

# PROCEDURAL INTERPLAY OF ART AND TECHNOLOGY IN SELJUK MAUSOLEUM ACROSS EMPIRE PHASES: A CHRONOLOGICAL AND COMPARATIVE ANALYSIS

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## Research Article


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**ABSTRACT:** This study examines the dynamic interplay between artistic expression and structural technology in Seljuk mausoleum across the Early (1037–1063 CE), Middle (1063–1100 CE), and Late (1100–1194 CE) phases of the empire, extending into their Post-Seljuk legacy. Through a chronological and comparative analysis of key examples from Persia and Anatolia—such as Gonbad-e Qabus, the Kharāqan Towers, the Mausoleum of Sultan Sanjar, the Tomb of Mama Hatun, the Melik Gazi Tomb, and the Hüdavend Hatun Tomb—we demonstrate how Seljuk architects integrated ornamentation and structure as interdependent elements. Our findings revealed an evolution: the Early phase used material-driven ornamentation, the Middle phase advanced craft-based techniques, and the Late phase achieved a complex synthesis of form and decoration with regional variations. Shaped by cross-cultural influences from Persian, Byzantine, Armenian, Central Asian, and Turkic traditions, this process left a lasting impact on Islamic architecture. We conclude that this procedural interplay, rooted in Tektonik and material poiesis, not only defined Seljuk architectural innovation but also offers a framework for analyzing integrated design in broader architectural contexts.

**KEYWORDS:** Seljuk mausoleum, Ornamentation, Geometric Patterns, Medieval Architecture, Chronological Analysis, Cross-Cultural Transmission, Procedural Design, Architectural Tectonics, Material Poiesis

## INTRODUCTION

The Seljuk empire (1037–1194 CE) produced remarkable architecture by combining artistic vision with technical skill, particularly in its mausoleum across Persia, Anatolia, and Central Asia. These structures went beyond their role as tombs, serving as expressions of dynastic power, religious devotion, and cultural identity across a vast region. Scholars have widely explored their styles, forms, and regional differences. However, the process of how art and technology were united in their design and construction has received less focus. This study fills that gap by arguing that ornamentation in Seljuk mausolea was not a separate layer but an essential part of their structure, planned and built as one. To analyze this, we propose the concept of “procedural interplay,” grounded in Tektonik (the science of construction) and material poiesis (the expressive potential of materials), as a new framework to interpret this architectural evolution. This framework shows how Seljuk design principles balanced aesthetic innovation with structural integrity, leaving a lasting mark on Islamic architecture and extending into Post-Seljuk adaptations, such as the Hüdavend Hatun Tomb. We use Tektonik—where form and structure align—and material poiesis—where materials shape design—to

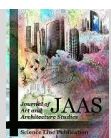
trace this process. From the Early phase’s material focus to the Late phase’s detailed designs, and across Persia and Anatolia, we reveal an approach that was both innovative and influential. This work explains Seljuk architecture and provides insights for studying design processes in other settings.

### Historical and architectural context: cross-cultural synthesis and material tectonics

The Seljuk period marked a key moment in Islamic architecture. It blended influences from Persian, Byzantine, Armenian, Central Asian, and early Turkic traditions into a unique style [1]. This style featured large buildings, skilled brickwork, vaulted structures, and detailed ornamentation. Mausolea were not just burial sites; they symbolized Seljuk power, faith, and goals across the empire. Nazer et al. [2] showed how these structures (cylindrical towers or domed chambers) stood as lasting signs in their landscapes. Their effect came from a process where art and structure were planned together.

Critically, the profound aesthetic impact of Seljuk mausoleum emerged organically from a deeply ingrained procedural integration of artistic and technological considerations from the

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conceptual genesis of design and throughout the complex construction process. As Oleg Grabar astutely observed, Seljuk architecture strategically deployed decoration to articulate and accentuate underlying structural forms [3]. This inherent procedural interaction, therefore, is not merely a stylistic preference, but a fundamental organizing principle, signifying a deliberate design ethos rooted in Tektonik principles.

The material landscape profoundly shaped Seljuk architectural expression. The Iranian Plateau's scarcity of timber elevated brick to a primary building material, stimulating exceptional brick quality and innovative vaulting techniques [3]. Brickwork became a sophisticated medium for decorative articulation, imbued with poiesis. Seljuk architects masterfully utilized varied bonding patterns, glazed tiles, stucco, plaster, and muqarnas to create rich decorative surfaces and spatial effects. In Anatolia, dressed stone predominated, leading to regional adaptations in material and decorative styles, while still reflecting the overarching Seljuk design ethos of integrated art and technology.

## Literature review

### Addressing the gap in procedural analysis of Seljuk mausoleum

Seljuk architecture has been thoroughly studied, with mausolea recognized as key examples of technical and artistic success in Islamic research. Scholars like Ettinghausen et al. [4] and Bloom [5] have detailed their forms, materials, styles, and cultural ties (Table 1). Yet, the step-by-step integration of art and technology in these buildings is less examined. Often, ornamentation is seen as an end step, not part of the construction process. The current study aimed to address that with “procedural interplay,” a concept showing how structure and decoration were connected from the beginning. Hence we break this into four stages (proto technology, developed technology, innovative technology, and influential art) to follow its growth. Based on Tektonik and material poiesis, this approach looks at the methods behind Seljuk design, adding a fresh view to past studies.

**Table 1.** Summary of key literature on Seljuk mausoleum

Author(s)/Year	Title/Publication	Focus	Period Addressed	Key Contribution	Relevance to Study
Ettinghausen et al. [4]	Islamic Art and Architecture 650-1250	Early Islamic architecture, Persian traditions	Early	Describes Gonbad-e Qabus as structurally focused with minimal ornamentation	Supports Proto Technology as the initial stage
Pope and Ackerman [6]	A Survey of Persian Art	Persian architectural history, brickwork	Early	Emphasizes structural clarity in early brick mausolea	Connects form to ornamentation in Early phase
Komaroff & Carboni [7]	The Legacy of Genghis Khan	Central Asian influences on Islamic art	Early	Links simplicity to nomadic traditions	Explains cultural roots of Early Seljuk design
Tabbaa [8]	The Transformation of Islamic Art	Sunni revival, geometric ornamentation	Middle	Examines brick patterns as craft in Kharāqan	Highlights Developed Technology's craft focus
Makovicky [9]	Tomb Towers and Minarets	Technical analysis of Kharāqan	Middle	Details planned brick ornamentation	Reinforces focus on embedded decoration
Bloom [5]	The Minaret	Structural evolution, vaulting techniques	Middle	Studies octagonal forms and vaulting advances	Adds structural insight to Middle phase
Gharipour and Blessing [10]	Mausoleums of the Islamic World	Sultan Sanjar's design and decoration	Late	Shows brick and tile integration	Evidence for Innovative Technology's synthesis
Pancaroglu [11]	The Seljuks of Anatolia	Mama Hatun, geometric stone carving	Late	Details geometric precision on stone surfaces	Supports Anatolian innovation in Late phase
Blessing [12]	Rebuilding Anatolia after the Mongol Conquest	Post-Seljuk Anatolian architecture	Post-Seljuk	Views Gök Medrese and Doner Kumbet as Seljuk continuations	Defines Influential Art as legacy
Öney [13]	Anadolu Selçuklu Mimari Süslemesi	Anatolian Seljuk ornamentation	Post-Seljuk	Documents Hüdavend Hatun's figural designs	Shows post-Seljuk adaptation of Seljuk ideas

## METHODOLOGY

We used a case study approach, analyzing selected Seljuk mausoleum from the Early (1037–1063 CE), Middle (1063–1100 CE), Late (1100–1194 CE), and Post-Seljuk periods. This timeline helps us see changes over the empire's history. We chose examples from Persia and Anatolia, using research like Hillenbrand [14] and Blair [15]. These mausolea were picked for their architectural importance, historical value, and good documentation. Our main idea, “procedural interplay,” means art and technology were blended during design and construction. Based on Tektonik and material poiesis, this makes ornamentation and structure work together. We divided this into four stages:

**A) Proto technology (structure shapes decoration):** Early phase where the structure itself is the ornamentation, using materials directly.

**B) Developed technology (craft builds art):** Middle phase where decoration is built into the structure through skilled work.

**C) Innovative technology (form and art unite):** Late phase where structure and decoration fully merge, varying by region.

**D) Influential art (legacy guides design):** Post-Seljuk phase where Seljuk ideas shape later buildings.

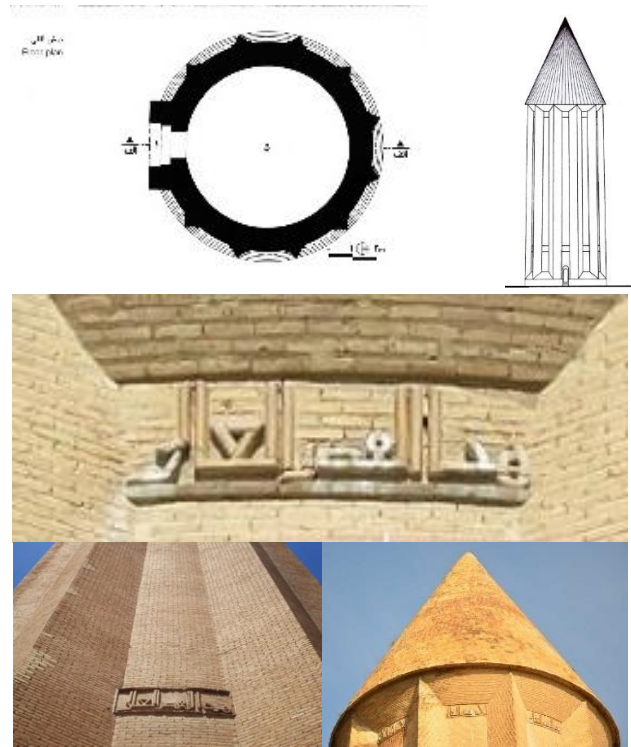
For each mausoleum, we looked at the structure (form, materials, techniques), ornamentation (patterns, tiles, carvings), and how they fit together, showing the process behind their unity.

### Analysis: procedural evolution across Seljuk periods

This section looks at the mausolea by period to show how art and technology changed over time and across regions.

#### 1. Early Seljuk period (1037–1063 CE): Proto technology - structural form as ornament in Persia

In the Early phase, Proto Technology used structural form as ornamentation. Gonbad-e Qabus has a cylindrical tower, decagonal plan, and conical roof in plain fired brick. Buttresses and a Kufic inscription blend into the structure, relying on material texture for effect. Gunbad-i ‘Ali, a cylindrical tower with a conical roof, uses brick texture and minimal inscriptions the same way. This approach focuses on structural clarity and material use.



**Figure 1.** Gonbad-e Qabus represents Proto Technology, where the decagonal plan and plain brickwork form the ornamentation, reflecting a basic tectonic approach. (Photos: authors' archive).

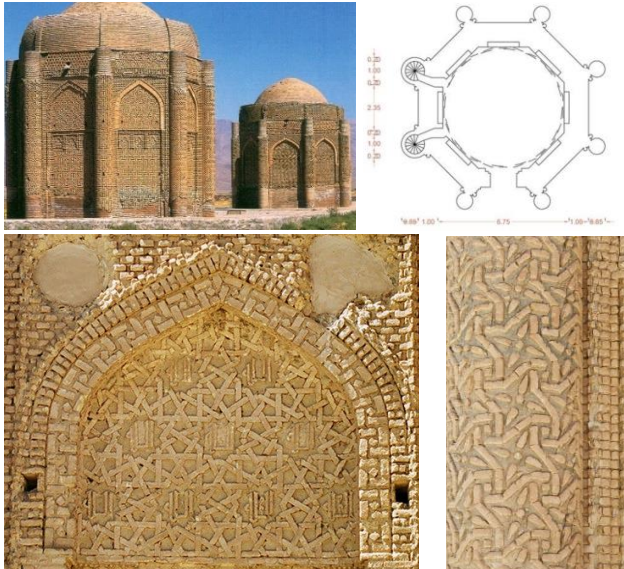


**Figure 2.** Gunbad-i ‘Ali refines Proto Technology, with its cylindrical tower and conical roof in plain brick, enhanced by texture and Kufic inscriptions, emphasizing material and form (Photos: authors' archive).

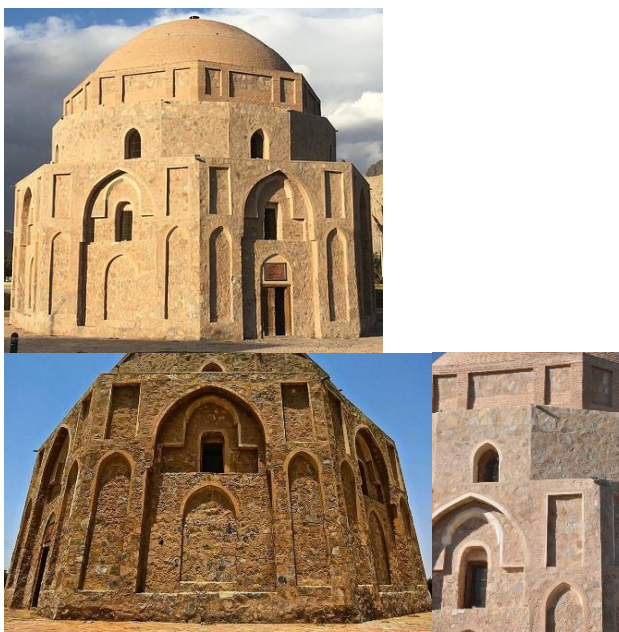
#### 2. Middle Seljuk period (1063–1100 CE): developed technology - craft-integrated ornament in Persian brickwork

The Middle phase, Developed Technology, added ornamentation into construction. The Kharāqan Towers have octagonal brick forms with

double conical roofs. Polygons and strapwork are carved into the brick as it's built, making craftsmanship artistic. Gunbad-e Jabaliye, with an octagonal stone base and domed roof, uses geometric brick patterns in stucco, showing more complexity. This phase relies on skill to join structure and decoration.



**Figure 3.** Kharāqan Towers detail shows developed Technology, with geometric patterns carved into brickwork, turning structure into an artistic medium through material poiesis (Photos: authors' archive).



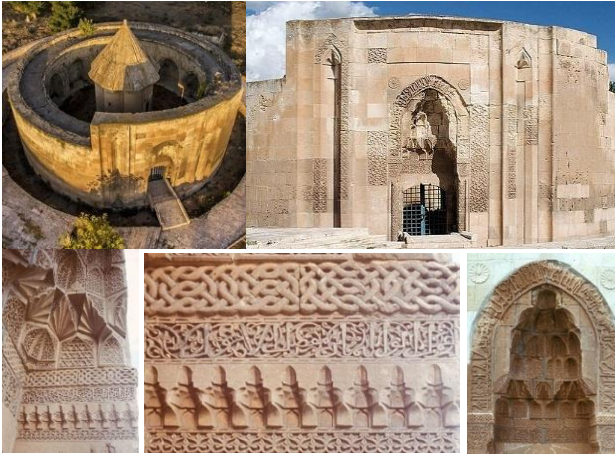
**Figure 4.** Gunbad-e Jabaliye reflects developed Technology in stone, its octagonal form and domed roof with brick patterns in stucco adapting brick techniques. (Photos: authors' archive).

### 3. Late Seljuk period (1100–1194 CE): innovative technology - symbiotic art & structure and regional diversification

The Late phase, Innovative Technology, fully united structure and ornamentation. The Mausoleum of Sultan Sanjar mixes Hazārḡāf brickwork, turquoise tiles, and interior painting into one design, boosting both form and meaning. In Anatolia, the Tomb of Mama Hatun has geometric stone carvings on a curved drum, while the Sitte Melik tomb uses turquoise tile revetment as its main ornamentation. This phase shows advanced methods and regional styles.



**Figure 5.** Mausoleum of Sultan Sanjar reflects innovative technology, integrating Hazārḡāf brickwork, tile revetment, and painting into a unified structure with symbolic depth. (Photos: authors' archive).



**Figure 6.** Tomb of Mama Hatun shows innovative technology in Anatolian stone, with geometric carvings on curved surfaces highlighting regional skill (Photos: authors' archive).



**Figure 7.** The Sitte Melik tomb (c. 1190–1200 CE) demonstrates innovative technology, with its octagonal base, cylindrical drum, and conical roof showcasing intricate stone carvings and geometric patterns that integrate structure and ornamentation in Anatolian Seljuk design (Photos: authors' archive).

#### 4. Post-Seljuk period (Post-1194 CE): influential art - legacy design principles and adaptation

In the Post-Seljuk phase, influential art kept Seljuk ideas alive. Gök Medrese Türbe has an octagonal stone form with a conical roof, using turquoise tiles and geometric carvings. Doner Kumbet, a dodecagonal two-story structure, has carvings and tile traces, continuing Seljuk principles. This phase shows how Seljuk methods lasted and changed.



**Figure 8.** Gök Medrese Türbe reflects influential art, maintaining Seljuk style with octagonal stone, tiles, and carvings aligned with the form (Photos: authors' archive).



**Figure 9.** Doner Kumbet shows influential art, its dodecagonal two-story form with carvings and tile traces extending Seljuk design. (Photos: Authors' Archive).

## RESULTS AND DISCUSSION

This section synthesizes our findings to elucidate the evolution and variation of procedural interplay in Seljuk mausolea, contextualizing them within prior scholarly work.

### Procedural interaction types in Seljuk mausoleum

Our analysis identifies four distinct types of procedural interplay, each corresponding to a specific period:

**Proto technology (Early Seljuk Period, 1037–1063 CE):** Characterized by minimal ornamentation where the structure itself serves as the decorative element, relying on material texture and form, as seen in Gonbad-e Qabus. [Ettinghausen et al. \[4\]](#) note that early Seljuk mausolea, like Gonbad-e Qabus, prioritized structural clarity with minimal applied decoration, aligning with our observation of form-driven ornamentation in this phase.

**Developed technology (Middle Seljuk Period, 1063–1100 CE):** Ornamentation is embedded into the structure through skilled craftsmanship, as exemplified by the Kharāqan Towers' carved brick patterns. [Makovicky \[9\]](#) emphasizes the planned integration of geometric brickwork in the Kharāqan Towers, reinforcing our finding that craft became a medium for artistic expression during construction.

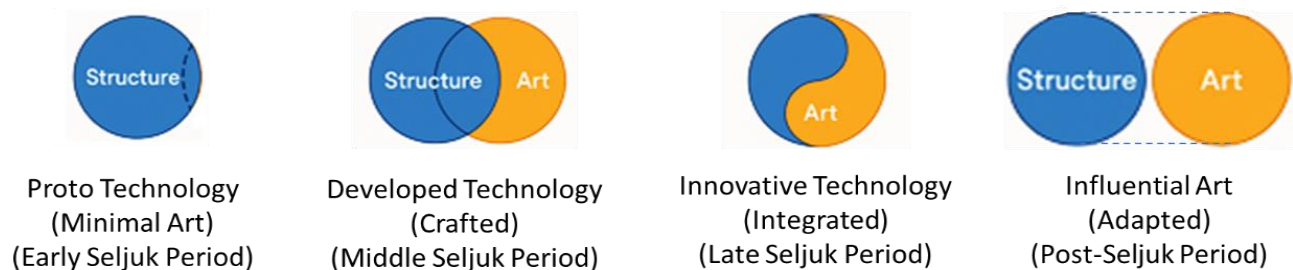
**Innovative technology (Late Seljuk Period, 1100–1194 CE):** A seamless blend of structure and complex ornamentation, with regional variations, as seen in the Mausoleum of Sultan Sanjar and Tomb of Mama Hatun. [Gharipour and Blessing \[10\]](#) highlight the sophisticated integration

of brick and tile in Sultan Sanjar's mausoleum, supporting our conclusion that this phase achieved a symbiotic unity of form and decoration.

**Influential art (Post-Seljuk Period, Post-1194 CE):** Seljuk principles guide later designs, as in Doner Kumbet, where geometric carvings and tile traces extend the Seljuk legacy. [Asefi et al. \[16\]](#) discuss historical architectural globalization, which parallels our conceptualization of this phase as a continuation of Seljuk design ethos in adapted forms. These four types illustrate a progressive sophistication in integrating art and technology, evolving from material-based simplicity to a refined legacy. This evolutionary framework aligns with [Asefi et al.'s \[16\]](#) analysis of art-technology interactions across Islamic and Christian contexts, but our study extends this by focusing specifically on the procedural methodologies of Seljuk mausolea.

### Framework for evolution of procedural interaction in Seljuk mausoleum

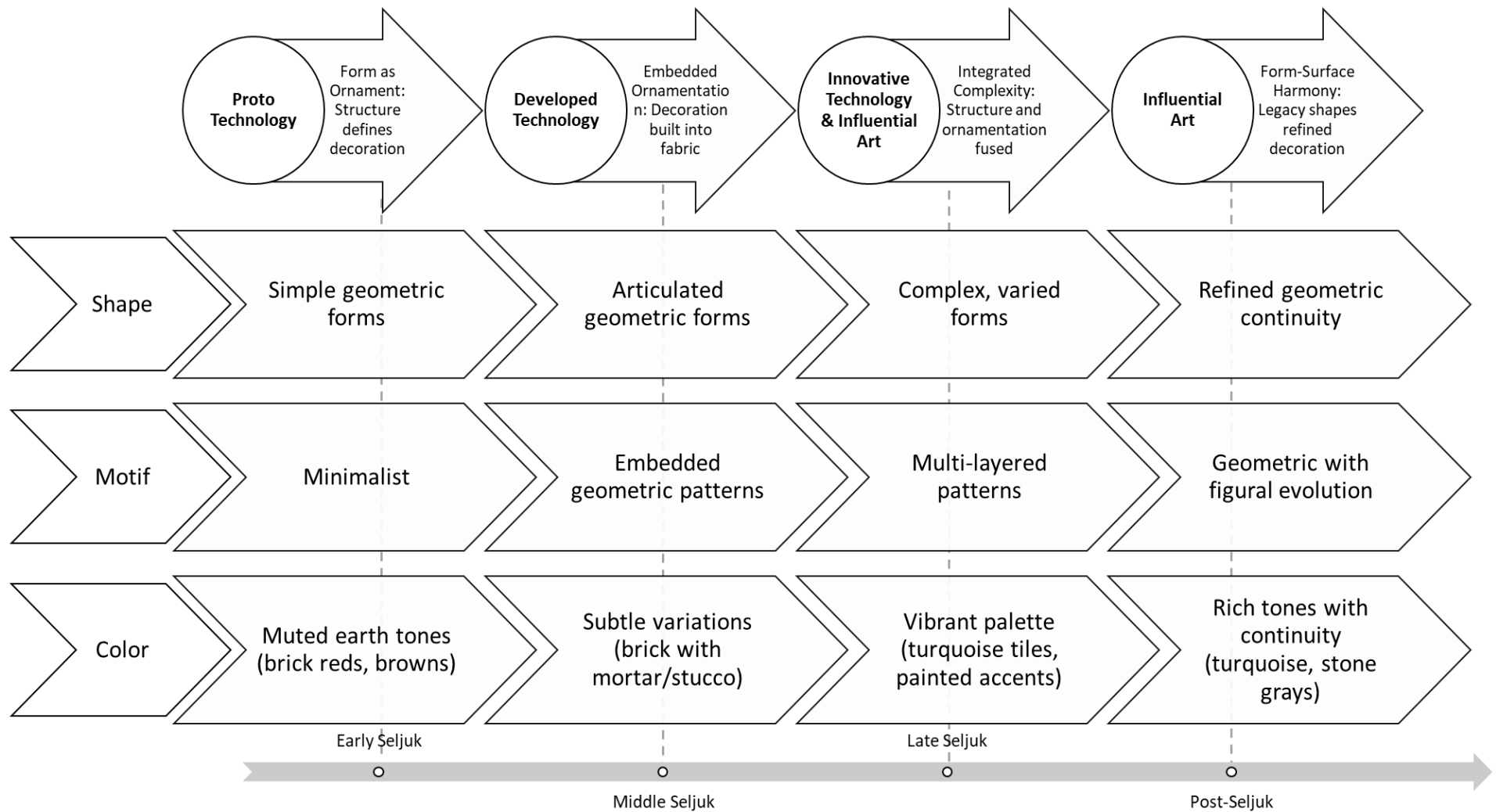
Our framework, detailed in Tables 2 and 3 and Figures 10–12, tracks the progression of procedural interplay across shape, motif, and color. From Proto Technology's reliance on structural geometry to Influential Art's refined form-surface harmony, this framework moves beyond stylistic analysis to uncover the deliberate design ethos of Seljuk architects. Bloom [5] notes the evolution of vaulting techniques and geometric forms in Middle Seljuk architecture, which supports our observation of increasing structural complexity in the Developed Technology phase. Similarly, [Pancaroglu \[11\]](#) details the geometric precision of Anatolian stone carvings in the Late phase, corroborating our findings of regional diversification in Innovative Technology. This framework provides a robust tool for analyzing procedural integration, offering insights applicable to broader architectural studies.



**Figure 10.** Schematic evolution of procedural interplay; structure and art interaction across Seljuk phases (source: Authors inspired by [Asefi et al. \[16\]](#)).

**Table 2.** Procedural interaction types in Seljuk mausoleum (source: Authors)

	<b>Mausolea- Date (CE)</b>	<b>Region</b>	<b>Structural Design</b>	<b>Ornamentation</b>	<b>Procedural Interaction Type</b>	<b>Description</b>
<b>Early</b>	Gonbad-e Qabus 1006-07	Persia (Iran)	Cylindrical tower, decagonal plan, conical roof	Plain fired brick, buttresses, Kufic band	Proto technology: structure shapes decoration	Geometry (decagonal plan) and brick texture define decoration without applied elements.
	Chehel Dokhtaran c. 1055	Persia (Iran)	Cylindrical tower, conical roof	Plain brick, Kufic inscription, subtle brick texture	Proto technology: structure shapes decoration	Brick texture and Kufic band enhance structural form with minimal ornamentation.
	Gunbad-i 'Ali 1056	Persia (Iran)	Cylindrical tower, conical roof	Plain brick, minimal texture, Kufic inscription	Proto technology: structure shapes decoration	Brick texture and inscriptions enhance structural clarity with minimal ornamentation.
<b>Middle</b>	Kharāqan Towers 1067 & 1093	Persia (Iran)	Octagonal brick, double conical roofs	Carved brick (polygons, strapwork), inscriptions	Developed technology: craft builds art	Patterns carved into bricks during construction, merging art and structure.
	Gunbad-e Jabaliye c. 1080–1090	Persia (Iran)	Octagonal stone, domed roof	Geometric brick patterns, minimal stucco	Developed technology: craft builds art	Brick patterns integrated into stone structure, marking transitional complexity.
<b>Late</b>	Gunbad-e Sorkh 1147	Persia (Iran)	Square brick, conical roof	Brick strapwork, early muqarnas, inscriptions	Innovative technology: form and art unite	Brick strapwork and early muqarnas enhance square form, reflecting advanced synthesis.
	Mausoleum of Sultan Sanjar 1157	Persia (Turkmenista n)	Domed square, large single dome	Hazārbāf brick (chevron, diaper), tile, interior paint	Innovative technology: form and art unite	Brick, tile, and interior paint symbiotically enhance structure and spatial symbolism.
	Tomb of Mu'mina Khatun 1186	Persia (Azerbaijan)	Decagonal brick, domed roof	Brick strapwork, early muqarnas, inscriptions	Innovative technology: form and art unite	Brickwork and muqarnas amplify structural geometry in a refined synthesis.
	Sitte Melik Tomb c. 1190–1200	Anatolia (Turkey)	Octagonal base, cylindrical drum, conical roof	Turquoise tile revetment, geometric patterns	Innovative technology: form and art unite	Turquoise tile revetment enhances structure as primary ornament, reflecting regional style.
	Tomb of Mama Hatun c. 1191–1192	Anatolia (Turkey)	Curved stone drum, squinch, column	Geometric stone carving (hexagonal, dodecagonal), muqarnas	Innovative technology: form and art unite	Geometric carvings on curved stone integrate form and decoration via advanced techniques.
	Melik Gazi Tomb c. 1196–1197	Anatolia (Turkey)	Square with muqarnas, tripartite elevation	Brick muqarnas hoods, decorative bonds	Innovative technology: form and art unite	Brick muqarnas articulate structure, reflecting Iranian influence in Anatolian context.
<b>Post-Seljuk</b>	Gök Medrese Türbe c. 1270	Anatolia (Turkey)	Octagonal stone, conical roof	Turquoise tile, geometric stone carvings	Influential art: legacy guides design	Tile and stone carvings harmonize with octagonal form, continuing Seljuk traditions.
	Doner Kumbet 1276	Anatolia (Turkey)	Dodecagonal, two-storey, conical roof	Geometric carvings, turquoise tile traces	Influential art: legacy guides design	Dodecagonal form and carvings/tile traces harmonize, extending Seljuk principles.
	Tomb of 'Abd al-Samad c. 1299	Persia (Iran)	Octagonal brick, domed roof	Glazed tile, geometric brickwork, stucco	Influential art: legacy guides design	Tile and stucco refine octagonal form, evolving Seljuk decorative systems.
	Hüdavend Hatun 1312	Anatolia (Turkey)	Octagonal stone, pyramidal roof	Stone carvings (geometric, figural), muqarnas	Influential art: legacy guides design	Octagonal form with geometric and figural carvings evolves Seljuk style into a new synthesis.



**Figure 11.** Conceptual diagram of procedural interaction evolution in Seljuk mausoleum (source: Authors)

**Table 3.** Conceptual framework for evolution of procedural interaction in Seljuk mausoleum (source: Authors)

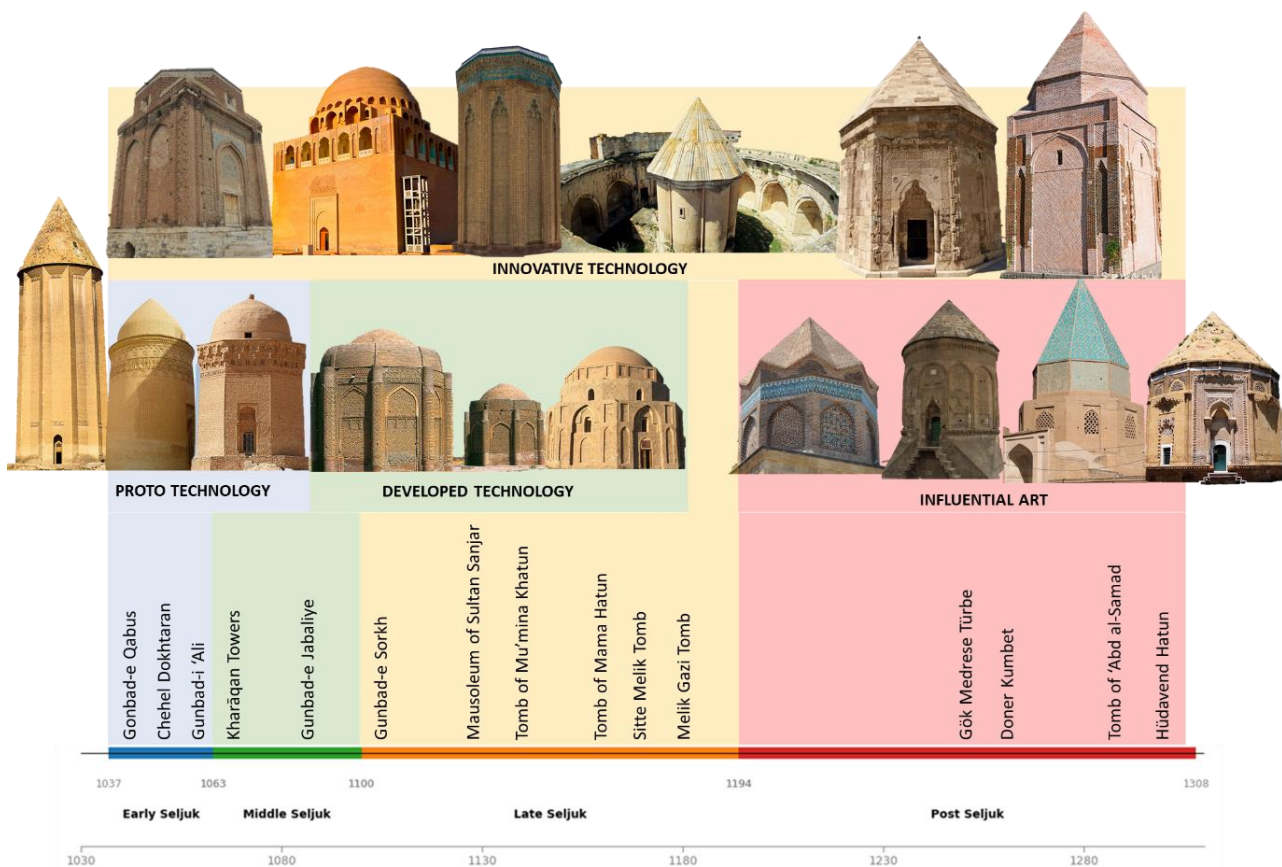
Visual Representation	Early-Seljuk	Middle-Seljuk	Late-Seljuk	Post-Seljuk
	<i>Proto Technology</i>	<i>Developed Technology</i>	<i>Innovative Technology</i>	<i>Influential Art</i>
Shape	Simple, bold geometric forms	More articulated geometric forms	Highly complex and varied forms	Refined geometric continuity
	<i>Gonbad-e Qabus</i> : Cylindrical tower, decagonal plan	<i>Kharāqan Towers</i> : Octagonal with double conical roofs	<i>Sultan Sanjar</i> : Large domed square	<i>Gök Medrese Türbe</i> : Octagonal stone
	<i>Chehel Dokhtaran</i> : Plain cylinder	<i>Gunbad-e Jabaliye</i> : Octagonal stone base	<i>Mu'mina Khatun</i> : Decagonal dome	<i>Doner Kumbet</i> : Dodecagonal two-storey
	<i>Gunbad-i 'Ali</i> : Plain cylinder		<i>Gunbad-e Sorkh</i> : Square with conical roof	<i>Hüdavend Hatun</i> : Octagonal with pyramidal roof
			<i>Mama Hatun</i> : Curved stone drum	
			<i>Sitte Melik</i> : Octagonal with cylindrical drum	<i>'Abd al-Samad</i> : Octagonal brick
			<i>Melik Gazi</i> : Square with tripartite elevation	
Motif	Minimalist design	Interwoven geometric patterns embedded in brick or stone	Intricate, multi-layered patterns	Geometric with evolving figural and refined synthesis
	<i>Gonbad-e Qabus</i> : Kufic band, buttress light-shadow interplay	<i>Kharāqan Towers</i> : Polygons, strapwork in brick	<i>Sultan Sanjar</i> : Chevron, diaper brick, tile, star-painted interiors	<i>Gök Medrese Türbe</i> : Tile, geometric stone carvings
	<i>Chehel Dokhtaran</i> : Kufic band, subtle brick texture	<i>Gunbad-e Jabaliye</i> : Geometric brick patterns	<i>Mu'mina Khatun</i> : Strapwork, early muqarnas	<i>Doner Kumbet</i> : Geometric carvings, tile traces
	<i>Gunbad-i 'Ali</i> : Basic brick texture, Kufic inscription		<i>Gunbad-e Sorkh</i> : Strapwork, early muqarnas	<i>Hüdavend Hatun</i> : Geometric and figural carvings
			<i>Mama Hatun</i> : Hexagonal, dodecagonal stone carvings	
			<i>Sitte Melik</i> : Turquoise tile geometric patterns	<i>'Abd al-Samad</i> : Glazed tile, geometric brickwork
			<i>Melik Gazi</i> : Brick muqarnas hoods	
Color	Muted, earthy tones reflecting material honesty	Subtle variations—earthy tones with mortar/stucco contrast	Rich, vibrant palette	Sustained rich tones with continuity
	<i>Gonbad-e Qabus</i> : Brick reds, browns	<i>Kharāqan Towers</i> : Brick tones, mortar grays	<i>Sultan Sanjar</i> : Turquoise tiles, brick reds, painted yellows	<i>Gök Medrese Türbe</i> : Turquoise tiles, stone grays
	<i>Chehel Dokhtaran</i> : Brick reds, browns	<i>Gunbad-e Jabaliye</i> : Brick with stucco grays	<i>Mu'mina Khatun</i> : Brick reds	<i>Doner Kumbet</i> : Turquoise hints, stone grays
	<i>Gunbad-i 'Ali</i> : Brick reds, browns		<i>Gunbad-e Sorkh</i> : Brick reds	<i>Hüdavend Hatun</i> : Stone grays
			<i>Mama Hatun</i> : Stone grays	
			<i>Sitte Melik</i> : Turquoise tiles, brick undertones	<i>'Abd al-Samad</i> : Turquoise tiles, brick tones
			<i>Melik Gazi</i> : Brick reds	
Key Characteristic	Form as Ornament	Embedded Ornamentation	Integrated Decorative Complexity & Regional Diversification	Form-Surface Harmony
	Emphasis on structural geometry and material expression as primary decoration	Decoration integrated into construction, bricklaying as craft	Seamless synthesis of structure and elaborate ornamentation with regional adaptations	Refined legacy of Seljuk principles shaping design

### Chronological evolution and regional divergence of procedural harmony

The chronological analysis reveals a clear trajectory from structural ornamentation to a sophisticated synthesis of form and decoration. In Persia, brick-based patterns dominated, as seen in the Hazārbāf brickwork of Sultan Sanjar's mausoleum, while Anatolia favored stone and turquoise tiles, as in the Tomb of Mama Hatun. This regional divergence, driven by material availability and cultural preferences, is consistent with Blair and Bloom's [1] observation of cross-cultural synthesis in Islamic architecture, where Persian, Byzantine, and Turkic influences enriched Seljuk designs. Despite these variations, the core principle of procedural integration remained consistent, as evidenced by the shared emphasis on harmonizing art and technology across both regions. Ettinghausen et al. [4] further

note the adaptability of Seljuk architecture to local materials, which aligns with our finding that regional styles did not dilute but rather enhanced the unified Seljuk design ethos. Cross-cultural transmission, as discussed by Asefi et al. [16], played a pivotal role in this process, with Seljuk architects creatively adapting diverse influences to create a rich and varied architectural language.

In summary, our results demonstrate that the procedural interplay of art and technology in Seljuk mausolea evolved through distinct phases, shaped by technical advancements, material poiesis, and cross-cultural exchanges. By comparing our findings with prior studies [1, 4, 5, 9, 10, 11, 16], we affirm that this interplay was not merely stylistic but a fundamental design principle, offering a new lens for understanding Seljuk architectural innovation and its lasting influence.



**Figure 12.** Chronological interaction of art and technology in Seljuk mausoleum case studies, (source: Authors)

### CONCLUSION

This study establishes that the integration of artistic expression and structural technology was a defining feature of Seljuk mausolea throughout their development across the Early (1037–1063 CE),

Middle (1063–1100 CE), and Late (1100–1194 CE) phases, with its influence persisting into the Post-Seljuk period. Our chronological and comparative analysis of key examples—Gonbad-e Qabus, Kharāqan Towers, Mausoleum of Sultan Sanjar, Tomb of Mama Hatun, Melik Gazi Tomb, and

Hüdavend Hatun Tomb—reveals a clear evolution in this process. In the Early phase, as seen in Gonbad-e Qabus, ornamentation relied on the structural form and material texture, using minimal elements like Kufic inscriptions and brick patterns to enhance clarity. The Middle phase, exemplified by the Kharāqan Towers, shifted to a craft-driven approach, embedding geometric patterns into brickwork during construction, showing increased technical and artistic skill. By the Late phase, structures like the Mausoleum of Sultan Sanjar and Tomb of Mama Hatun achieved a sophisticated balance, fully uniting complex ornamentation—such as Hazārbāf brickwork, turquoise tiles, and stone carvings—with structural design, tailored to regional materials and styles. This trajectory continued into the Post-Seljuk period, where mausolea like Hüdavend Hatun Tomb adapted Seljuk principles, blending geometric and figural carvings with traditional forms.

This evolution reflects a consistent design approach where art and structure were not separate but worked together, rooted in Tektonik and material poiesis. Tektonik ensured that form and construction aligned, while material poiesis allowed materials like brick and stone to express both function and beauty. This method went beyond decoration, embedding it into the building process to strengthen both visual impact and symbolic meaning—whether dynastic power, religious devotion, or cultural identity. Cross-cultural influences from Persian, Byzantine, Armenian, Central Asian, and Turkic traditions enriched this approach, making Seljuk mausolea adaptable and diverse across Persia and Anatolia. The result was an architectural legacy that shaped Islamic design and influenced later periods, as seen in Post-Seljuk examples.

The concept of “procedural interplay” introduced here offers a new way to understand this integration. It highlights how Seljuk architects balanced innovation with stability, creating mausolea that stood as both technical achievements and artistic statements. This framework is not limited to Seljuk architecture; it can help analyze how art and technology merge in other times and places, offering a tool for broader studies in medieval and Islamic architecture. Looking ahead, future research could dig deeper into the geometric and mathematical basis of Seljuk patterns, explore the social and political factors behind this design approach, or trace its influence on later architectural traditions in greater detail. For now, this study positions Seljuk mausoleum as a powerful example

of how art and technology can combine, leaving a lasting mark on architectural history and providing lessons for design today.

## DECLARATIONS

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### Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

### Authors' contribution

Z. Nazer: Conceptualization, methodology, computational analysis, data curation, formal analysis, validation, writing – original draft, review, and editing. P. Rabb: Conceptualization, methodology, art historical validation, supervision, project administration, resources, writing – review and editing, and validation.

### Competing interests

The author declares that there is no competing interest.

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