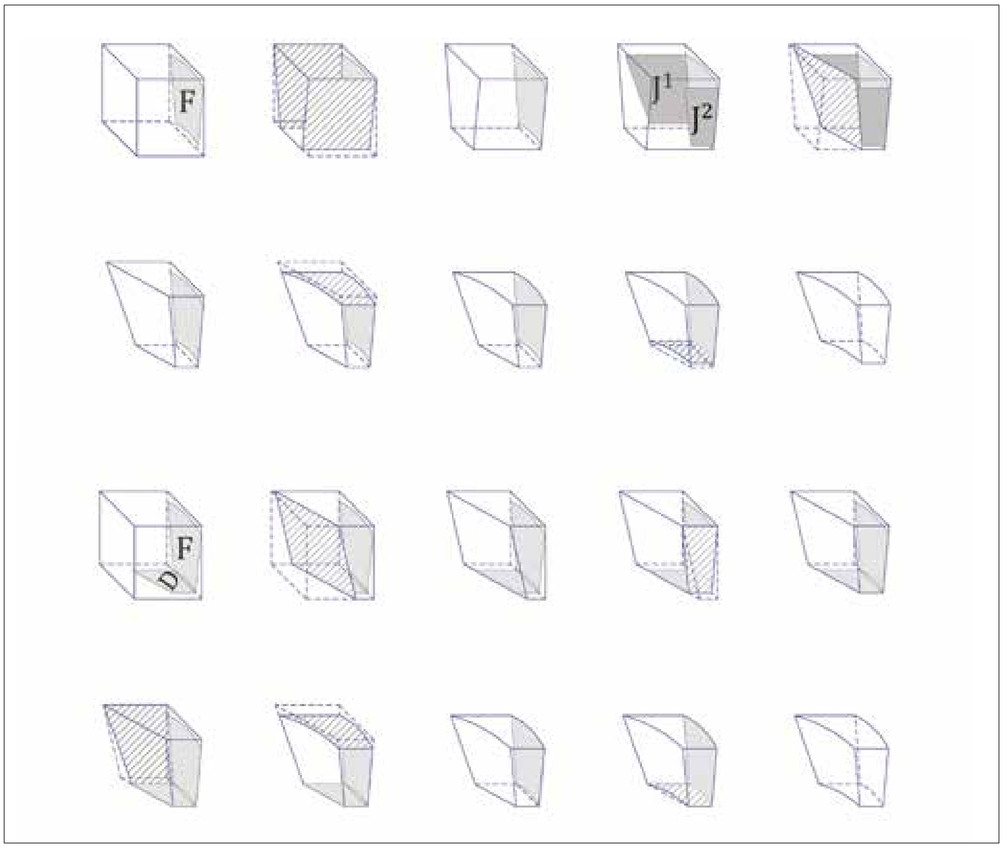


Fig. 12 *Templates cutting method applied to the entrance to a descente de cave (drawing S. Galletti).*

Fig. 13 *Paper template for stonecutting (photo Journal d'une formation de taille de pierre, in http://formationtailledepierre.blogspot.com/, last accessed on 22 May 2019).*

time was not due to practical reasons only but, for the most ambitious among stereotomy's theoreticians, to intellectual ones as well: because the use of the templates cutting method and the production of *épures* require the mastery of Euclidean geometry, they provide some latitude for claiming that stereotomy belongs with the mathematical sciences rather than the mechanical arts. Such a claim is especially central to de L'Orme's attempt, in the *Premier tome*, at defining the professional figure of the architect as "*docte*" (learned) – that is, conversant in both theoretical and practical matters. Indeed, it is unsurprising that de L'Orme's description of such *arteficem doctum* is found in the opening chapter of Book III, the first of two books he dedicates to stereotomy in his treatise[19].

Viewers are easily baffled by the *épures* of stereotomic vaults, which seem unintelligible to the non-initiated eye and, at times, even hardly recognizable as representations of architectural objects. The comparison between a trumpet vault and its *épure* is a case in point (figs. 16-17). The challenge these drawings pose is twofold: on the one hand, because they represent architectural objects at full scale, *épures* were codified in order to occupy the least possible space so that they can fit in the very same room where they will be used. This implies that a vault's defining orthographic views are not separated but superimposed in its *épure*, as are the geometric constructions derived from them in order to establish the true sizes and shapes of the vault's voussoirs. On the other hand, contours, section lines, and projection lines – which modern practitioners mark in their drawings by using regular, thick, and dashed lines respectively – are not graphically distinguished from each other in *épures*. This lack of graphic codification is due not only to the fact that the use of *épures* predates by several centuries the conventions introduced by descriptive geometry, but also to the fact that such conventions would have been hardly applicable anyway under the original conditions of production of *épures*, as it is virtually impossible to accurately define a line's thickness when tracing at full scale on a plaster bed or directly on stone.

Pre-modern stereotomy books that illustrate the reduced-scale renderings of full-scale *épures* do not simplify the readers' task. Quite to the contrary, the combined challenges of small-scale representation and of coordinating text and illustration add layers of visual barriers to the material. The sketchbook of Villard de Honnecourt is a case in point, for it was only in the late 1980s, and only thanks to a team of practitioners, that a number of its illustrations were recognized as small-scale *épures* of stereotomic arches

[19] De L'Orme, *Premier tome*… cit., ff. 50*r*-51*v*.

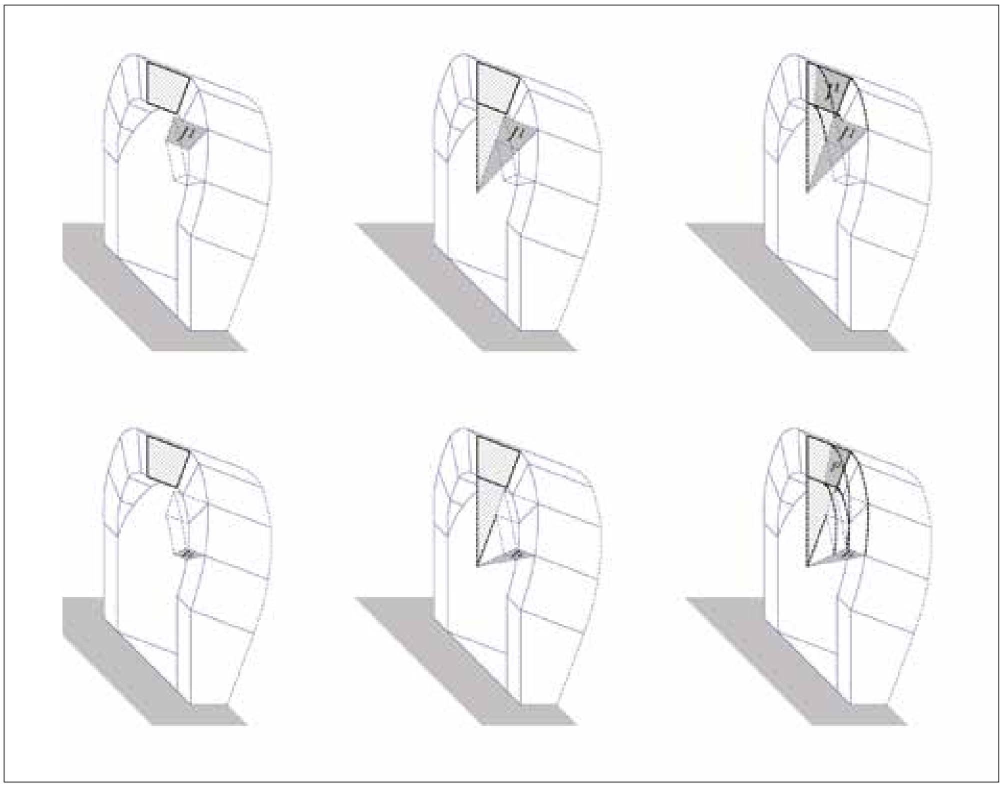


Fig.14 *Geometric constructions necessary to derive the templates of joint faces J*[1] *and J*[2] *from the orthographic views of the entrance to a descente de cave (drawing S. Galletti).*

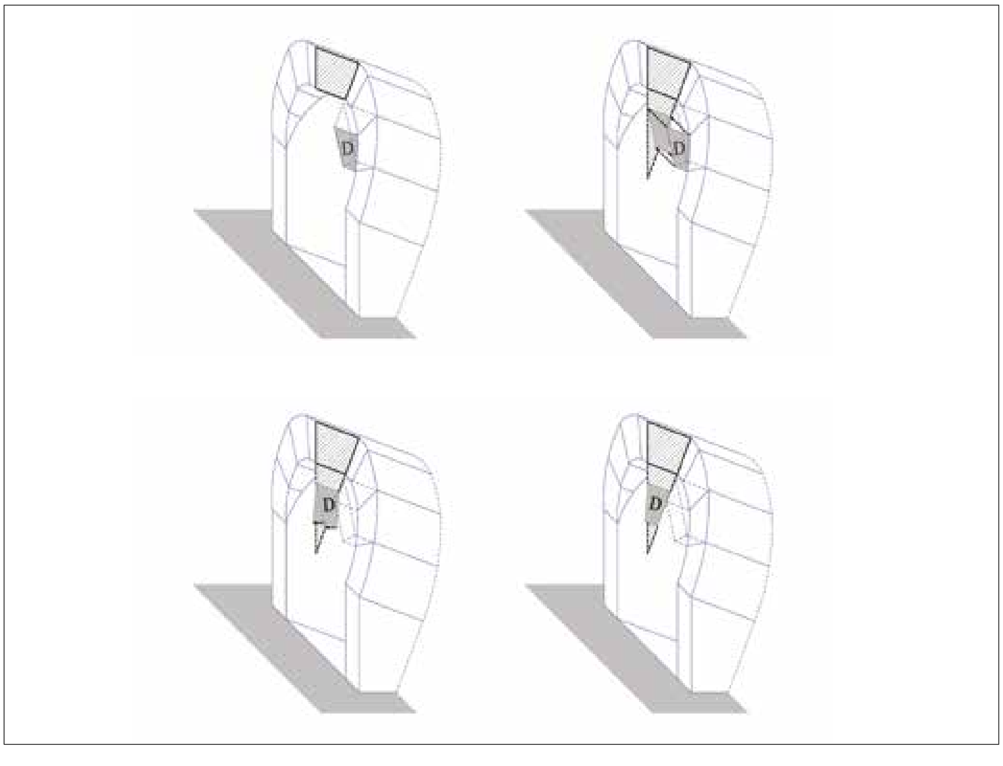


Fig. 15 *Geometric constructions necessary to derive the template of intrados face D from the orthographic views of the entrance to a descente de cave (drawing S. Galletti).*

and vaults[20]. Unsurprisingly, the reduced-scale *épures* illustrated in the cohesive works of sixteenth-century theoreticians are far more readable than those found in Villard's sketchbook – if only because they are bigger in scale and accompanied by textual descriptions.

The layout of de L'Orme's Books III and IV dedicated to stereotomy is exceptionally well organized: the *épures* are arranged according to the level of difficulty of their execution, from the easiest to the most complex of stereotomic works; they are illustrated in the largest possible format allowed by the width of the page, often in full page format; and they are accompanied by textual descriptions that precede the drawings. Also, de L'Orme's illustrations are neatly and carefully executed, with minimal deformation of the geometries represented, i.e. the geometries described in the accompanying text are easily recognizable in the illustrations themselves.

[20] See works cited in note 17.
[21] M. Jousse, *Le secret d'architecture découvrant fidèlement les traits géométriques, couppes, et derobemens nécessaires dans les bastiments enrichi d'un grand nombre de figures, adioustées sur châque discours pour l'explication d'iceux*, La Flèche 1642; G. Martínez de Aranda, *Cerramientos y trazas de montea* [ca. 1600], Biblioteca Central Militar, ms 457, in *Cerramientos y trazas de montea: Ginés Martínez de Aranda*, edición A. Bonet Correa, Madrid 1986.

In some cases, the *épures* are marked by letters and/or numbers that are referenced in the body of text, to facilitate the identification of specific elements of the drawing. Yet, de L'Orme uses the same superimposition of plans, elevations, and cross-sections that characterizes the full-scale *épures* used in building sites and, again like in full-scale tracings, he does not distinguish graphically between contour, section, and projection lines or does so inconsistently, for instance by using interchangeably continuous and dashed lines for projections, as exemplified by his *épure* of the entrance to a *descente de cave* (fig. 1, in which the longitudinal and transversal cross-sections of the vault are shown in white and black, respectively, along with the joint and intrados faces of one of its voussoirs J^1 and D, at the center; at the bottom, the section, contour, and projection lines of the épure are shown in black, white, and dashed lines, respectively). The same is true of de L'Orme's sixteenth-century peers, including Pedro de Alviz, Hernán Ruiz the Younger, and Vandelvira. (It is only in the seventeenth century that a degree of consistency will be introduced in the use of continuous and dashed lines, for instance in the treatises of Martínez de Aranda and Mathurin Jousse)[21]. Indeed, one of the most striking features of early books dedicated to stereotomy is that their authors did not take full advantage of the medium onto which they translated their material. Books, both manuscript and printed, afforded the possibility of presenting *épures* in their building-site, synthetic form *as well as* including a series of separate images for orthographic projections and geometric constructions, each provided with distinctive graphic conventions; yet, the paper *épures* illustrated in early modern books remained conceptually identical to their stone predecessors. Moreover, because the *Premier tome* marks the first appearance of *épures* in printed form, the book testifies to the extra set of challenges raised by the technological advance of the printing press. It should be kept in mind that, at the time of publication of the *Premier tome*, in 1567, the illustrated printed book of architecture was still a novelty – the first of such publications, Fra' Giocondo's *Vitruvius*, had come out only in 1511. As a genre, these had a potential yet to be fully explored with technical glitches far from being solved. The diffusion of the printing press helped avoid the issues associated with unreliable manual copies of architectural illustrations differing from one manuscript to the next, but the possibility for images to be mechanically reproduced was no guarantee of either their accuracy or their fixity[22]. Indeed, the printing process introduced a number of intermediate steps in the transfer of architectural drawings onto paper: from an architect's originals, to the cutter's matrices (or plates), and from these to the printer's damp paper folios, the quality of which may vary from one ream to the next. Each of these steps had the potential to introduce elements of inaccuracy, especially in the case of reduced-scale geometric drawings like *épures*. Indeed, the printing press transferred the problem of illustration inaccuracy from the process of reproduction of a book to that of its production. De L'Orme warns his readers of precisely this type of issue in a passage illustrating the *épure* of a trumpet vault:

> I want nonetheless warn readers that my illustrations were not as accurately executed as I had drawn them because woodcutters dampen, and sometimes boil, the paper [of the original drawing] before fixing it on the woodblock for carving and, depending on the way they stretch said paper, it extends in one direction and shrinks on the opposite one, which is why, in many instances, my illustrations are not as accurate as I had drawn them, nor have they preserved their original proportions[23].

Discrepancies between letter and/or number references found in the illustrations and in the explanatory texts that accompany them are also a

[22] On the instability of early modern printed material, see A. Johns, *The Nature of the Book: Print and Knowledge in the Making*, Chicago 1998. Cf. with the exaggerated notion of fixity of early printed texts and images in E.L. Eisenstein, *The Printing Press as an Agent of Change*, Cambridge 1979, and M. Carpo, *L'architettura dell'età della stampa: oralità, scrittura, libro stampato e riproduzione meccanica dell'immagine nella storia delle teorie architettoniche*, Milano 1998.
[23] De L'Orme, *Premier tome*… cit., f. 106*v*. My translation.
[24] For example, in De L'Orme, *Premier tome*… cit., ff. 5*r* and 178*r*. In the *erratum* that closes the volume, de L'Orme provides corrections for some but not all of these discrepancies, several of which remained unaccounted for at the time of printing (ivi, f. 285*r*).

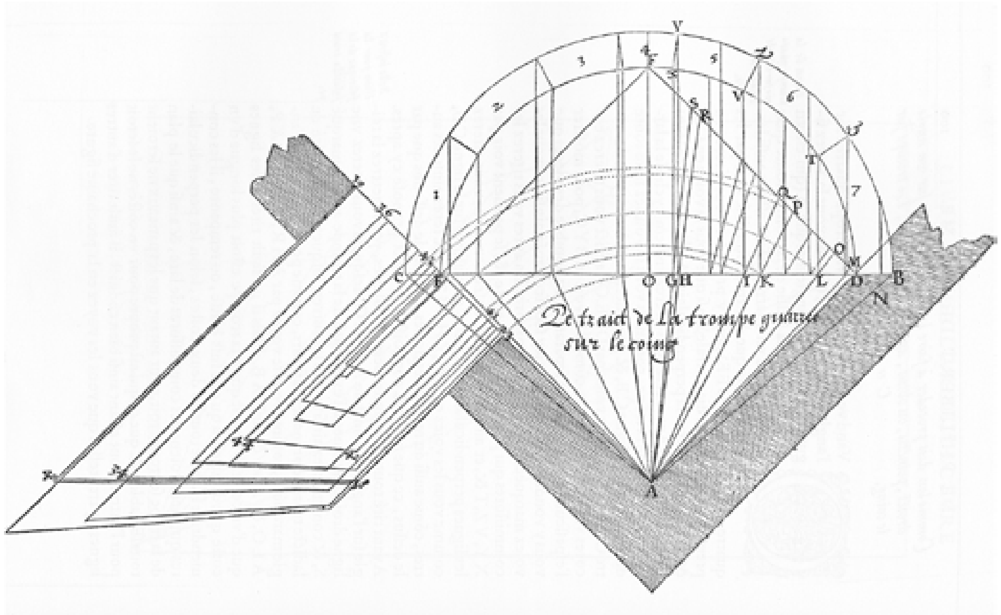


Fig.16 *Porte du Capitole, Toulouse, ca. 1620. Twin stereotomic trumpet vaults on square plan (photo C. Léna, Wikimedia Commons, CC BY-SA 4.0).*

Fig. 17 *Philibert de L'Orme's épure of a trumpet vault on square plan (in* De L'orme, *Premier tome… cit., f. 100v).*

common problem in sixteenth-century printed books, and one that de L'Orme mentions in several instances[24]. Of course, disagreements of this kind can be an annoying source of confusion for any image, but in the case of *épures*, where numbers and letters guide the reader step-by-step through the workings of combined orthogonal projections, plane rotations, and surface developments, they can easily invalidate the readability of an image and of the text that accompanies it. Reading *épures*, both full scale and on paper, is a complex task for non-practitioners, but not an impossible one. It requires a basic understanding of solid geometry, of the conventions that characterize stereotomic drawings, and of the production process of stereotomic vaults. Here, I use de L'Orme's *épure* for the entrance to a *descente de cave* to demonstrate how *épures* are produced and how they should be read.

As described earlier, the entrance to a *descente de cave* materializes the sectioning of an inclined semi-cylinder (the barrel vault covering the ramp or flight of stairs) by a vertical plane (the entrance wall) and its defining orthographic projections are the transversal and longitudinal cross-sections, which provide the shape and size of the barrel vault and the inclination at which it meets the vertical plane of the wall (see fig. 9). In his *épure*, de L'Orme draws the longitudinal and transversal cross-sections of the vault (highlighted in white and black, respectively, in figure 1); he then solves the stereotomic problem posed by this vault by finding the joint and intrados faces of its voussoirs (J^1 and D for the voussoir labeled L), which will allow cutting with the templates method. Figures 18 and 19 show, in a format that unpacks the synthetic representation that is characteristic of *épures*, the geometric constructions de L'Orme employs to find the true shapes and sizes of joint and intrados faces of voussoir L.

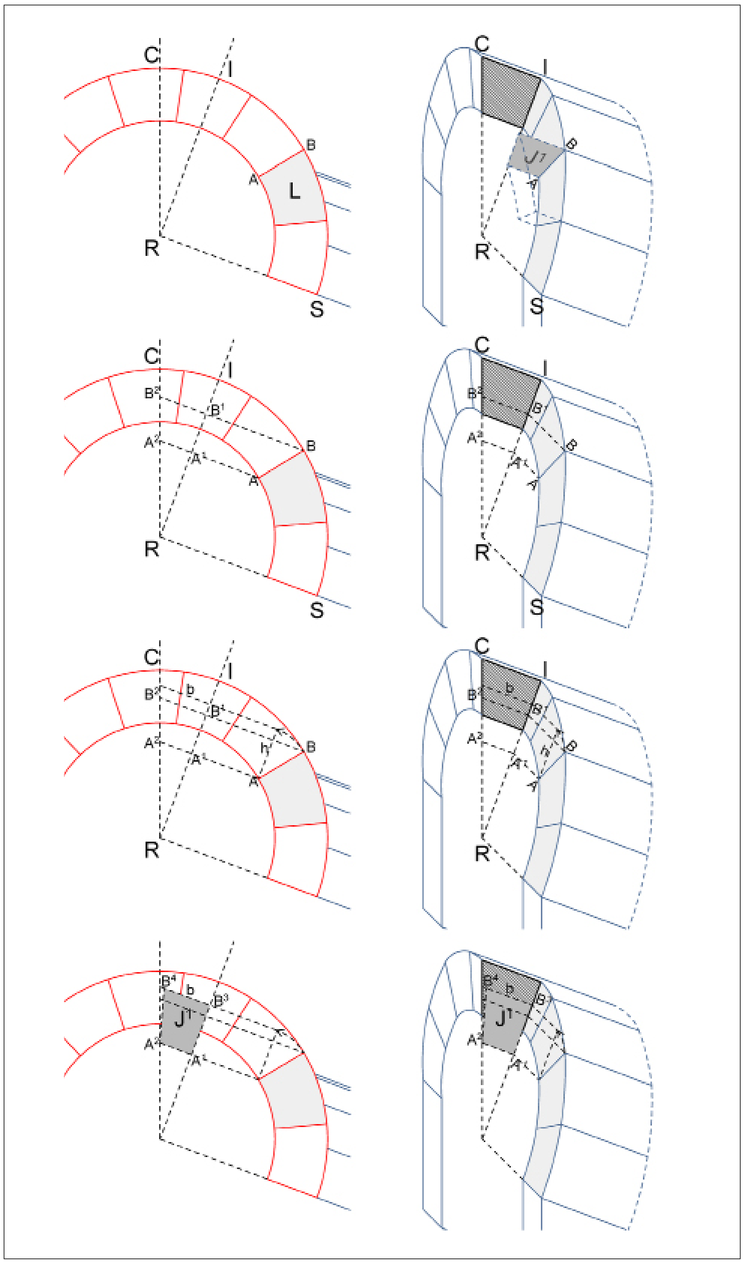
Figure 18 shows the subsequent steps necessary to find the joint face J^1, which are visualized as paired drawings illustrating, on the left column, a simplified version of de L'Orme's *épure* and, on the right column, the axonometric view of the vault. The first pair of drawings illustrates the geometric problem: the axonometric view on the right shows the joint face J^1 de L'Orme is looking for, and the simplified *épure* on the left shows the two-dimensional representation of de L'Orme's three-dimensional problem – note that in the *épure* the perpendicular planes IRS and CRI are represented as coplanar, i.e. the *épure* implies a 90° rotation of plane CRI along the axis $\overleftrightarrow{RI}$ to form plane CRS. Also note that the side of J^1 marked $\overline{AB}$ is the only one provided in true shape and size by the vault's defining orthographic views, for it is featured on the transversal cross-section. The second pair of drawings shows how de L'Orme first projects the segment $\overline{AB}$ onto the longitudinal cross-section plane CRI, finding points A^1 and B^1, and then projects A^1 and B^1 onto the vertical plane of the *descente*'s entrance, CRS, finding points A^2 and B^2. The trapezoid $A^1B^1B^2A^2$ thus obtained is the vertical orthographic view of the joint face J^1 – that is to say that its top and bottom sides, $\overline{B^1 B^2}$

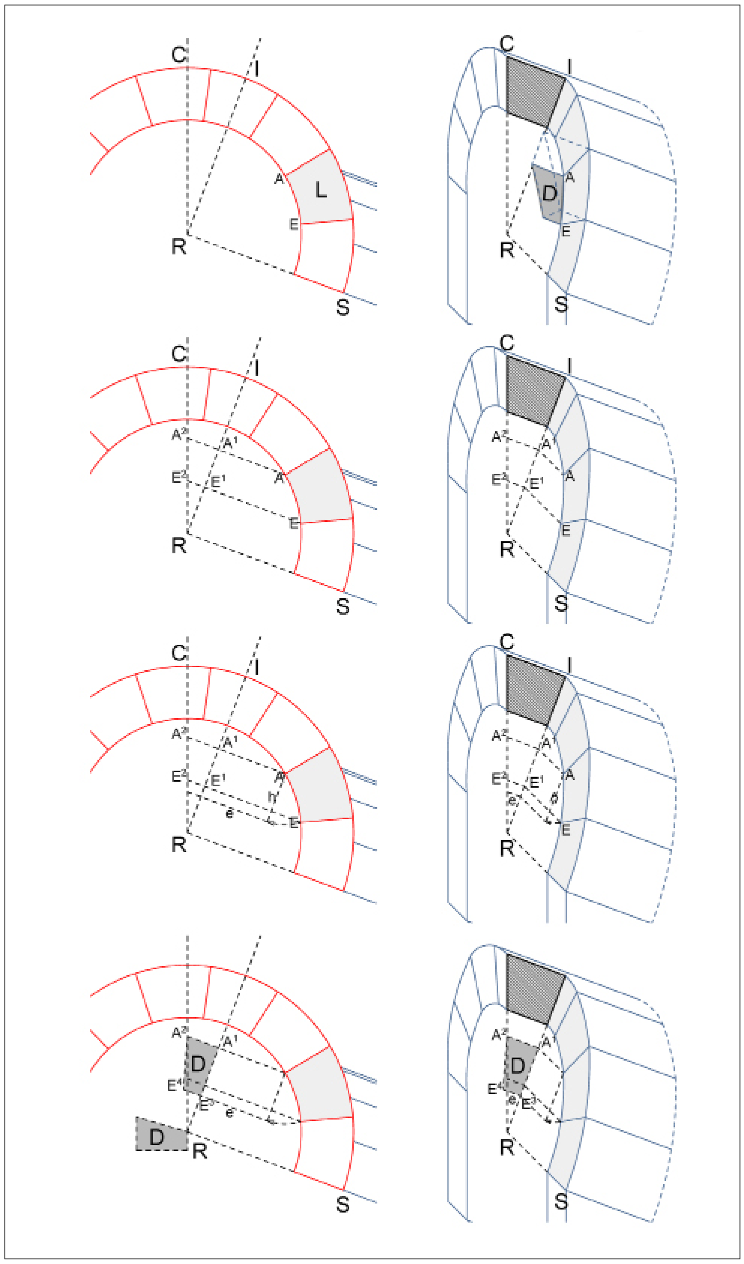
and $\overline{A^1A^2}$, have the true lengths of the top and bottom sides of J^1, whereas its height is shorter than that of J^1, which is segment $\overline{AB}$. The third pair of drawings shows how, in order to find the true height of the trapezoid $A^1B^1B^2A^2$, de L'Orme transfers the length of segment $\overline{AB}$ onto plane *CRI* by rotating it to a position parallel to $\overleftrightarrow{RI}$, thus obtaining height *h* and tracing the projection line *b*. Finally, the fourth pair of drawings shows how de L'Orme transfers the length of segment $\overline{B^1B^2}$ – the true length of the upper side of J^1 – onto line *b*, finding points B^3 and B^4. The trapezoid $A^1B^3B^4A^2$ thus obtained is the true shape and size of joint face J^1 de L'Orme was looking for (cf. fig. 1). The four steps illustrated in figure 18 are the equivalent of the rotation of the plane that contains J^1 onto the vertical plane of the vault's longitudinal cross-section illustrated in figure 14.

Figure 19 illustrates the same geometric constructions applied to the intrados face *D* of voussoir *L*. The first pair of drawings illustrates the geometric problem: the simplified *épure* on the left is the same as in the previous example, whereas the axonometric view on the right shows the intrados face *D* de L'Orme is looking for. The second pair of drawings shows how de L'Orme first projects the arc length $\widehat{AE}$ onto the longitudinal cross-section plane *CRI*, finding points A^1 and E^1, and then projects A^1 and E^1 onto the vertical plane of the *descente*'s entrance, *CRS*, finding points A^2 and E^2. The trapezoid $A^1A^2E^2E^1$ thus obtained is the vertical orthographic view of the intrados face *D* – that is to say that its top and bottom sides, $\overline{A^1A^2}$ and $\overline{E^1E^2}$, have the true lengths of the top and bottom sides of *D*, whereas its height $\overline{A^1A^2}$ is shorter than that of *D*, which is arc $\widehat{AE}$. The third pair of drawings shows how, in order to find the true height of the trapezoid $A^1A^2E^2E^1$, de L'Orme transfers the length of arc $\widehat{AE}$ onto plane *CRI* by rotating it to a position parallel to $\overleftrightarrow{RI}$, thus obtaining height *h* and tracing the projection line *e*. Finally, the fourth pair of drawings shows how de L'Orme transfers the length of segment $\overline{E^1E^2}$ – the true length of the lower side of *D* – onto line *e*, finding points E^3 and E^4. The trapezoid $A^1A^2E^4E^3$ thus obtained is the intrados face *D* de L'Orme was looking for (cf. fig. 1). Note that, in his *épure*, de L'Orme transfers the representation of the intrados faces, including *D*, to the bottom part of his illustration, under the sectioning line $\overleftrightarrow{RS}$, in order to avoid overlapping with the joint faces above it (see fig. 1). Also note that the curvature of *D* along the arc $\widehat{AE}$ is disregarded in this construction because the cutting of the voussoir will be executed in two phases: first, a template of the size and shape of trapezoid $A^1A^2E^4E^3$ will be used to define the intrados of the voussoir as a flat surface; then, a bevel square will be used to carve on such surface the curvature corresponding to the arc $\widehat{AE}$[25]. The four steps illustrated in figure 19 are the equivalent of the horizontal translation and rotation of the plane that contains *D* onto the vertical plane of the vault's longitudinal cross-section illustrated in figure 15.

The plane rotations shown here are key to the understanding of stereotomy and its graphic expression in *épures*. The geometric challenge posed by stereotomy is precisely about the definition of voussoirs' surfaces that lie on neither the vertical nor the horizontal plane and which, thus, need to be rotated or developed onto either one of the orthographic views in order to be graphically described in their true shape and size. The difficulty in the reading of *épures* is largely due to their nature as synthetic images in which the orthographic views of a given stereotomic work overlap with the geometric constructions required to derive the templates of its voussoirs from those same views, as well as with the final templates themselves. Yet, as shown in the case study of the entrance to a *descente de cave*, a ba-

[25] A bevel square (*biveau*) is a square with movable arms that has one straight arm and a second, curved arm that reproduces the curvature of the desired voussoir's face. An illustration is found in De L'Orme, *Premier tome*… cit., f. 56*r*, where the bevel square is labeled with the letter A.





sic understanding of solid geometry, of the conventions that characterize stereotomic drawings, and of the production process of stereotomic vaults are sufficient to unpack an *épure*'s multi-layered format and to access its geometric content. As also shown in this case study, *épures* are not only multi-layered drawings, but also drawings in which non-coplanar planes are represented as co-planar. As such, they are the direct precedent for descriptive geometry's convention of representing as co-planar (or unfolded) the horizontal, frontal, and profile planes containing the three defining orthographic views of a three-dimensional object. Indeed, the rotation of orthographic and auxiliary planes, and of the points, lines, and surfaces that they contain, is the defining element of *épures* as instruments of spatial representation, as well as the important legacy of pre-modern stereotomy to modern mathematics. Understanding how *épures* are produced and read allows assessing with precision the level of geometric knowledge possessed by their designers, for these drawings function as clear markers of the ability to conceive and control different sets of three-dimensional geometries and their two-dimensional renditions. Indeed, the case study of the entrance to a *descente de cave* illustrated in the *Premier tome* demonstrates that de L'Orme's mathematics skills were far more advanced than scholarship has traditionally recognized[26]. As such, it not only serves as a methodological key that allows accessing other, more complex *épures* illustrated in de L'Orme's treatise, but it also significantly improves our appreciation of the intellectual scope and ambition of the treatise as a whole.

Fig.18 *Step-by-step geometric constructions used by de L'Orme in the épure for the entrance to a descente de cave in order to find the true shape and size of joint face J^1 of voussoir L (drawing S. Galletti).*

Fig.19 *Step-by-step geometric constructions used by de L'Orme in the épure for the entrance to a descente de cave to find the true shape and size of intrados face D f voussoir L (drawing S. Galletti).*

[26] See, among others, J.P. Manceau, *La culture mathématique de Philibert De l'Orme*, in *Philibert De l'Orme, un architecte dans l'histoire. Arts, sciences, techniques*, éd. F. Lemerle, Y. Pauwels, Turnhout 2016, pp. 191-198.