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Philibert de L'Orme's Dome in the Chapel of the Château d'Anet: The Role of Stereotomy

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ABSTRACT

The coffered dome designed by Philibert de L'Orme (1514–70) for the chapel of the Château d'Anet in northern France between 1549 and 1552 is a masterpiece of stereotomy — the stone vaulting technique characterised by the custom cutting (or dressing) of a vault's components or voussoirs. The dome was executed by first individually dressing its large voussoirs, so that they would fit one another precisely, and then dry assembling them like the pieces of a three-dimensional jigsaw puzzle. The spiralling ribs that form the coffers added a layer of complexity to the work, for they are embedded in the voussoirs; thus the exact shape and position of the rib sections belonging to each voussoir had to be calculated precisely before dressing to ensure that, after assembling, they would form the correct pattern over the vault's surface. The dome's execution method continues to baffle historians, in particular with regard to the transfer of the complex pattern formed by the ribs on to the templates used by the stonecutters to shape the voussoirs. Based on a new 3D laser scan of the dome and on the analysis of late medieval and early modern stereotomic practices and theories, this article offers a new interpretation of the methods that de L'Orme adopted at Anet and of their significance within the panorama of sixteenth-century architectural practice and theory.

The dome covering the chapel of the Château d'Anet in northern France (Fig. 1) was designed and realised by Philibert de L'Orme between 1549 and 1552 as part of the campaign of renovations that the architect undertook for Diane de Poitiers (1500–66), Duchesse de Valentinois, seneschal of Normandy and all-powerful mistress of King Henry II of France (1519–59). The dome is regarded as a masterpiece of stereotomy — the stone vaulting technique characterised by the custom cutting (or dressing) of a vault's components or voussoirs — and de L'Orme as one of the most influential theoreticians of the practice, of which he was the first to produce a printed theory in books III and IV of his architectural treatise *Le Premier tome de l'architecture* (1567). While an abundant literature exists on both the Anet dome and its architect, as well as on French stereotomy in general, the vault's geometry and its method of execution puzzle architectural historians to this day. The literature is laden with unresolved documentary, interpretative and methodological questions; the very appearance of the vault has been consistently misrepresented; the generative pattern of its intersecting ribs has been

Fig. 1. *Château d'Anet, dome covering the chapel, 1549–52 (Binche, Wikimedia Commons)*

often misunderstood, along with its relationship to the *opus sectile* (marble inlay) floor that lies below (Fig. 2); and the practical challenges involved in its execution — the geometrical and dressing methods applied by its makers — have been left unexamined. As a result, the significance of the dome has been misunderstood, in terms of both its relations with medieval traditions of vaulting and its role in architectural invention as conceived by de L'Orme.

Analyses of the chapel have typically been based on drawings made from the sixteenth to the nineteenth century, none of which represents its architecture correctly. The most commonly used were produced by Jacques Androuet du Cerceau for *Les Plus excellents bastiments de France* (1576–79), which provide a rather loose rendering of the dome's surface of intrados and an incorrect representation of its projection on the floor

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Fig. 2. *Château d'Anet*, opus sectile *floor of the chapel, 1549–52 (photograph by the author)*

of the chapel. The floor pattern features six ranges of coffers between its outer and inner circles, whereas du Cerceau's plan shows only three and a half (Figs 2 and 3). Moreover, scholars have often taken at face value the passage of the *Premier tome* in which de L'Orme states that the floor's design is the orthogonal projection of the intrados of the dome, which is not true.[1] The dome features seven and a half ranges of coffers between its base and its oculus, whereas the floor features only six and is better described as a pseudo-projection than a proper projection (compare Figs 1 and 2). Philippe Potié added a layer of confusion to this matter by stating that the floor is the *épure* of the dome above — that is, the geometric construction drawing employed in its execution — and that, as such, it reveals the 'secret' of the vault itself.[2] His statement is directly contradicted by the floor's design, which features none of the elements that characterise the *épures* of

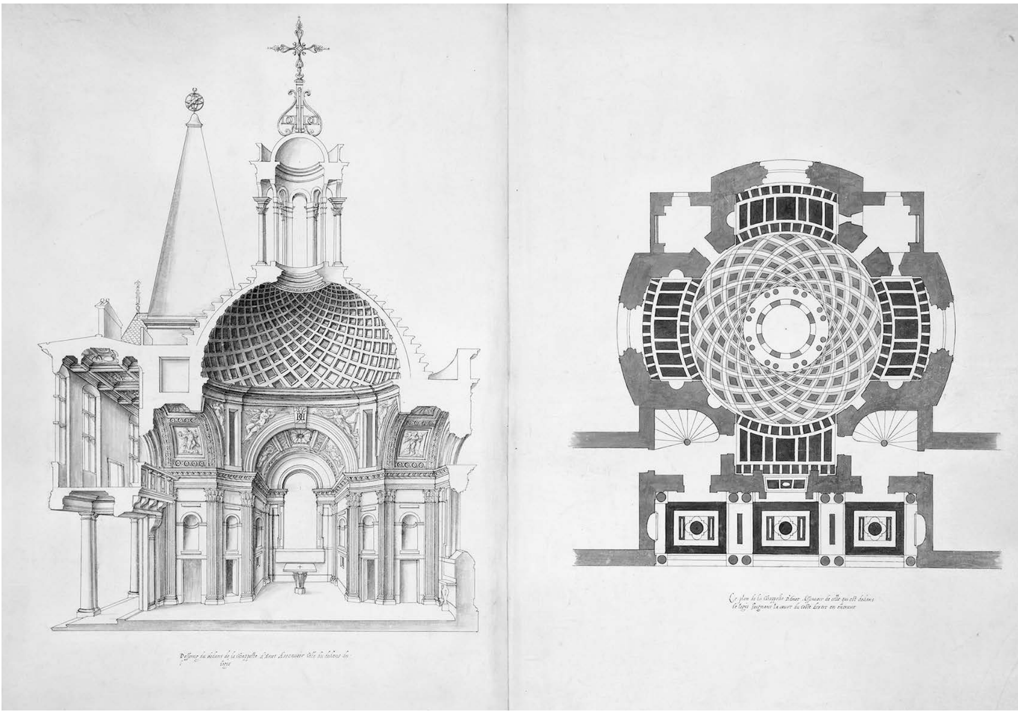

Fig. 3. *Jacques Androuet du Cerceau, perspectival cross-section and plan of the chapel of the Château d'Anet*, c. *1570 (British Museum 1972 U.888; British Museum Creative Commons)*

semi-spherical vaults, such as the cross-section and the surface developments employed to define the templates of its voussoirs. The coffers' distribution on the dome's intrados has also been misrepresented, with most authors from du Cerceau to Potié failing to notice that the dome sits on a low, one-course drum that raises its springing about 56 cm above the tall entablature below.

The inaccuracy of the chapel's visual documentation has affected historians' analyses of the dome's geometry and, in particular, of the methods de L'Orme may have used to generate the rib pattern that defines the coffering of its intrados. Anthony Blunt understood that such a pattern was produced by the interplay of a set of circles on the vault's ground plan, but his description applies to du Cerceau's drawing of the chapel's floor, featuring sixteen pairs of ribs, not the actual dome, which features eighteen.[3] Robin Evans corrected Blunt's mistake but introduced a different one, concerning the relation between the set of circles that generate the ribs and the circumference of the dome's base.[4] The first correct model for the dome's ground-plan geometry, produced by Manolo Gava and Nicola Trintinaglia, was not published until 2004.[5]

From a methodological perspective, the analyses of the Anet dome all share a fundamental conceptual flaw: that of employing three-dimensional geometry and illustrations to explore and explain a practice that is strictly two-dimensional. Stereotomists work exclusively with orthographic views — ground plans, elevations

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and cross-sections — of the vaults they realise, never with their three-dimensional renditions, such as axonometric or perspectival views. The geometric construction drawings that stereotomists derive from a vault's orthographic views — the above-mentioned *épures*, which are passed on to the stonecutters to execute the work — are also strictly two-dimensional. Because this convention makes stereotomic drawings almost unreadable for non-specialists, three-dimensional drawings are often employed in modern literature to discuss stereotomic practice. However, such drawings are often superfluous — that is, they do not add to the information provided by photographs of the vault at hand — and always deceptive because they suggest stereotomy is best understood in three dimensions. In fact, they prevent readers from appreciating the two-dimensional geometric constructions that lie at its core.

Based on a new 3D laser scan of the dome and on analyses of late medieval and early modern stereotomic practices and theories, this article offers a new hypothesis for the methods de L'Orme adopted to design and execute the Anet dome. To illustrate de L'Orme's working process, the analysis presented here relies exclusively on two-dimensional drawings and on the geometric knowledge available to stereotomists in de L'Orme's time. By clarifying the process behind the making of the Anet dome, the article shows how de L'Orme used stereotomy to engage with issues central to the architectural discourse of his time, such as the reinterpretation of ancient models and the role of geometry in the generation of architectural space. The chapel at Anet emerges as a practical demonstration of the creative possibilities afforded to designers by projective geometry and, as such, the built complement to de L'Orme's theory of stereotomy in the *Premier tome*.

STEREOTOMY

Stereotomy is the art of dressing 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 court of Charles V's Palace in Granada, from the larger category of stone vaults, such as those covering the nave of the church of St Séverin in Paris (Fig. 4). In Granada, the large voussoirs (compared to the overall dimensions of the vault) were individually cut to fit one another precisely and then assembled like the pieces of a three-dimensional jigsaw puzzle. In St Séverin, instead, the vaults' webs (the compartments between the ribs) were built using smaller stones of standard shape and size that, 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, whereas the shape and stability of the webs of St Séverin result from the wedge-like shaping of its mortar fillings.[6]

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 so-called Temple of Diana in Nîmes (Fig. 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

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Fig. 4. *Left: Pedro and Luis Machuca, Palace of Charles V, Granada, annular stereotomic vault covering the portico of the ground floor, 1562–68 (photograph by the author). Right: Church of St Séverin, Paris, non-stereotomic vaults covering the nave, late fifteenth century (Romanceor, Wikimedia Commons)*

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 on neither the vertical nor 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 dressing techniques, as was most probably the case at Jerash.[7] This distinction helps clarify why the ribs of St Séverin are also non-stereotomic, even though their components are large-sized and custom-cut, for ribs of the St Séverin type are linear elements whose geometries are fully defined in plan and elevations.

Stereotomy is best known for the variety of acrobatic masterpieces produced in early modern Spain and France.[8] However, stereotomy is neither European nor early modern; it has been practised over a wide chronological span, from Hellenistic Greece to contemporary Apulia, and across a broad geographical area, centred in the Mediterranean but reaching

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Fig. 5. *Left: West Bath, Jerash, stereotomic dome covering the caldarium, second century* CE *(Erics, Wikimedia Commons). Right: the so-called Temple of Diana, Nîmes, first century* CE *(Ji-Elle, Wikimedia Commons)*

far beyond — including the British Isles, Armenia and the Caucasus, as well as colonial Latin America.[9] The art is also known for a substantial body of theory that started with the books of architects such as de L'Orme and Alonso de Vandelvira (1544–*c.* 1625) and engaged practitioners and mathematicians alike in a heated debate continuing through the eighteenth century.[10] By focusing on the geometry of solids, this body of theory also crucially contributed to the definition of Gaspard Monge's theory of descriptive geometry, the branch of mathematics concerned with the two-dimensional representation of three-dimensional objects.[11] As the historian of mathematics Joël Sakarovitch has shown, modern solid geometry owes a substantial debt to the practice of stereotomy and to the experiments in complex vaulting conducted by generations of architects, *appareilleurs* (the master masons responsible for the production of *épures*) and stonecutters.[12]

THE ANET CHAPEL

In the original layout of Anet (Fig. 6), the chapel was located behind the east wing (since demolished) of the chateau, and was accessible from the portico of the ground floor as well as from the gallery of the apartment on the upper floor, where a balcony afforded a privileged view of its interior. The exterior of the chapel could only be appreciated from the *basse cour* (secondary courtyard) to the east of the chateau, whereas the bulk of its volume was invisible from the main courtyard, with the exception of the pointed twin roofs of the towers containing the stairs and, perhaps, of the very top of the lantern that sits over the dome. The extraordinary architecture of the chapel's interior was thus presented as a surprise to the visitor, unannounced by the homogenous elevations of the main courtyard, the sole accent of which was the frontispiece at the centre of the *corps de logis* (main residential wing).

The chapel is circular in plan, with four short arms radiating from the centre and four small rooms at the corners, which host the stairs and the sacristies (see Fig. 3). As Niklas Naehrig has pointed out, the plan is defined by a square modular grid and

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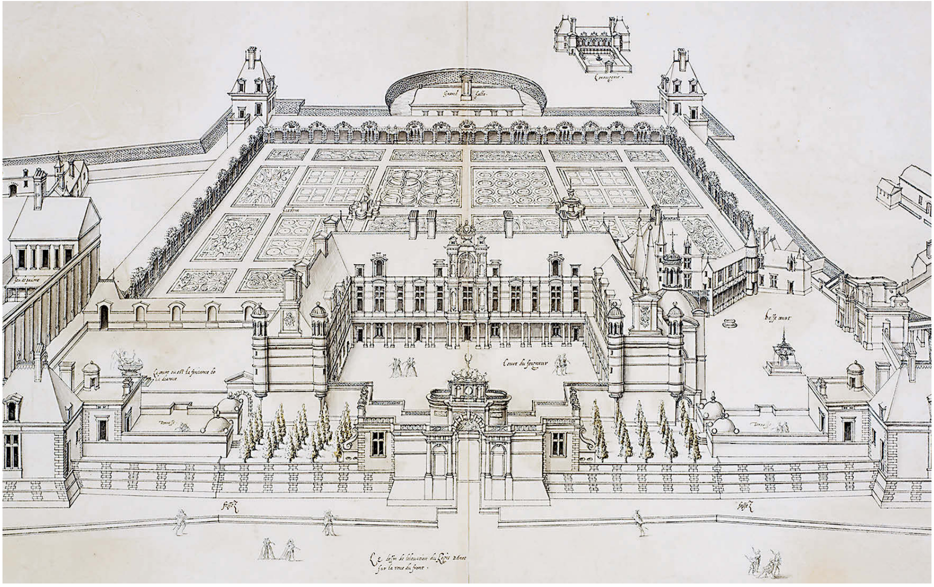

Fig. 6. *Jacques Androuet du Cerceau, view of the Château d'Anet,* c. *1570 (British Museum 1972 U.887; British Museum Creative Commons)*

Fig. 7. *Château d'Anet, chapel, arch covering the southern arm (photograph by the author)*

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by a *quadratura*-like interplay of circles and squares: the circle that marks the base of the dome; the square that contains it; the square defined by the exterior corners of the chapel; and the circle defined by the curved arcs of the arms' outer walls.[13] The chapel's interior elevation counters the modular logic of its plan. The hemispherical dome rests on a circular wall penetrated by the arched openings of the four short arms that radiate from the centre of the building. The coffers articulating the surfaces of the dome and of the lateral arches, as well as the lantern that sits over the dome's oculus, are mimicked by pseudo-projections on to the polychrome *opus sectile* floor of the chapel. The spiralling pattern of the dome's ribs, combined with its negative reflection on the floor, contribute to an optical distortion of the chapel's geometry, which gives viewers the impression of a space extending vertically beyond its physical limits. Such spatial distortion is enhanced by the wavy shape of the lateral arches which, because they open on a curved drum, feature three-dimensional profiles — that is, curves that do not lie on a single plane (Fig. 7). The optical effects produced by the chapel's architecture are the result of the advances in geometric knowledge brought about by stereotomic practice and embraced by de L'Orme, at Anet and elsewhere, to challenge Renaissance notions of measurable, rational space.

The dome is composed of large-sized, custom-cut voussoirs arranged in thirteen horizontal, concentric courses of stone, and it features seven and a half ranges of diamond-shaped coffers, the dimensions of which diminish progressively from the base towards the oculus. The pattern of the dome's coffering is produced by the interlacing of eighteen pairs of symmetrical, clockwise and anti-clockwise ribs, which taper from the base towards the oculus. In cross-section, the ribs present a flat upper surface and moulded lateral surfaces; the latter define the shape and depth of the coffers. There is no separation between the structure and the ornamental apparatus of the dome: the ribs that form the coffering are not separate or produced independently from the voussoirs; they are embedded in them so that each rib section forms one body with the voussoir to which it belongs. This characteristic significantly complicated the execution of the work, because the rib sections needed to match one another precisely in order to create the intended pattern once the voussoirs were assembled.

The 3D laser scan of the Anet dome executed by digital modelling engineer Grégory Chaumet of the Centre André Chastel at Sorbonne University in 2019 adds to our understanding of the dome's configuration by showing details which are hardly appreciable from the ground floor of the chapel (Fig. 8).[14] The cross-section shows, for instance, that the dome sits on a blank, one-course-high drum, which is hidden from view by the tall entablature underneath. By slightly raising the vault's springing, this drum allows for the projection of the entablature while preserving the full view of the dome's hemisphere from below. The same cross-section also shows that the dome's intrados can be thought of as composed of two non-concentric hemispherical envelopes — a raised envelope formed by the flat surfaces of the ribs, and a recessed envelope formed by the bottoms of the coffers, in which lie the sculpted figures that decorate them. The space between the two envelopes tapers from the base towards the oculus of the vault, as the depth of the coffers progressively diminishes along with their size. The ground plan is the instrument that de L'Orme used to control this complex work from design through execution.

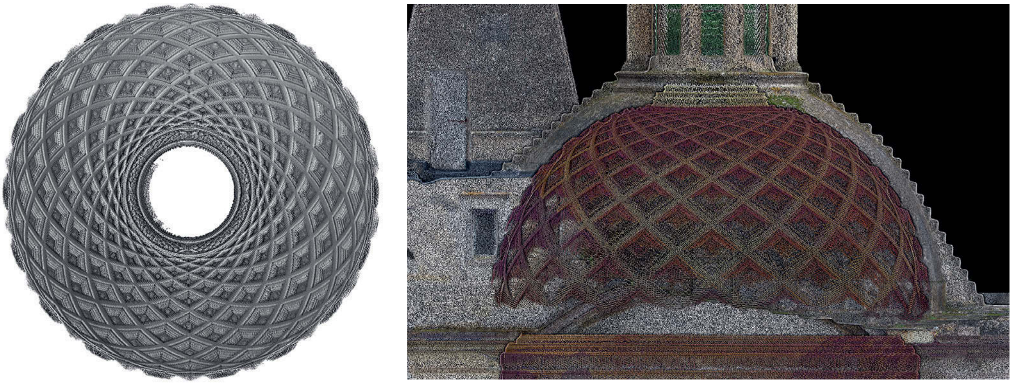

Fig. 8. *Château d'Anet, chapel, plan and cross-section of the dome derived from the 3D laser scan, 2019 (Grégory Chaumet, PLEMO 3D, Centre André Chastel, Sorbonne University)*

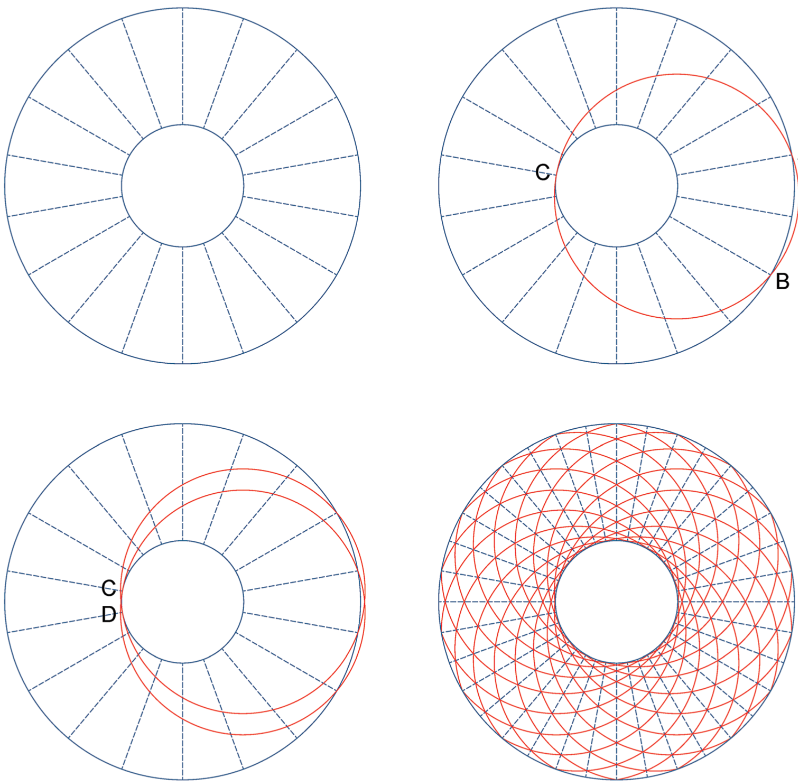

Fig. 9. *Generation of the dome's coffering in plan (drawing by the author)*

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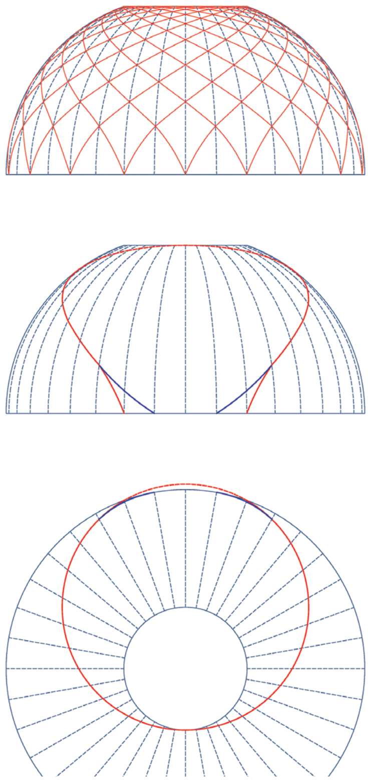

Fig. 10. *Modification of the lowest segment of the ribs' axes (drawing by the author)*

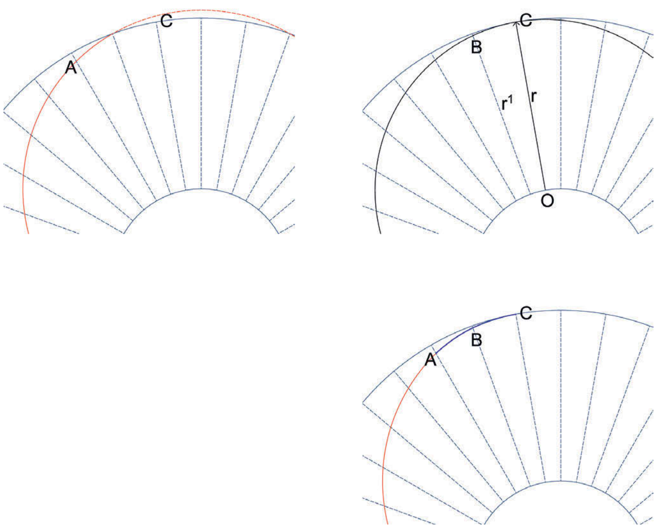

Fig. 11. *Geometric process used for modifying the lowest segment of a rib's axis (drawing by the author)*

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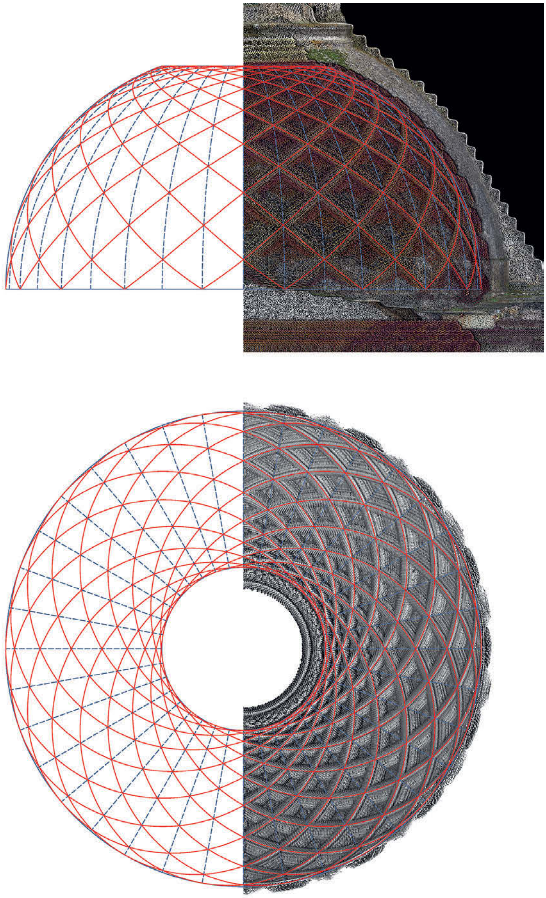

Fig. 12. *Reconstruction of the dome's geometric pattern superimposed on the orthogonal views obtained from the 3D laser scan (scan by Grégory Chaumet; drawing by the author)*

GEOMETRY OF THE DOME

The geometry of the dome proceeds from the manipulation of the ground plan to define the ribs. The coffers, along with the mouldings on the ribs' sides, are defined later, during dressing and, for some details, after assembling. The interlaced pattern of the ribs' axes on the dome's ground plan has been deduced from the point-cloud orthogonal view obtained from the 3D laser scan via tracing, and then reverse-engineered graphically in order to identify its generative process (Fig. 9).[15] This process consists of three steps. First, the vault's circumference is divided into eighteen equal parts with the help of a compass (Fig. 9, top left) — a geometric method that Sebastiano Serlio illustrates in his *Primo libro d'architettura* for the construction of the nonagon.[16] Then a circle is identified that intersects the vault's outer circumference in points *A* and *B* and is tangent in point *C* to its inner circumference, the projection of the oculus (Fig. 9, top right) — this is done by applying the method of the *trois*

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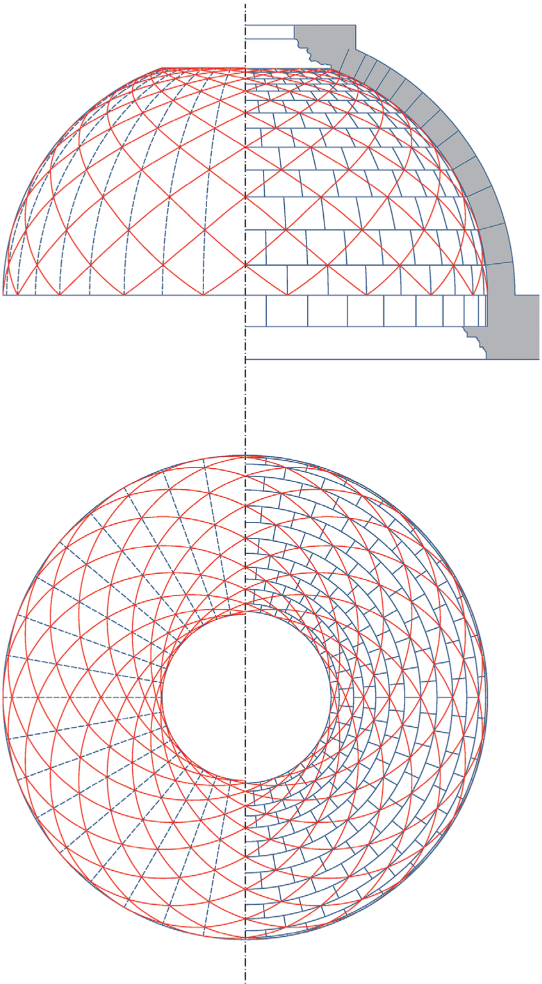

Fig. 13. *Ground plan and cross-section of the dome's geometric pattern (left) and its translation (right) into the dome's constructive elements (drawing by the author)*

points perdus (three lost points) illustrated by de L'Orme in the *Premier tome*.[17] Finally, the operation is repeated at each of the eighteen divisions of the vault's circumference, thus obtaining the circle whose tangent point is *D* and all of the following circles (Fig. 9, bottom left). The axes of the ribs thus defined intersect one another at regular concentric intervals and at diminishing radial intervals, which determines both the diamond shape of the coffers and their decreasing size (Fig. 9, bottom right).

The pattern formed by the ribs' axes on the ground plan, orthogonally projected on to the dome's hemispherical surface, produces the spiralling forms that distinguish the architecture of the chapel (Fig. 10, top). Thus the ribs' pattern at Anet is the result not of a three-dimensional design process, but of the application of two-dimensional ground plans, elevations and cross-sections to produce complex shapes by the transfer

Fig. 14. *Details of the dome's surfaces of intrados (left) and extrados (right) showing the joint lines and the progressively diminishing size of its stone courses (photographs by the author)*

of plane forms on to curved surfaces. The translation from two to three dimensions imposed an adjustment in the lower part of the Anet dome, near the base, where, in order to avoid the curvature of the ribs' axes shifting from concave to convex, the shape of the spirals' lowest segment was modified (Fig. 10, centre). This modification, too, was probably executed on the ground plan, by changing the curvature of the final segments of the ribs' axes so that they would be tangent to the dome's outer circumference instead of intersecting it (Fig. 10, bottom).[18] In plan, this modified curvature is the arc of a circle defined not through its centre and radius, but through three points on its circumference, which are found with the method of the *trois points perdus* mentioned above. The geometric problem consists in finding a circle that is tangent to the vault's outer circumference in point *C* and that also passes through point *A*, where the original rib's axis intersects the radius of the same circumference (Fig. 11, top left). To solve the problem, a circle of radius *r* centred in *O* is traced; such circle, tangent in point *C* to the vault's outer circumference, will intersect the radius r^1 of the same circumference in a point which will be called *B* (Fig. 11, top right). The next step uses the *trois points perdus* method to find the unique circle that passes through points *A*, *B* and *C*, the arc thus generated satisfying the problem's requirements (Fig. 11, bottom). This geometric reconstruction of the dome's coffering pattern matches in both ground plan and cross-section the orthogonal views obtained from the 3D laser scan of the vault (Fig. 12).

The pattern formed by the ribs' axes on the ground plan also governs the construction of the vault, for de L'Orme positioned its joint lines — both the horizontal ones, separating each course from the next, and the vertical ones, separating the voussoirs of each course — to run through the points of intersection of the ribs' axes (Fig. 13).

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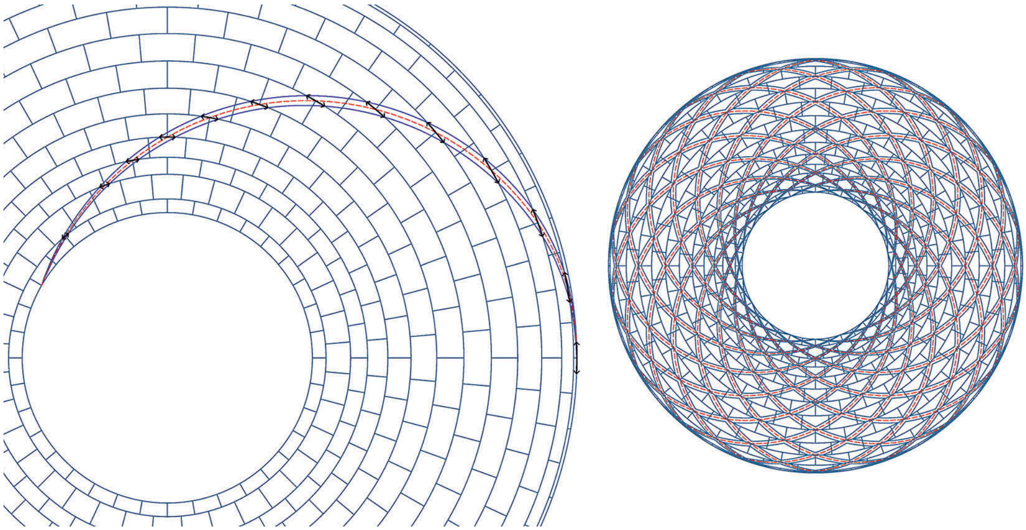
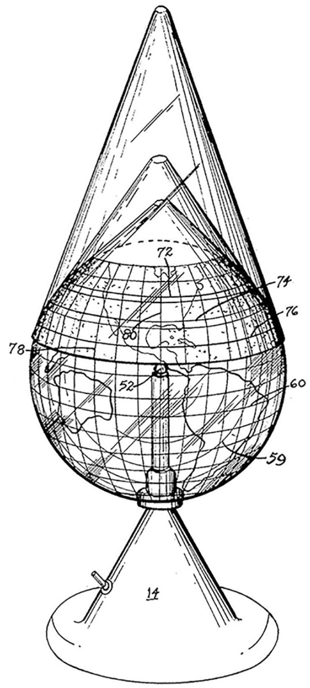
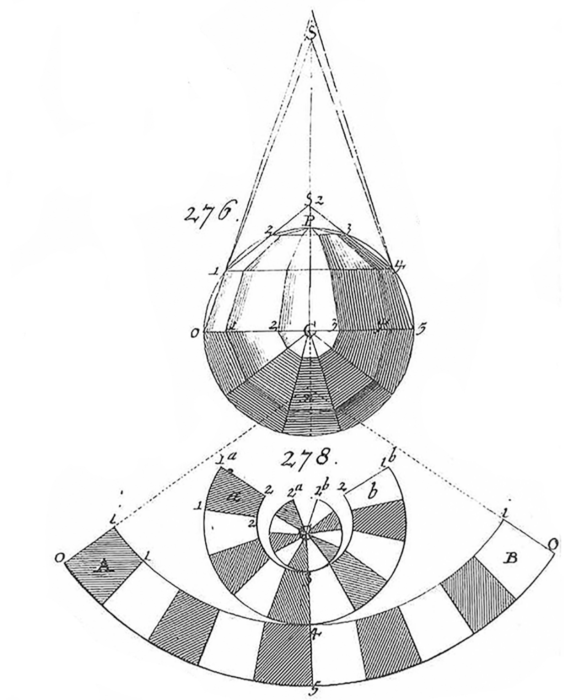


Fig. 15. *Generation of the outer profiles of the dome's ribs: detail of one rib (left) and overall view (drawing by the author)*

This choice simplifies the execution of the vault by aligning as many of its components as possible. It also follows that the Anet dome features courses of progressively diminishing heights from the base towards the oculus (Fig. 14), instead of the regular heights featured in most stereotomic domes, including the one at Jerash mentioned above. The translation of the plan's geometric pattern into the vault's construction design required a second adjustment, visible in the cross-section: near the dome's oculus, de L'Orme eliminated the final half-range of coffers, too small to be clearly seen from below and hard to define in stone. This explains why the final vault features seven and a half ranges of coffers, whereas the original geometric pattern shows eight (Fig. 13). Although the survey does not provide data on this, it is most likely that de L'Orme also compounded the four undersized courses near the oculus into two regular-sized ones to facilitate the stonecutters' work during execution.

As to the ribs' profiles, these are not arcs of circles, but composite curves that taper from the base to the oculus of the vault (Fig. 15). The shape of these profiles, like the axes themselves, has been deduced from the point cloud orthogonal views obtained from the 3D laser scan via tracing. The composite curves of the ribs' profiles are obtained by connecting — with the method of the *trois points perdus* — the end points of a series of arcs traced on the dome's horizontal courses (Fig. 15, left). The widths of these arcs are determined at each interval by progressively increasing multiples of a sixteenth-century *pouce* (inch).[19] They are defined using real dimensions because they lie on the horizontal plane of the ground plan. Having established these fundamental geometries on the ground plan, de L'Orme could move on to the next phase of a stereotomist's work: the preparation of the vault's *épure*, the geometric construction drawing necessary for its execution.





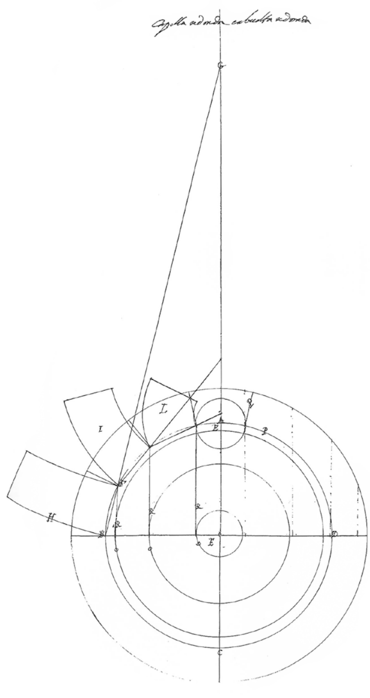


Fig. 16 *(above). Left: Joseph A. Stieber and John B. Weldon, polyconic map projection demonstrator, 1959 (US patent no. 2932907 filed on 16 January 1959). Right: Amédée-François Frézier, polyconic development of a sphere, from* La Théorie et la pratique de la coupe des pierres et des bois, ou traité de stéréotomie à l'usage de l'architecture, *1737–39*

Fig. 17 *(right). Alonso de Vandelvira,* épure *of a spherical vault featuring the polyconic method,* c. *1585, from 'Libro de traças de cortes de piedras',* c. *1585 (Madrid, Biblioteca de la Escuela Técnica Superior, MS R10, f. 61r)*

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TEMPLATES, *ÉPURES* AND POLYCONIC PROJECTIONS

Stereotomic vaults can be executed with a variety of dressing methods, which can be organised in three main categories: the reduction (*ravalement*) method, in which some of the voussoirs' faces are cut after assembling the vault; the squaring (*équarissement*) method, in which the voussoirs' orthographic projections are transferred to the stone blocks for dressing in progressive phases; and the templates (*panneaux*) method, in which wooden forms that replicate the true shapes and sizes of the voussoirs' faces are applied to the stone blocks in order to cut their final shape directly.[20] While there is no fully reliable way to tell solely from observation which method was employed in executing a vault, it is reasonable to assume that the Anet dome was realised with the templates method, for de L'Orme recommends it for all the spherical vaults he illustrates in the *Premier tome*.[21]

When compared to reduction and squaring, the templates dressing method chosen by de L'Orme presents the significant advantage of reducing both the stonecutters' labour and the volume of stone necessary to produce a vault. A smaller volume of stone also reduces the costs of transportation, one of the items of highest expenditure in pre-modern building construction. On the other hand, applying the templates method requires more sophisticated geometrical skills: whereas dressing by reduction simply involves a basic understanding of three-dimensional forms, and dressing by squaring only calls for the ability to work with orthographic projections, producing templates requires the mastery of plane rotations and solid surface developments. Indeed, costs and construction site management do not account for what may be the most relevant factor in determining the dressing method for a stereotomic work: the pride stereotomists take in executing a vault with what they view as the most elegant methods — that is, skilful, streamlined and waste-free — that they can master. The choice of using templates is often the way such pride manifests, and probably the reason why de L'Orme chose it at Anet.

From the standpoint of geometry, the challenge posed by spherical vaults is that their ground plans and cross-sections do not provide the templates of the defining faces of their voussoirs — the intrados (*faces de doile* or *douelles*) — because these lie on neither the horizontal nor the vertical plane and, therefore, their projections on orthographic views are skewed in both size and shape. For the stonecutters to be able to shape the voussoirs with the templates method, then, the designer needs to derive the true shapes and sizes of the intrados geometrically from the vault's orthographic views. This operation implies the development, or flattening, of the vault's spherical surface and is done through the production of an *épure*, a 1:1 scale technical drawing that visualises a vault's orthographic views as well as the geometric processes employed to derive from them the templates of its voussoirs' faces.

The geometric development of the sphere was a centuries-old problem that sixteenth-century stereotomists shared with cartographers. Yet, while cartographers adopted conical and cylindrical projections — that is, projections which imagine the sphere of the earth on either a conical or cylindrical surface, which is then rolled out on a plane — stereotomists established a separate, practice-specific method of polyconic projection.[22] According to this method (known today as the American polyconic and introduced to the world of cartography in the early nineteenth century through an independent invention attributed to Ferdinand Hassler), the sphere is construed as composed of separate sections of stacked cones of progressively diminishing size, which allows its

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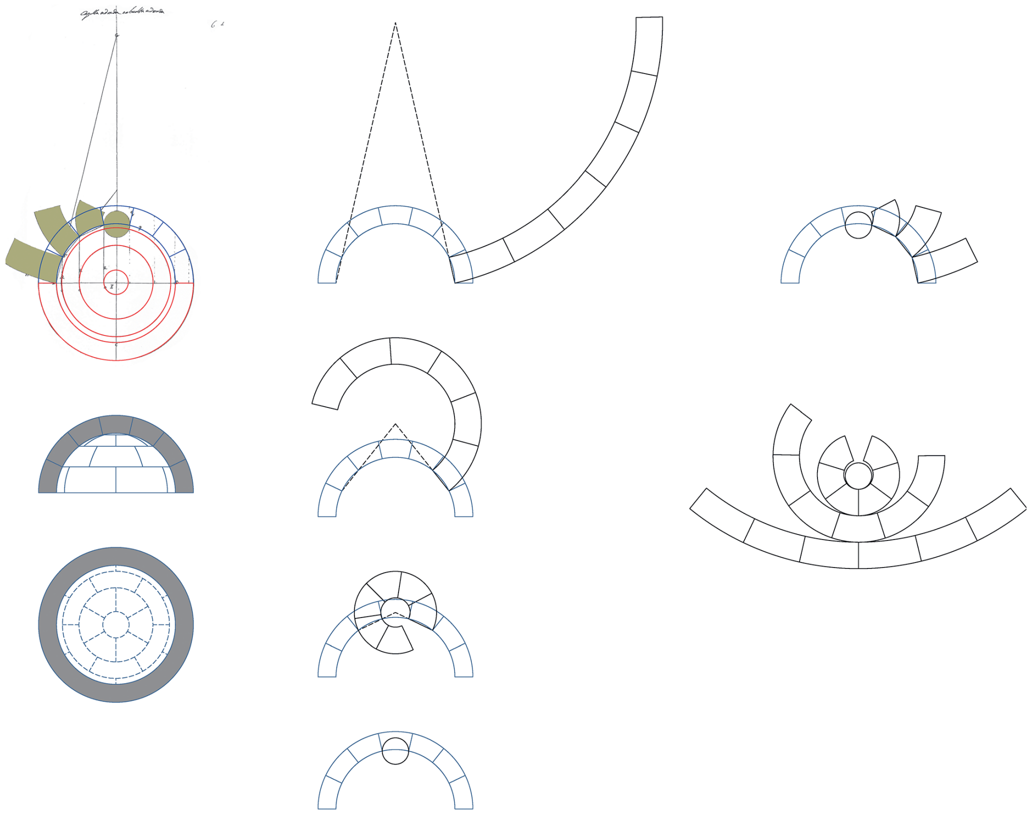

Fig. 18. *Decoding of Vandelvira's* épure *of the hemispherical vault shown in Fig. 17 (drawing by the author)*

doubly curved, non-developable surface to be simplified into a series of developable cone-strips that can be unrolled on to a plane (Fig. 16).

While no testimony of the *épure* for the Anet dome is preserved, abundant evidence suggests that it was produced with the polyconic method, which is applied to all the *épures* of spherical vaults included in the *Premier tome* as well as in a variety of sixteenth- and seventeenth-century stereotomy books from both France and Spain, including those by Vandelvira and Mathurin Jousse (Fig. 17).[23] Tracings found in the cathedrals of Seville and Murcia show that the polyconic method pre-dated the circulation of these books and was already employed by Spanish practitioners in the early decades of the sixteenth century.[24]

Viewers are easily baffled by the *épures* of stereotomic vaults, which seem unintelligible to the non-initiated. The challenge these drawings pose is twofold. First, 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 find the templates of its voussoirs' faces. This characteristic originates in the function of *épures* as full-scale construction drawings traced on building sites, on plaster beds or, as in the above-mentioned cases of Seville

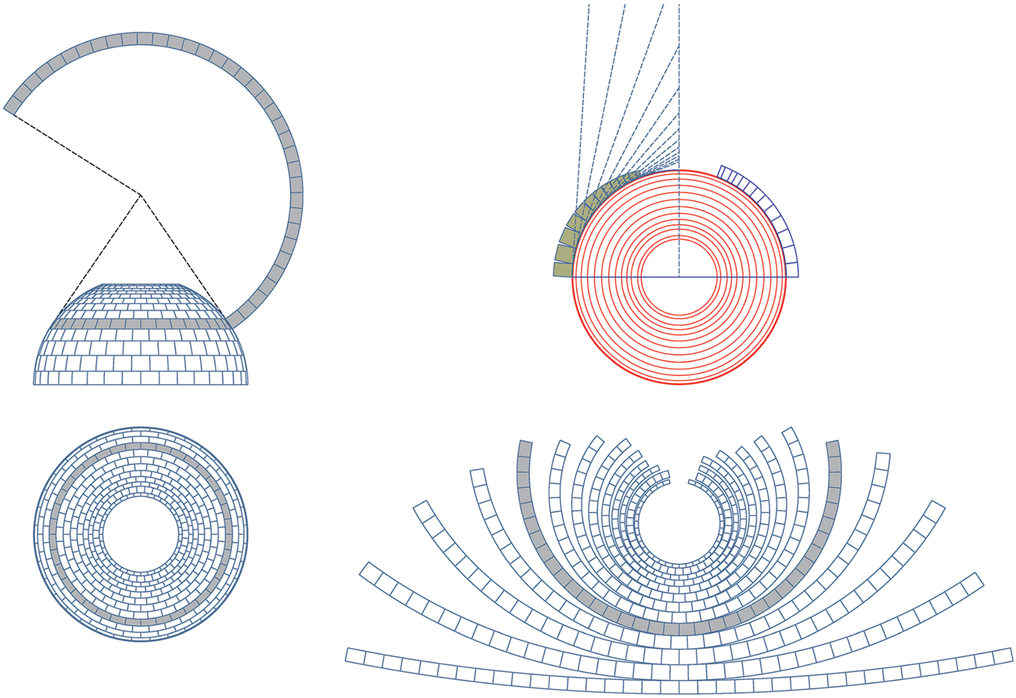

Fig. 19. *Development of the raised envelope of the Anet dome. Left: ground plan and cross-section showing the development of one course of stones, highlighted in grey, according to the polyconic method. Right: representation of the developed surface as map projection (bottom) and* épure *(top) of the same (drawing by the author)*

and Murcia, directly on stone under the vaults they represent.[25] As such, these drawings were codified in order to occupy the least possible physical space so they could fit in the rooms where they were employed. Second, contour, section and projection lines — which modern practitioners mark in their drawings by using regular, thick and dashed lines respectively — are not graphically distinguished from one another in *épures*. This lack of graphic codification is due not only to the fact that the use of *épures* pre-dates by several centuries the conventions introduced by descriptive geometry and modern architectural drawing, 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 define accurately a line's thickness when tracing at full scale on a plaster bed or on stone. Pre-modern stereotomy books that illustrate the reduced-scale renderings of full-scale *épures* do not simplify the reader's task.[26] Quite to the contrary, the combined challenges of small-scale representation and of coordinating text and illustration added layers of visual complexity to the material.[27] Yet, reading *épures* is not an impossible task. We can use Vandelvira's *épure* for a stereotomic dome with

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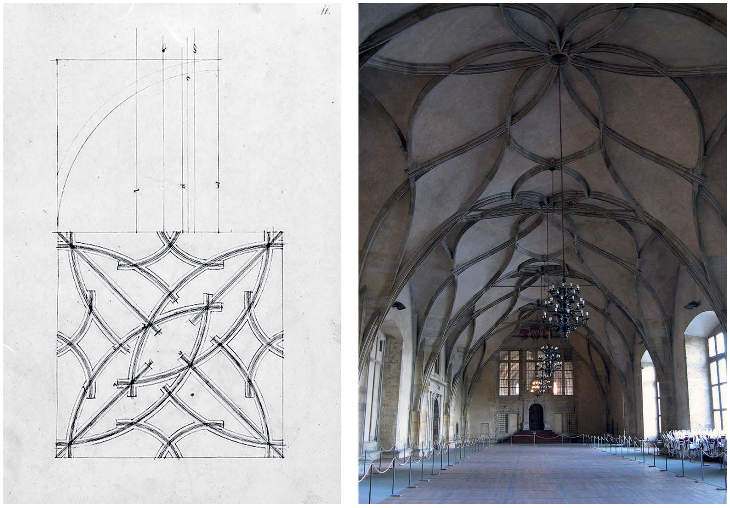

Fig. 20. *Left: Anon., German method for the construction of looping rib vaults*, c. *1544–67 (Vienna, Austrian National Library, Codex Miniatus 3, f. 11r). Right: Benedict Rejt, Vladislav Hall, Prague, 1490–1502 (Yair Haklai, Wikimedia Commons)*

horizontal, concentric courses to demonstrate how these drawings were produced and read, before moving on to the reconstruction of the Anet *épure*.

The first step in decoding an *épure* is identifying the vault's orthographic projections. In the case of Vandelvira's dome, the ground plan has been marked in red and the cross-section in blue, and they are accompanied by representations according to modern architectural drawing standards (Fig. 18, left). The templates Vandelvira obtains through the development of the vault's spherical surface are highlighted in green. All the remaining unmarked lines on Vandelvira's *épure* are construction lines —that is, lines that do not represent the final, built object but materialise, instead, the geometric processes employed to obtain the templates from the given orthographic projections. Separating these geometric constructions is the second step required by the reader (Fig. 18, centre). The polyconic method for the development of the sphere adopted by Vandelvira is separated here in its four iterations, one for each course. Each cone section is also shown as fully developed — that is, including the intrados faces of all six voussoirs that compose each course. Finally, the developed cone sections are brought together in a map-projection-like representation of the dome's surface of intrados as well as in a synthetic representation similar to that adopted by Vandelvira, in which only one of the voussoirs' faces of intrados is shown for each course (Fig. 18, right). Once deconstructed into their components, *épures* not only become legible, but they can also be appreciated for the elegance of their synthetic graphic expression.

THE *ÉPURES* OF ANET

To produce the *épure* of the Anet dome according to the polyconic method, the same steps shown above for Vandelvira's *épure* need to be followed. First, for each course a cone needs to be identified whose base coincides with the bottom of the course itself; then the section of the cone that corresponds to the height of the course is developed

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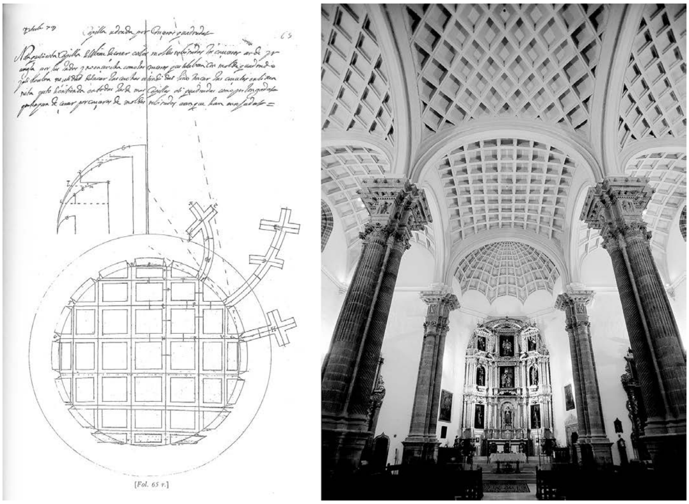

Fig. 21. *Left: Alonso de Vandelvira, method for developing ribbed spherical vaults, from 'Libro de traças de cortes de piedras'*, c. *1585 (Madrid, Biblioteca de la Escuela Técnica Superior, MS R10, f. 65r). Right: Martín de Gainza, Church of Nuestra Señora de la Consolación, Cazalla de la Sierra, begun 1538 (Spinola13, Wikimedia Commons)*

on plane, thus obtaining a strip that shows the true shapes and sizes of the intrados faces of its voussoirs (Fig. 19, left). By repeating the same process for all the courses that compose the dome, and then aligning all the strips thus obtained, one can produce the full development, or the equivalent of a map projection, of the entire raised envelope of the dome's intrados — that is, as mentioned above, the half sphere that contains the flat upper surfaces of the dome's ribs — as well as its *épure* (Fig. 19, right).

Once the *épure* of the dome's intrados is obtained, the ribs that define its coffering — or, more precisely, the ribs' flat upper surfaces — need to be transferred on to it. Late medieval and early modern stereotomy books offer two geometric methods for the execution of complex rib patterns: the German method employed to realise vaults such as that covering the Vladislav Hall in Prague Castle (Fig. 20), and the Spanish method employed to realise coffered vaults such as those of the Church of Nuestra Señora de la Consolación in Cazalla de la Sierra (Fig. 21). The German method uses two-dimensional geometry to solve the three-dimensional problems posed by looping rib vaults — that is, vaults featuring space (or three-dimensional) ribs whose curvatures do not lie on a single plane. According to this method, looping ribs are construed not as parts of three-dimensional surfaces that need developing, but as individual curves dissociated from the vault's shell and described as arches in both plan and elevation.[28] An illustration of this method is found in the Codex Miniatus 3 (*c.* 1544–67) of the Austrian National Library (Fig. 20, left), which shows the plan of the vault and the plane elevation of its arches, the only elements necessary to determine the shape of the ribs and their voussoirs. The Spanish method, instead, uses three-dimensional geometry to find the true shapes and sizes of the ribs that articulate a vault. According to this method, the ribs are construed as embedded in the three-dimensional surface that needs developing. In the case of a spherical vault, the ribs are developed with the same polyconic projection method described above for the voussoirs. This is shown in Vandelvira's illustration of the method, where the reader can recognise the stacked cones as well as the developed

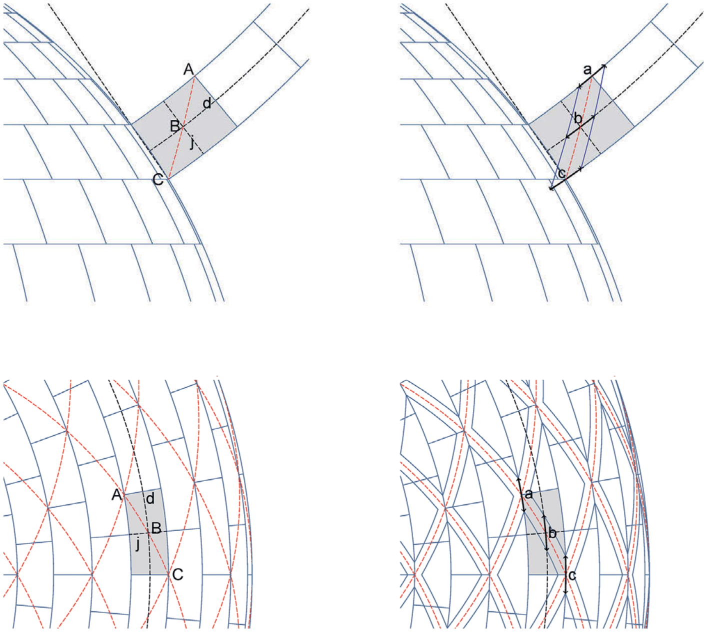

Fig. 22. *Transfer of a rib segment from ground plan (bottom) to the developed intrados of the voussoir to which it belongs (top) (drawing by the author)*

rib sections and coffers (Fig. 21, left).[29] Neither the German nor the Spanish method could have been applied to the Anet ribs. Providing solutions for individual ribs, the German method can hardly be combined with the surface-development method de L'Orme employed for the voussoirs' intrados. The Spanish method, on the other hand, can only be applied to ribs either that overlap with a vault's joint lines or whose projection on ground plan are straight lines, as in the case of Cazalla de la Sierra.

The method applied at Anet was most probably the one illustrated by José Carlos Palacios Gonzalo for both Spanish and Islamic domes with decorative patterns that could not be developed in their entirety along with the vault's intrados. This method entails transferring on to the *épure* the separate sections of each rib that belong to the individual voussoirs (Fig. 22).[30] Such a method was applicable because, as illustrated above, the shape and width of the ribs were defined on ground plan by connecting the end points of a series of arcs traced on the dome's horizontal courses in their real length (see Fig. 15). As such, these arc lengths can be transferred directly on to the developed intrados of their respective voussoirs; then the outline of each voussoir's rib section can be defined with the method of the *trois points perdus*. To do so, first one needs to identify on the ground plan of a chosen voussoir three points on the axis of the rib section whose locations can be easily transferred to the voussoir's developed intrados. Two such points are provided by the opposite corners of the voussoir, through which the axis runs (Fig. 22, bottom left, *A* and *C*). A third point, *B*, can be located at the intersection between the axis and the line *j*, which is the extension of the joint lines from the courses above and below the one of the voussoir at hand. A circle, *d*, concentric to the vault's circumference, is then run through point *B*. Line *j* and circle *d* can be transferred to the

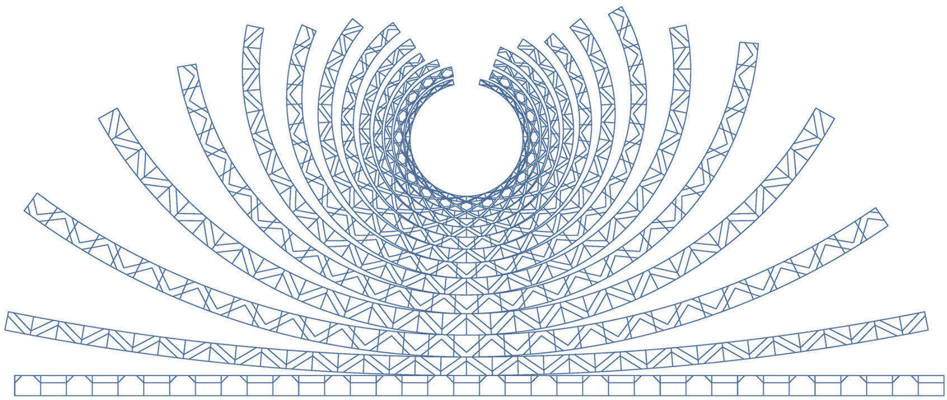

Fig. 23. *Development of the raised envelope of the Anet dome as map projection (drawing by the author)*

developed voussoir with the same polyconic method described earlier, so that their intersection point *B* is identified on the *épure* (Fig. 22, top left). The true shape and size of the portion of the rib's axis that belongs to the chosen voussoir is the arc of circumference that contains points *A*, *B* and *C*. Next, to define the ribs' edges, the arc lengths $\hat{a}$, $\hat{b}$ and $\hat{c}$ are transferred, with the help of a compass, from the ground plan to the voussoir's developed intrados (Fig. 22, right). The true shape and size of the rib section that belongs to the chosen voussoir is defined by the arcs of circumference that connect the end points of $\hat{a}$, $\hat{b}$ and $\hat{c}$ on each side of the rib's axis. As each course of the Anet dome is composed of two, alternating, types of voussoirs, this operation needs to be executed only twice for each course to obtain the complete development of the dome's intrados with embedded ribs (Fig. 23). The sole exceptions are the voussoirs of the uppermost two courses, near the oculus, which feature a more complex rib design than those of the courses below them — that is, here a single voussoir contains multiple rib sections. However, this extra complexity does not require a different approach to the transferring of the ribs' outlines from the ground plan to the *épure*; the same operation illustrated for the lower courses only needs to be repeated twice in order to transfer a higher number of points and arc lengths for a single voussoir.

Once the main lines of both the raised and recessed envelopes of the dome have been defined, the voussoirs can be dressed and assembled into the vault as semi-finished pieces. This step would leave the definition of each voussoir's finer details — the mouldings on each side of the ribs and the sculpted figures at the centre of the coffers — for the post-assembling phase of the dome's execution. Technically, these details could also be finalised before assembling the vault; in practice, however, this would not only significantly complicate the production of templates (as the *appareilleur* would have to design the templates for each set of mouldings), but also, most importantly, drastically reduce the ability to correct possible mismatching errors after assembling. Leaving the definition of mouldings and sculpture for the post-assembling phase of construction of the vault allows stonecutters to treat the mouldings surrounding each coffer as separate units, easier to work than the sections of a much larger pattern, and it also leaves room for the adjustment

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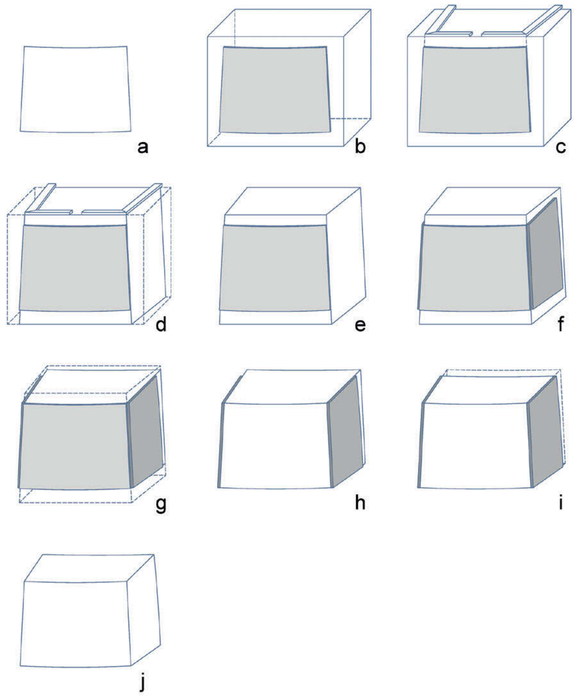

Fig. 24. *First dressing phase for a voussoir of the Anet dome (drawing by the author)*

of potential misalignments of the main elements of the dome's intrados. Given the precision with which the voussoirs and the ribs mouldings and profiles match one another at Anet, this approach was most probably the one adopted by de L'Orme (see Fig. 14).

The dressing of each voussoir into a semi-finished piece is done in two phases and with the use of four flat templates, all shaped after the dome's *épure*.[31] In the first phase, the chosen voussoir is carved out of the stone block; in the second, the raised and recessed surfaces of the intrados are defined (Figs 24 and 25). The first template is shaped after the development of the voussoir's intrados face and is applied to the side of the block that will constitute the raised envelope of the dome (Fig. 24a–b). A *sauterelle*, a square with movable arms, is then used to transfer the angles formed by the voussoir's intrados and lateral faces from the vault's ground plan — where such angles are shown in their true size — to the block in order to define the lateral surfaces on to which the voussoir's faces will lie (Fig. 24c–e).[32] A second template, shaped after the voussoir's lateral faces — the *faces de joint*, which are shown in their true size and shape on the vault's cross-section — is then applied to the sides of the block in order to complete the first phase of dressing (Fig. 24f–j). In the second phase, the templates for the intrados of the dome's voussoirs can be finalised by defining the edges of the recessed envelope of the dome, on to which the sculpted figures at the centre of each coffer will be located. This is done by simply tracing, on each template, lines parallel to the rib's edges at the desired distance (Fig. 25a). A third template thus obtained is then applied to carve the areas of each voussoir that lie on the dome's recessed

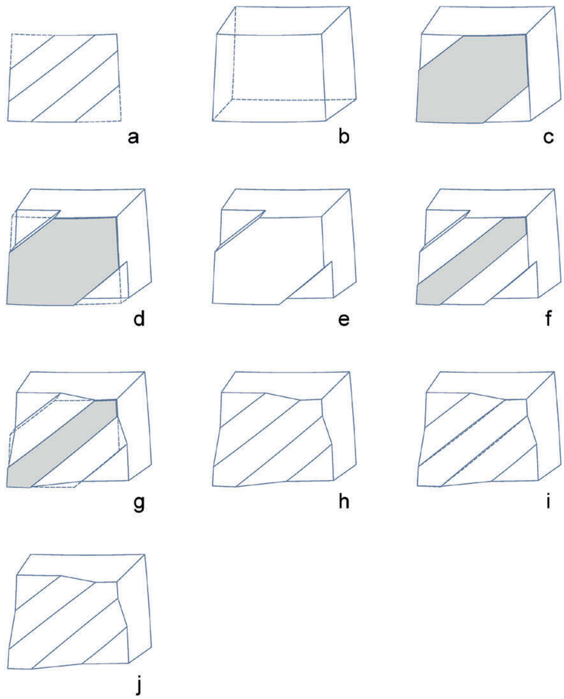

Fig. 25. *Second dressing phase for a voussoir of the Anet dome (drawing by the author)*

envelope, on to which the sculpted figures will be later defined (Fig. 25c–e). The dome's curvature is then transferred to the surfaces thus obtained with the help of a *biveau* (bevel square), a custom-built square with movable arms — one straight arm and one curved — that reproduces the curvature of the dome's intrados.[33] A fourth template is applied to define the area of the voussoir that lies on the dome's raised envelope, where the flat surface of the rib will be situated, and to carve the diagonal surfaces that will contain the coffer's mouldings (Fig. 25f–h). Finally, the *biveau* is used again to carve on to the flat rib surface thus defined the curvature of the dome's intrados (Fig. 25i–j). As the dome is divided into thirteen courses, each containing eighteen identical pairs of voussoirs, the dressing process as described here would only require the production of four reusable templates for each odd-numbered course (in which the voussoirs of each pair are also symmetrical) and six reusable templates for each even-numbered course, a total of sixty-four templates.

PROBLEMATIC PRECEDENTS AND NEW PERSPECTIVES

Despite the portrayal of French early modern stereotomy as the continuation of well-established medieval practices, and of de L'Orme's theory of the art in the *Premier tome* as mere transcriptions of such practices, French architecture offers no relevant precedent for the design of the Anet dome.[34] In fact, stereotomic domes were a rare occurrence on French territory until well into the seventeenth century, and only two (non-ribbed)

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examples pre-date the construction of Anet, at the Château de Bournazel (1545) and the so-called Pendentif de Valence (1548).[35]

Indeed, historians agree that it was not in France but in Italy, during his 1533–36 sojourn, that de L'Orme derived the inspiration for Anet, and they have identified a number of potential sources. Blunt mentioned the twin exedras of the Temple of Venus and Rome and the twin Medusa Head mosaics from the villa in Via Emanuele Filiberto in Rome, as well as an unidentified dome that Nicodemus Tessin recorded in the city during his 1673–79 sojourn; Potié proposed Michelangelo's original design for the pavement of the Campidoglio (*c.* 1538); Evans added the semi-domes of the portico of Palazzo Massimo alle Colonne (1532–36); and Jean-Marie Pérouse de Montclos pointed to Antonio da Sangallo the Younger's interest in Florentine brick vaults featuring herringbone patterns, and in particular to his drawing of 'Brunelleschi's cupola' and the vault he designed around 1534 for the Sala Ottagona of the Fortezza da Basso.[36]

None of these examples, however, can be identified as a direct model for Anet. In some instances, their geometries simply do not match those of de L'Orme's dome — as is the case in Michelangelo's design for the Campidoglio, which features a pattern of rotating logarithmic spirals, not circles. Nor are the brick vaults of Brunelleschi and Sangallo suitable, as their herringbones materialise loxodromes that project on to the ground plan as, again, logarithmic spirals.[37] In other instances, the problem is one of access, as it seems unlikely if not impossible for de L'Orme to have seen some of these models. This is the case with the Medusa Head mosaics, which were excavated in 1910, and with the dome recorded in Tessin's drawing, which may be the product of the artist's imagination rather than the record of an existing building, for it is improbable that such an exceptional object would have escaped notice in Rome both before and after Tessin's days.[38] Admittedly, the semi-domes of the Temple of Venus and Rome and, to a lesser extent because of their scale, those of the Palazzo Massimo alle Colonne may have offered de L'Orme visual references for the spiralling pattern of the ribs at Anet. They did not, however, provide suitable models for the architect to imitate, for their geometries and the overall spatial effects they produce are substantially different from those of Anet.

The Anet chapel is distinguished by its construction technique and by the projective geometry that generates its design from ground plan into the third dimension. Through these characteristics, the chapel engages with precedents, both ancient and Renaissance, in ways more sophisticated than the simple relation of model and modelled-after. First, through stereotomy de L'Orme connects to a number of ancient works whose aesthetic centred on the unity of their structural and decorative apparatuses, such as the coffered concrete vaults of the Pantheon and the Temple of Venus and Rome. Arguably, it is this aspect of the latter building that matters the most for Anet, rather than the loosely related geometric pattern of its ribs. From this perspective, de L'Orme's practice of stereotomy, at Anet and elsewhere, is analogous to the revival of ancient design and construction methods that excited the interest of Donato Bramante and Giuliano da Sangallo, among others, in concrete vaulting. Indeed, stereotomy was an ancient practice with which Roman architects were familiar, as shown by the many complex and beautifully executed vaults still extant in the regions of Lazio and Umbria in particular; examples include the arches opening in curved walls of the Colosseum and the Theatre of Marcellus in Rome, those of the theatres in Ferento and Gubbio, the conical vault of the Emissary of Lake Albano, the dome covering the funerary monument of Ummidia Quadratilla in Cassino and the semi-domes of the Nicchioni in Todi. While modern stereotomy literature has largely overlooked them, these ancient works were well known by sixteenth-century Italian architects, as shown by the survey drawings produced by Baldassare Peruzzi and Antonio da Sangallo the Younger, among others, where the details of their geometries and execution techniques are often annotated.[39]

Second, the geometry of the chapel puts de L'Orme in conversation with sixteenth-century practitioners and theoreticians whose research centred around the role of double projections in the production and control of architectural designs, such as the Sangallos and, later, Palladio, and on the creative possibilities afforded by projective geometry. The latter is a theme Albrecht Dürer developed at length in the *Underweysung der Messung* published in Nuremberg in 1525, which was available to de L'Orme in a number of Latin translations published in Paris in the 1530s. In a passage of the *Underweysung* concerning spirals, Dürer illustrates a method for the generation of complex three-dimensional curves through projective geometry that is conceptually the same as that demonstrated by de L'Orme at Anet.[40] In his text, Dürer states that the method he illustrates is borrowed from stonemasonry practices, thus clarifying not only that he and de L'Orme were exploiting the same sources, but that they were similarly interested in translating the geometric knowledge underlying such practices into theoretical form.[41] Dürer and de L'Orme shared this theoretical ambition with the authors of the many stereotomy manuals circulating in sixteenth-century Spain, including Pedro de Alviz, Hernán Ruiz the Younger and Vandelvira.[42] The passages of the *Premier tome* that indicate de L'Orme may have been familiar with these manuals — such as the illustrations of vault types which were common in Spain but non-existent in France — further suggest that the architect's intellectual horizon was far broader than has been admitted thus far.[43]

Finally, projective geometry was also a means for de L'Orme to challenge, at Anet, Renaissance notions of modular, measurable space as exemplified by Brunelleschi's Old Sacristy at San Lorenzo in Florence, among other works. Basing his composition on the same fundamental geometries of square, circle and sphere employed by Brunelleschi, de L'Orme applied the projective practices developed by stereotomists to produce an optically distorted space populated by extraordinary three-dimensional curves not yet mastered by mathematicians of his time, a space that could hardly be in starker contrast with the Old Sacristy. Unorthodox forms similar to those displayed at Anet were not without precedents in ancient buildings: the two arches opening into the circular drum of the Pantheon, while not dressed in stone, are an early example of the employment of space curves in architecture, as are the arches inside the above-mentioned funerary monument of Ummidia Quadratilla and those featured on the outer envelopes of many Roman theatres and amphitheatres. These works did not always meet the taste of sixteenth-century architects, as shown, for instance, by Antonio da Sangallo the Younger's harsh criticism of the Pantheon's three-dimensional arches, which he describes as 'back-leaning' and 'very disgraceful'.[44] In contrast, de L'Orme was deeply fascinated by the virtually limitless catalogue of audacious forms afforded to architects by projective geometry.

CONCLUSION

As is often the case with puzzles, the dome covering the Anet chapel is revealed to be simpler than expected, once reverse-engineered into the series of practical steps comprising its design and execution. The vault was designed and controlled on ground plan and cross-section, the traditional means of architectural representation, with the sole help of compass and square, the practice's basic tools. Its execution relied on geometric methods and dressing techniques and tools that were established already in late medieval Mediterranean stereotomic practice, as proven by precedents in the regions of Cairo and Andalusia. Even the projective geometry that informs its composition was not a novelty by the mid-sixteenth century, when works such as Dürer's *Underweysung* were well known already and the use of double projections in architectural drawings was common in both practice and theory, as shown in the drawings of the Sangallos' workshop and in Serlio's treatise, among others. Indeed, from a strictly technical point of view, nothing in the production of the Anet dome is truly novel or can be attributed to an invention of de L'Orme's.

Yet the originality of the Anet chapel is undeniable, as is the role of stereotomy in achieving it. Its spatial qualities, its illusionistic effects and its very forms are unprecedented in Renaissance architecture and would remain unmatched well into the baroque era. Indeed, once its practical secrets are unveiled, the chapel challenges the traditional construal of de L'Orme's stereotomy as merely a technical device, part of an approach to vault-making inherited through familial lines within the building trades and uncritically passed forward, in both stone and paper, by an architect/master mason who is often portrayed as somewhat suspended between Middle Ages and Renaissance.[45] This notion is incongruent not only with the architecture of the Anet chapel, but also with de L'Orme's own assessment of stereotomy as an instrument not of tradition, but of invention. In a commentary on the celebrated undulating squinch that he also realised at Anet (since demolished), he advised:

> that [a squinch] can be built on a right, obtuse, or acute angle and it can take any form you wish in elevation: straight, projecting square, half a hexagon, or octagon, or round. And you can build straight, concave, or rampant squinches or of any type that you may think of, depending on the need and the constraints of the site where you want to build them. All sorts of vaults can be built in the form of squinches, and all of them hanging in the air with no support on the ground other than on the side walls, and all of them with the same method for tracing, as I will show below here, and of any kind which may please you.[46]

Tracing — the graphic production of *épures*, as in the French *tracé d'épure* or the Spanish *traza de montea* — is to de L'Orme not the instrument that keeps the architect anchored to tradition but, quite to the contrary, that which offers access to a limitless variety of forms through a simple and consistent method. A better comprehension of the material aspects of such a method, through the analysis of the apparently capricious curves and spirals of the Anet chapel and their production, allows for a better understanding of the crucial passage of the *Premier tome* quoted above. It also provides a deeper insight into de L'Orme's ambition. As the architect strived to demonstrate, in both theory and practice, stereotomy offers far more than constructive solutions for stone vaulting: it provides the key to the geometric processes through which the most daring architecture can be conceived and controlled, from planning to execution. Indeed, along with books III and IV of the *Premier tome*, the Anet chapel is arguably de L'Orme's most significant contribution to sixteenth-century architectural discourse on geometry's creative potential.

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BIOGRAPHY

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NOTES

1 Philibert de L'Orme, *Le Premier tome de l'architecture* (Paris: F. Morel, 1567), f. 112r <architectura.cesr.univ-tours.fr/Traite/Notice/ENSBA_Les1653.asp?param=en> [accessed 12 January 2021].
2 Philippe Potié, *Philibert de l'Orme, figures de la pensée constructive (Marseille*: Parenthèses, 1996), pp. 114, 124.
3 Anthony Blunt, *Philibert de l'Orme* (London: Zwemmer, 1958), p. 42.
4 Robin Evans, *Translations from Drawing to Building* (Cambridge, MA: MIT Press, 1997), pp. 153–93. Working from photographs, Evans misread the circles forming the axes of the dome's ribs as tangent to the circumference of the dome's base, rather than intersecting it.
5 Manolo Gava and Nicola Trintinaglia, 'Un capriccio di pietra. La cupola del Duomo di Anet di Philibert de L'Orme', in *Geometrie segrete. L'architettura e le sue immagini*, ed. by Giuseppe D'Acunto (Padua: Poligrafo, 2004), pp. 175–97. Gava and Trintinaglia's various representations of both the dome and the pavement are not always consistent in the numbers of coffers represented.
6 Stereotomy is an ill-defined term which has been employed to signify a range of stonecutting practices, many of which require no stereotomic expertise. For an operative definition, see Sara Galletti, 'Stereotomy and the Mediterranean: Notes Toward an Architectural History', *Mediterranea*, 2 (2017), pp. 73–120 <doi.org/10.21071/mijtk.v0i2.6716> [accessed 14 March 2020]. I repeat that definition here and use the same examples from Granada and Paris to highlight the difference between stereotomic and non-stereotomic works.
7 On the dressing methods employed in ancient stereotomy, see especially Joël Sakarovitch, *Épures d'architecture: de la coupe des pierres à la géométrie descriptive, XVI^{e}–XIX^{e} siècles* (Basel: Birkhäuser, 1998), pp. 111–17. For an ancient Roman case study, see Giulia Piccinin and Pau Natividad-Vivó, 'Stereotomy

in Ancient Rome: The Mausoleum of Ummidia Quadratilla', in *Geometria e costruzione: Stereotomia e configurazione in architettura*, ed. by José Calvo-López, Alessio Bortot and Giulia Piccinin (Rome: Aracne, 2020), pp. 33–43.

8 For an overview, see especially José Calvo-López, *Stereotomy: Stone Construction and Geometry in Western Europe 1200–1900* (Cham: Birkhäuser, 2020); Jean-Marie Pérouse de Montclos, *L'Architecture à la française: du milieu du XV^e^ à la fin du XVIII^e^ siècle*, 3rd edn (Paris: Picard, 2013); José Carlos Palacios Gonzalo, *Trazas y cortes de cantería en el Renacimiento español*, 2nd edn (Madrid: Instituto Juan de Herrera, 2003); and Marco Rosario Nobile, *Architettura e costruzione in Italia meridionale (XVI–XVII secolo)* (Palermo: Caracol, 2017).

9 Galletti, 'Stereotomy and the Mediterranean', *passim*.

10 De L'Orme, *Le Premier tome*, and Alonso de Vandelvira, 'Libro de traças de cortes de piedras' (*c.* 1585), Madrid, Biblioteca de la Escuela Técnica Superior, MS R10. For a facsimile of the latter, see *Libro de trazas de cortes de piedras: copia manuscrita presentada por Bartolomé de Sombigo y Salcedo*, ed. by José Carlos Palacios Gonzalo (Madrid: Instituto Juan de Herrera, 2015).

11 Gaspard Monge, *Géométrie descriptive: leçons données aux Écoles normales l'an 3 de la République* (Paris: Baudouin, 1798).

12 Sakarovitch, *Épures d'architecture*, *passim*.

13 Niklas Naehrig, *Weise, gelehrt und erfahren: Philibert Delorme und die gesellschaftliche Verantwortung des Architekten in der französischen Renaissance* (Zürich: gta Verlag, 2016), p. 273.

14 Grégory Chaumet provides the following information: the digital survey of the Château d'Anet was executed with a laser scanner Focus S120, which can record 300,000 points per second. Data acquisition was carried out without contact with the object, by scanning a laser beam at 360° over a range of up to 120 m and with data accuracy of 1 mm. To obtain a full 3D model of the chateau, the laser scanner was positioned at several stations chosen with a maximum distance of 10 m between them. During the scanning of the chapel, the laser scanner recorded more than 52 million points to produce a three-dimensional image. Following this first phase of the survey, a digital camera integrated in the laser took a series of panoramic shots, to restore the colours and textures of the chapel. Following the data collection, the points from each station were digitally extracted with Trimble Realworks, processed and analysed to produce a complete registration of the scans and a point cloud of the chapel. The point cloud was then segmented to create orthonormal images of the site, such as plans and cross-sections.

15 Both the horizontal and vertical orthogonal views obtained from the 3D laser scan showed slight asymmetries in the dome, especially in the south-west quarter of the vault. This deformation is most probably due to settlement and is not significant enough to affect my reconstruction.

16 Serlio's illustration of the nonagon, from which Anet's octadecagon can be derived, is found in the *Primo libro d'architettura* (Paris: Jean Barbé, 1545), f. 20v <archive.org/details/ldpd_12050504_000/page/n53/mode/2up> [accessed on 23 December 2020].

17 See Blunt, who describes a similar configuration but with the vault's circumference divided into sixteen equal parts instead of eighteen (Blunt, *Philibert de l'Orme*, p. 42), and Evans, who divides the circumference into eighteen parts but whose rotating circle is smaller in radius and tangent to the outer circumference of the vault (Evans, 'Translations from Drawing to Building', p. 177). Gava and Trintinaglia show, instead, that the circle intersects the outer circumference of the vault in two points (Gava and Trintinaglia, 'Un capriccio di pietra', pp. 191–92). De L'Orme's description of the *trois points perdus* is found in the *Le Premier tome*, ff. 55r–55v and illustrated at f. 56v (circle centred in *C*, to the right of the image).

18 Any circle intersecting the outer circumference on ground plan produces the same shift of curvature from concave to convex on cross-section. While correctly identifying the ribs' axes as intersecting the vault's outer circumference on ground plan, Gava and Trintinaglia did not address this issue (Gava and Trintinaglia, 'Un capriccio di pietra').

19 In de L'Orme's time, the royal units of length were the *toise* (*c.* 195 cm), the *pied du roi* (*c.* 32.4 cm) and the *pouce* (*c.* 2.7 cm). Several methods can be used to determine these arcs' widths. A simple one is shown in Antonio Ginesi, *Nuovo corso d'architettura civile* (Florence: Batelli, 1835), Tav. XXVII.

20 For detailed descriptions of these methods, see especially Calvo-López, *Stereotomy*, pp. 179–97, and Sakarovitch, *Épures d'architecture*, pp. 111–21.

21 De L'Orme, *Le Premier tome*, ff. 111v–19v.

22 On the cartographic projections employed in the sixteenth century, see John P. Snyder, *Flattening the Earth: Two Thousand Years of Map Projections* (Chicago, IL: University of Chicago Press, 1993), pp. 1–54. On the polyconic method applied to stereotomic domes, see, among others, José Carlos Palacios Gonzalo, 'La estereotomía de la esfera', *Arquitectura*, 68 (1987), pp. 54–65 (pp. 56–59).

23 Other illustrations of the same method are found in manuscript treatises by Jean Chéreau, 'Traité d'architecture' (*c.* 1567–74), Gdansk, Biblioteka Publiczna, 2280; and Jacques Gentillâtre, 'Livre d'architecture' (*c.* 1615–25), Paris, Bibliothèque nationale de France, fonds français 14727.

24 See José Antonio Ruiz de la Rosa, 'Evolución de las tradiciones operantes en arquitectura: el dibujo sobre soporte pétreo', in *I tracciati di cantiere: disegni esecutivi per la trasmissione e diffusione delle conoscenze tecniche*, ed. by Carlo Inglese and Antonio Pizzo (Rome: Gangemi, 2016), pp. 18–28; and José Calvo López, Juan Carlos Molina Gaitán, Pau Natividad Vivó, Miguel Ángel Alonso-Rodríguez, Enrique Rabasa-Díaz, Ana López Mozo, Miguel Taín Guzmán and José Antonio Sánchez Pravia, 'The Tracing for the Sail Vault at the Murcia Cathedral Vestry: Surveying a Sixteenth-Century Full-Scale Working Drawing', *International Journal of Architectural Heritage: Conservation, Analysis, and Restoration*, 7 (2013), pp. 275–302.

25 Further examples are found in José Calvo López, Miguel Taín Guzmán, Miguel Ángel Alonso Rodríguez, and Idoia Camiruaga Osés, 'Métodos de documentación, análisis y conservación de trazados arquitectónicos a tamaño natural', *Arqueología de la Arquitectura*, 12 (2015), e026 <dx.doi.org/10.3989/arq.arqt.2015.024> [accessed 22 May 2020]; Miguel 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*, ed. by Juan Roldán Martín (Madrid: CEU Ediciones, 2009), pp. 173–204; and Manuel 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)*, ed. by Fernando Bores Gamundi (Madrid: CEHOPU, 1998), pp. 173–80.

26 On the relation between full-scale *épures* used on building sites and their reduced-scale renderings in stereotomy books, see also David Wendland, 'Architekturzeichnung und ihre Rolle beim Entwurf komplexer Werksteinkonstruktionen in Spätmittelalter und Früher Neuzeit: Überlegungen am Beispiel der Katharinenkapelle im Straßburger Münster', *Architectura*, 47 (2017), pp. 1–23 (p. 20).

27 The sketchbook of Villard de Honnecourt is a case in point, for it was only in the late 1980s, and thanks to a team of practitioners, that a number of its illustrations were recognised as small-scale *épures* of stereotomic works. See Claude Lalbat, Gilbert Margueritte and Jean Martin, 'De la stéréotomie médiévale: la coupe des pierres chez Villard de Honnecourt, I', *Bulletin monumental*, 145 (1987), pp. 387–406, and Claude Lalbat, Gilbert Margueritte and Jean Martin, 'De la stéréotomie médiévale: la coupe des pierres chez Villard de Honnecourt, II', *Bulletin monumental*, 147 (1989), pp. 11–34.

28 On the geometry and construction of looping rib vaults, see especially David Wendland, *Entwurf und Planung spätgotischer Gewölbe und ihrer Einzelteile: Steinerne Ranken, wunderbare Maschinen* (Petersberg: Michael Imhof Verlag, 2019), and David Wendland, 'How to Design and Build Complex Rib Vaults from A to Z: Principles, Practices, and Geometric Processors in International Late Gothic', in *The Art of Vaulting: Design and Construction in the Mediterranean Gothic*, ed. by Paula Fuentes and Anke Wunderwald (Basel: Birkhäuser, 2019), pp. 43–78.

29 On the coffered vault type illustrated by Vandelvira, see especially José Carlos Palacios and Sandra Cynthia Bravo Guerrero, 'Diseño y construcción de las bóvedas por cruceros en España durante el siglo XVI', *Informes de la Construcción*, 65 (octubre 2013), pp. 81–94, as well as the online *Bóvedas Góticas de Crucería* platform <bovedasgoticasdecruceria.com> [accessed 21 December 2020], which provides a wealth of graphic, photographic and bibliographic material.

30 See Palacios Gonzalo, 'La estereotomía de la esfera', pp. 54–65 (pp. 60–63) and Palacios Gonzalo, 'La estereotomía islámica: El Cairo', in *Actas del Octavo Congreso Nacional de Historia de la Construcción. Madrid, 9–12 de octubre de 2013*, ed. by Santiago Huerta and Fabián López Ulloa (Madrid: Instituto Juan de Herrera, 2013), pp. 803–11 (pp. 808–10). On the many extradosed patterned domes of Cairo, see also Bernard O'Kane, 'The Carved Stone Domes of Cairo', in *Proceedings of the Masons at Work conference, University of Pennsylvania, 2012*, ed. by Robert Ousterhout, Renata Holod and Lothar Haselberger; Ahmed Wahby and Dina Montasser, 'The Ornamented Domes of Cairo: The Mamluk Mason's Challenge', in Ousterhout *et al.*, *Proceedings*; and Christel Kessler, *The Carved Masonry Domes of Mediaeval Cairo* (Cairo: American University in Cairo Press, 1976).

31 On the multiple alternative methods for dressing the voussoirs of a hemispherical dome, see in particular the encyclopedia *La Maçonnerie et la taille de pierre*, 8 vols (Paris: Librairie du compagnonnage, 1991–2010), III, *Traité pratique de coupe des pierres* (1996), pp. 264–73.

32 An illustration of the *sauterelle* is found in de L'Orme, *Le Premier tome*, f. 56v (tool marked B). The same operation can also be executed with a *biveau*, as shown in Palacios Gonzalo, 'La estereotomía de la esfera', pp. 54–65 (pp. 59–60).

33 For an image of the *biveau*, see De L'Orme, *Le Premier tome*, f. 56v (tool marked A). For an illustrated description, see Lalbat, Margueritte and Martin, 'De la stéréotomie médiévale, I', pp. 398–404.

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34 Potié writes that 'the art of stonecutting is almost definitively fixed by the end of the fourteenth century: squinches, domes and *arrière-voussures* only go through secondary, formal developments after this date': Philippe Potié, 'Le tracé d'épure, des carnet médiévaux aux traités de stéréotomie', in *La Construction savante: les avatars de la littérature technique*, ed. by Jean-Philippe Garric, Valérie Nègre and Alice Thomine-Berrada (Paris: Picard, 2008), p. 149. This statement is contradicted by both the rarity of stereotomic vaults and the lack of stereotomy manuals in late medieval France.

35 Pérouse de Montclos's survey of French early modern stereotomic vaults includes a third dome, in the chapel of the Château de Moulins (1497–1503). But the documentation does not clarify whether the dome was, in fact, stereotomic or not (Pérouse de Montclos, *L'Architecture à la française*, p. 148).

36 Blunt, *Philibert de l'Orme*, pp. 42–43; Potié, *Philibert de l'Orme, p. 118;* Evans, 'Translations from Drawing to Building', p. 173; Jean-Marie Pérouse de Montclos, *Philibert De L'Orme: architecte du roi, 1514–1570* (Paris: Mengès, 2002), p. 119. Pérouse de Montclos's identification of the subject of Sangallo's drawing GDSU 900 Av with Brunelleschi's cupola is incorrect. See Firenze, Gabinetto dei disegni e delle stampe degli Uffizi [hereafter GDSU], 900 Av; *The Architectural Drawings of Antonio da Sangallo the Younger and His Circle*, ed. by Christof L. Frommel and Nicholas Adams, 2 vols (New York: Architectural History Foundation, 1994–2000), II (2000), pp. 178–79.

37 Loxodromes, or rhumb lines, are curves defined by their crossing all the meridians of the sphere at a constant angle. Logarithmic spirals, loxodromes' projections on ground plan, cross all the radial lines of a circumference at a constant angle. See Giuseppe Conti, Beatrice Sedili and Alberto Trotta, 'Le curve lossodromiche in architettura', *Science & Philosophy*, 2, no. 2 (2014), pp. 65–86 <eiris.it/ojs/index.php/scienceandphilosophy/article/view/272/302> [accessed 26 March 2020].

38 Spinning-wheel patterns like those of the villa in Via Emanuele Filiberto were common across the Roman empire, in particular during the second century. A number of them were also excavated in France, including de L'Orme's hometown of Lyon, but none before the nineteenth century. See Catherine Balmelle, *Le Décor géométrique de la mosaïque romaine*, 2nd edn, 2 vols (Paris: Picard, 2002), II, pp. 135–48; and Catherine Balmelle, Michèle Blanchard-Lemée, Jean-Pierre Darmon, Henri Lavagne and Henri Stern, *Recueil général des mosaïques de la Gaule*, 4 vols (Paris: Centre National de la Recherche Scientifique, 1957–80).

39 See, for instance, Peruzzi's drawings of the Todi Nicchioni (GDSU, 402 Ar) and the Ferento Theatre (GDSU, 491 Ar) and Antonio da Sangallo the Younger's drawings of the funerary monument of Ummidia Quadratilla (GDSU, 1171 Av) and the Ferento Theatre (GDSU, 1132 Ar).

40 Albrecht Dürer, *Underweysung der Messung mit dem Zirckel und Richtscheyt in Linien, Ebnen und gantzen Corporen* (Nüremberg: Hieronymus Andreae, 1525), book I, figs 15–17.

41 Dürer, *Underweysung*, book I, text accompanying fig. 17.

42 Pedro de Alviz, 'Dibujos de trazados arquitectónicos' (*c.* 1550), Madrid, Biblioteca Nacional de España, 12686; Hernán Ruiz el Joven, 'El Libro de arquitectura' (*c.* 1559–69), in *El Libro de arquitectura de Hernán Ruiz, el joven*, ed. by Pedro Navascués Palacio (Madrid: Escuela Técnica Superior de Arquitectura, 1974); and Vandelvira, 'Libro de traças de cortes de piedras'.

43 See Sara Galletti, 'From Stone to Paper: Philibert de L'Orme, the *Premier tome de l'architecture* (1567), and the Birth of Stereotomic Theory', *Ædificare*, 2 (2017), pp. 143–62 (pp. 155–56); and José Calvo López, 'Philibert De l'Orme and Spanish Stereotomy', in *Philibert de l'Orme, un architecte dans l'histoire: arts, sciences, techniques*, ed. by Frédérique Lemerle and Yves Pauwels (Turnhout: Brepols, 2015), pp. 199–213.

44 GDSU, 306 Ar. For a discussion of Sangallo's commentaries, see Francesco Benelli, 'Antonio da Sangallo the Younger's Reactions to the Pantheon: An Early Modern Case of Operative Criticism', *Journal of the Society of Architectural Historians*, 78 (2019), pp. 276–91.

45 Pérouse de Montclos, among others, considers de L'Orme's theory of stereotomy as the most traditional component of the *Premier tome* and, in part because of de L'Orme's interest in stereotomy, consistently refers to him as a 'mason' and 'great mason' rather than architect (Pérouse de Montclos, *L'Architecture à la française*, for example pp. 80, 182).

46 De L'Orme, *Le Premier tome*, f. 89v: 'Vous serez donc avertis [que la trompe] se peut ériger sur un angle droit, obtus, ou pointu, et de quelque forme que vous voudrez par le devant, soit droite, carrée à pend, comme la moitié d'un hexagone ou octogone, ou bien toute ronde. Et par ainsi vous pouvez faire trompes droites, creuses, rampantes, ou de quelque façon qu'on pourra penser, selon la nécessité et contrainte du lieu auquel on les veut accommoder. Toutes sortes de voûtes se peuvent faire en forme de trompe, et toutes suspendues en l'air, sans avoir fondement par le dessous, sinon aux deux côtés qui font l'angle, le tout par une même méthode de trait, ainsi que vous le verrez ci-après, et sous telle sorte qu'il vous plaira' (author's translation).