RESEARCH PAPER

The Linen of the Turin Shroud: A Critical Multidisciplinary Assessment of Its Compatibility with a First-Century Eastern Mediterranean Origin

Otangelo Grasso

Independent Researcher, Aracaju, Sergipe, Brazil

ORCID: 0009-0005-6942-0593

Correspondence: otangelograsso@gmail.com

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ABSTRACT

This paper evaluates whether the physical construction and material history of the Turin Shroud linen supply a positive medieval signature or remain compatible with Roman-period eastern Mediterranean manufacture. Radiocarbon measurement is direct chronological evidence but depends on sample integrity, geographic representativeness, and the validity of the isotopic model applied to the measured carbon. Textile compatibility is indirect evidence: it can exclude anachronism but does not by itself assign an exact date. Evidence considered here includes flax morphology, yarn twist, 3/1 herringbone construction, thread density, loom requirements, sewing, archaeological comparisons, possible Indo-Mediterranean textile provenance, cellulose degradation, sampling geography, carbon mass balance, statistical behavior of the 1988 measurements, and neutron-induced isotope production.

Recent microscopy of retained Arizona fragments confirms that they are genuine portions of the principal Shroud cloth and found no visible repair or substantial surface contamination in the small area examined. These observations weaken a simple foreign-patch hypothesis but do not establish isotopic uniformity across the full cloth. Quantitative mass balance shows that shifting hypothetically first-century linen to an apparent medieval age by addition of truly modern carbon would require about 62-63% modern carbon in the analyzed carbon pool. That calculation strongly constrains ordinary contamination explanations, but it does not apply to hypotheses in which additional carbon-14 is produced in situ by nuclear reactions.

The textile itself lacks a feature demonstrated to be unique to fourteenth-century Europe. Z-spun fibers and complex twills predate the Middle Ages. Experimental work on a warp-weighted loom favored a horizontal treadle loom for reproducing the Shroud's 3/1 chevron structure, but the chronological significance of treadle technology requires more nuanced treatment than a simple ancient/medieval dichotomy. Barta-Gil's historiographic analysis explicitly evaluates first-century Israel, Egypt, and India alongside fourteenth-century Europe and draws attention to the combination of 3/1 twill, Z twist, reported cotton traces, and other provenance indicators. Archaeological evidence from Roman Red Sea ports independently demonstrates long-distance movement of Indian textiles into the Roman world.

A further alternative is neutron irradiation. Since Phillips's 1989 proposal, this hypothesis has suggested that neutron capture could generate additional carbon-14 and therefore make an old textile appear younger. The mechanism remains unproven for the Shroud and its required source is unresolved, but recent controlled irradiation experiments on linen show dose-dependent changes measurable by ultraviolet luminescence, ATR-FTIR, and Raman spectroscopy. These results provide a non-destructive strategy for testing whether the cloth carries a spatial radiation signature before any new destructive radiocarbon campaign.

The cumulative evidence supports a restrained conclusion. The 1988 AMS result remains the strongest direct chronological evidence for a medieval age, while the textile record does not yet demonstrate a medieval-exclusive technological marker. A first-century origin remains viable only if the 1988 sampling region is shown to be unrepresentative, or if a quantitatively adequate process - including a testable isotope-production mechanism - explains the measured carbon-14

concentration. The highest-priority future work is therefore a transparent, geographically resolved program beginning with whole-cloth non-destructive mapping and followed, only if warranted and permitted, by minimal multi-location destructive sampling.

KEYWORDS *Turin Shroud; linen; textile archaeology; first-century Judaea; herringbone twill; Z-spun yarn; radiocarbon dating; neutron irradiation; ATR-FTIR; ancient weaving; Indian textiles; cellulose degradation; sampling heterogeneity.*

1. Introduction

The Turin Shroud is a linen cloth approximately 4.30 m long and 1.08 m wide. A narrow longitudinal strip is attached along one side. The main textile bears faint frontal and dorsal images of an adult male displaying injuries associated with crucifixion [1-3]. The cloth is woven from flax in a 3/1 herringbone twill using hand-spun Z-twisted yarns.

In 1988, one corner region was divided among accelerator mass spectrometry laboratories in Arizona, Oxford, and Zurich. The combined measurements were published in 1989 and calibrated to 1260-1390 CE at a stated confidence of at least 95% [5]. Three laboratories obtaining medieval values from material now confirmed as genuine Shroud linen is not a trivial result. Random analytical error is not a plausible explanation for the agreement.

The unresolved issue is narrower: whether the sampled corner was chemically and isotopically representative of the entire textile and whether all processes capable of altering the measured isotope ratio have been excluded. Laboratory replication and geographic replication are not the same. Multiple laboratories can accurately measure adjacent portions of a locally anomalous region.

This study does not claim that textile analysis can assign an exact year or establish that the cloth covered Jesus of Nazareth. It examines whether the physical linen independently corroborates fourteenth-century European manufacture or whether the material remains compatible with an earlier eastern Mediterranean origin. It also distinguishes three different explanations for a discordant radiocarbon result: addition of younger carbon, localized textile replacement or alteration, and in-situ production of additional carbon-14 by nuclear reactions.

2. Methodological Framework

Textile chronology normally yields ranges of compatibility, not precise calendar dates. Fiber, twist, weave, density, sewing, loom technology, and trade context should therefore be evaluated through three distinct concepts.

First, technical possibility asks whether craftspeople in a period could make the structure. Second, historical probability asks whether comparable practices, tools, or textiles are documented in that context. Third, diagnostic exclusivity asks whether a feature is restricted sufficiently to identify one time or place.

The paper applies an asymmetrical-evidence principle. Radiocarbon measurement is direct chronological evidence but depends on sample integrity, representativeness, pretreatment, and the assumption that the measured carbon-14 inventory reflects atmospheric carbon fixed during flax growth. Textile compatibility is indirect evidence: it can exclude an anachronistic model but cannot by itself establish a first-century date. Here, 'compatible' means only that no feature has been shown to be technologically impossible or historically implausible for the period; it does not mean that the feature positively identifies that period.

A further methodological distinction is essential. A carbon mass-balance calculation addresses contamination by younger carbon added to the sample. It cannot be used without modification against a nuclear-transmutation hypothesis, because the latter proposes creation of additional carbon-14 within or on the cloth rather than admixture of a large mass of modern organic material. These hypotheses therefore require different quantitative tests.

3. What the 2026 Arizona-Fragment Study Establishes

Freer-Waters and Jull examined two retained Arizona fragments, A1A and A1B. Polarized-light microscopy identified flax fibers; warp and weft were single Z-twisted yarns; both fragments displayed 3/1 twill; and A1A preserved a herringbone reversal. Measured thread densities were consistent with earlier descriptions of the principal cloth [1].

These observations strongly support sample identity. The dated Arizona material was not an unrelated substitute textile. The study also found no visible repair in the retained fragments and no significant surface contamination in an approximately 2 x 1.5 mm SEM field. The authors explicitly cautioned that this field might not represent the entirety of either fragment and that the fragments form a small, potentially non-uniform subset [1].

The proper inference is consequently limited. The study undermines a theory in which the dated sample was wholly composed of visibly different medieval cloth. It does not rule out every localized alteration, every chemically incorporated carbon source, every isotopic modification, or every difference between the corner and distant regions. Most importantly, it performed no new radiocarbon dating and no spatial isotope mapping.

4. Flax, Manual Spinning and Textile Quality

Flax was common in ancient Mediterranean and medieval European textile production. Its presence is chronologically non-diagnostic. Manual variation in yarn diameter likewise fits both antiquity and the Middle Ages [1,4].

Archaeological burial textiles predominantly represent ordinary practice. An exceptional textile should therefore be compared with the upper range of production and trade, not only with the most frequently preserved local cloths. The Shroud's quality is consistent with both ancient Mediterranean

luxury manufacture and medieval European specialized weaving and therefore does not, by itself, distinguish the two periods.

5. Z-Twisted Yarn: Qualified Geographic Evidence

Both yarn systems of the Shroud are Z-spun. Much Egyptian linen is S-spun, and the natural morphology of flax tends to favor S twist. The Shroud therefore differs from the dominant Egyptian tradition [1,4].

Z-spinning is not, however, a medieval invention. Freer-Waters and Jull note an early Egyptian Z-spun linen example while emphasizing its rarity [1]. Spinning direction reflects regional and workshop tradition more than a universal chronology.

A first-century burial textile from Akeldama in Jerusalem had Z-spun warp, but it was wool, plain woven, and structurally unlike the Shroud [6]. It demonstrates only that Z-spun, possibly imported funerary textiles were present in first-century Jerusalem. It does not establish that a Z-spun 3/1 herringbone linen like the Shroud has been excavated there.

Accordingly, Z twist is compatible with a Roman Mediterranean trade context, but on its own provides only weak positive chronological support. Its value becomes greater when considered jointly with trade, fiber-transfer, and workshop-provenance evidence rather than as an isolated dating marker.

6. The 3/1 Herringbone Twill and Loom Technology

In a 3/1 twill, each weft passes over three warp yarns and under one; successive displacement forms a diagonal, and periodic reversal produces the herringbone. Twill weaving broadly predates medieval Europe.

The stronger chronological question is whether the precise single-layer Shroud structure required a treadle loom. Experimental work by Olsen attempted a 3/1 chevron on a warp-weighted loom and found that the arrangement produced an extra shed and a double weave. Olsen concluded that the Shroud could not have been woven on that warp-weighted setup and favored a treadle loom [7]. This materially strengthens the case for a multi-shaft horizontal loom.

It does not, however, establish that 'treadle loom' is synonymous with 'fourteenth-century European loom.' Barta-Gil's historiographic review treats the horizontal four-shaft treadle loom as one component of a broader provenance problem and discusses evidence used to argue for earlier horizontal and foot-operated loom traditions [17]. The archaeological history of treadle technology itself remains debated: the physical survival of looms is poor, loom pits can be difficult to interpret, and the date at which particular treadle configurations became widespread is not the same as the earliest possible use of foot-controlled shedding.

Therefore, the relevant question is not merely whether a treadle loom can reproduce the Shroud. It is whether the exact four-shaft drafting, shed sequence, selvedge behavior, defect pattern, and cloth width can be shown to require a loom configuration securely absent from the first-century Mediterranean and Indian Ocean textile world. That exclusivity has not yet been demonstrated.

7. Weave Defects and the Nicolotti Inference

Nicolotti's argument is more specific than the claim that herringbone merely looks medieval. Drawing on inversion patterns described by Vial and De Jonghe, he interprets the repeated sequence as skip-threading or irregular drafting on four shafts, a configuration readily associated with a horizontal treadle loom. The argument is technically serious because a regular drafting error can preserve information about harness order and loom setup [4,16].

For the defects to date the cloth, however, their frequency and distribution must be comprehensively mapped, the proposed drafting sequence reconstructed, alternative manual causes experimentally tested, and defect patterns compared with securely dated ancient, Byzantine, Indian, and medieval textiles. Published observations support a treadle-loom interpretation, but no open whole-cloth defect map or sufficiently broad comparative database has yet demonstrated chronological exclusivity.

Potential alternatives include missed heddle sequences, replacement of broken warps, tension changes, displaced heddle loops, and local correction. These cannot simply be asserted; they require replication. Conversely, the treadle interpretation should not be dismissed merely because the ancient record is incomplete. The responsible conclusion is that the defect evidence presently favors a multi-shaft loom but does not uniquely establish a medieval date.

8. Possible Indian or Indo-Roman Textile Provenance

Barta-Gil [17] expands the provenance comparison beyond a simple Judaea-versus-medieval-Europe contrast. His analysis explicitly evaluates first-century Israel, Egypt, and India, as well as fourteenth-century Europe, and considers the combined significance of the Shroud's 3/1 twill, Z twist, reported traces of Gossypium herbaceum or G. arboreum cotton, and biological material recovered from dust. His proposed synthesis is important because a luxury burial textile in Jerusalem need not have been locally woven.

Independent archaeological evidence confirms that Indian textiles moved into the Roman Red Sea trade system. First-century deposits at Berenike, a major Roman port on the route to India, yielded Z-spun cotton textiles interpreted as Indian imports [18]. This does not show that the Shroud was made in India, nor does cotton found on or near linen establish the origin of the linen itself. It does demonstrate that high-quality South Asian textiles and textile materials were capable of reaching the Roman eastern Mediterranean in the relevant period.

The Indian model must therefore be handled as a provenance hypothesis, not as a date. Reported cotton traces may reflect manufacture, workshop contact, later conservation, environmental transfer, or contamination. Dust-borne DNA is even more vulnerable to post-manufacture contact and cannot independently identify a loom workshop. Nevertheless, the combination of Z-spinning, long-distance Roman-Indian trade, and Barta-Gil's comparative textile analysis weakens any argument that an eastern or South Asian production route is historically impossible.

A useful next step would be a blinded comparison of Shroud fibers and adhering non-linen fibers with securely provenanced Roman-period textiles from Egypt, the Levant, and India, using microscopy, species-level fiber analysis where possible, trace-element chemistry, and non-destructive spectroscopic signatures.

9. Thread Density and Comparative Context

The Arizona fragments contain approximately 37-41 yarns per centimetre in one direction and 26-29 in the other, consistent with earlier counts [1]. Freer-Waters and Jull compare these values with northern European archaeological datasets in which most fabrics, including a limited linen corpus, fall around 10-30 threads per centimetre, with higher values uncommon [1,8].

This comparison suggests unusually high textile quality. It does not by itself prove a later date because density reflects fiber preparation, labor, function, and economic value. Moreover, northern European datasets are not a complete proxy for eastern Mediterranean or South Asian luxury production.

The evidence is therefore best stated negatively: density does not exclude antiquity, but neither does it positively locate the cloth in first-century Judaea, India, or any other specific production center.

10. The Significance and Limits of Missing Parallels

No securely dated textile identical in fiber, twist, density, weave, scale, and finishing has been established from either first-century Judaea or fourteenth-century Europe. Freer-Waters and Jull report that a comparable linen 3/1 herringbone could not be found for the 1988 controls and describe the textile as singular for its measured date [1].

This absence is not evidence against medieval manufacture. Textile survival is uneven; specialized products may have been rare; and relevant collections may remain unpublished or incompletely analyzed. It is more accurately described as lack of an independently established close medieval parallel.

The same caution applies to antiquity. The absence of an identical first-century cloth prevents the textile evidence from becoming positive archaeological proof of a Roman date. A more informative comparative program would include not only Judaean burial textiles but also high-status textiles and

imported fabrics from Roman Egypt, Syria, Mesopotamia, the Red Sea ports, and the Indian Ocean trade network.

11. The Side Strip and the Masada Comparison

A narrow strip is attached along one long edge. Mechthild Flury-Lemberg compared the joining construction with a seam or hem among Roman-period textiles from Masada [9]. The comparison concerns a compact edge-to-edge joining method with concealed or minimally exposed sewing rather than identity of fiber or ground weave. Published descriptions do not establish that the stitch family is confined to Roman Judaea, and the precise archaeological comparator should be documented photographically before strong chronological weight is assigned.

The Masada textile differs materially from the Shroud, and a systematic cross-period seam database has not demonstrated that the technique is unique to Roman Judaea. The comparison therefore supplies contextual compatibility, not a date.

Until the relevant stitches are documented through standardized high-resolution imaging and compared with ancient, Byzantine, Indian, Islamic, and medieval European corpora, the seam should be assigned low-to-moderate evidential weight.

12. Burial Textiles and the Luxury-Cloth Hypothesis

Known Roman-period Judaean burial textiles are generally simpler than the Shroud. The Akeldama cloth is an important example but is wool and plain woven [6]. This difference weakens any claim that the Shroud represents typical local burial practice.

An ancient-origin model instead treats the Shroud as an exceptional textile available through wealth and long-distance commerce. Roman Jerusalem participated in extensive Mediterranean and eastern trade. The presence of Indian textiles at Roman Red Sea ports [18] gives concrete archaeological support to the broader proposition that distant luxury cloth could circulate through the Roman economy. The Gospel description of Joseph of Arimathea as wealthy may provide a literary context, but it cannot serve as independent archaeological evidence for the Turin cloth.

Thus, the luxury-cloth model is historically plausible and can explain rarity, but it does not verify provenance or date.

13. Strengths of the 1988 Radiocarbon Evidence

Radiocarbon dating is normally highly effective for linen because the measured carbon derives principally from the flax plant's growth. The three laboratories analyzed genuine Shroud material and obtained medieval values that combined to 1260-1390 CE [5].

The agreement cannot reasonably be attributed to random analytical error. Any ancient-origin hypothesis must explain why adjacent genuine fragments carried a medieval carbon-14 concentration after independent laboratory pretreatments.

The confidence interval is not evidence that every conceivable systematic error was excluded. It describes uncertainty within the adopted model and the measured specimens. Still, the 1988 measurements remain the strongest direct chronological evidence in the case and should be treated as such.

14. Sampling Geography and Statistical Heterogeneity

All Shroud specimens used for the 1988 dating came from one corner region. Three laboratories therefore provided analytical replication but not geographic replication.

Casabianca and colleagues reanalyzed the published and subsequently released raw records using Shapiro-Wilk, Levene and Bartlett tests, analysis of variance, t tests, and Mann-Whitney comparisons. Their supplementary tables report failures of one or more homogeneity assumptions and led them to conclude that the procedure should be reconsidered [10]. Walsh and Schwalbe likewise reported heterogeneity absent from the control textiles and an approximate relationship between measured age and original sample position [11]. Riani and colleagues earlier applied regression methods and reported evidence consistent with a spatial trend, although the interpretation and chronological importance of that trend remain contested [15].

These analyses do not show that the true age is first-century. The studies use small datasets, different statistical formulations, and reconstructed sample positions; statistical significance may identify variation without showing a bias large enough to move the cloth by thirteen centuries. Heterogeneity can coexist with an overall medieval age and may reflect laboratory treatment, local variation, underestimated uncertainty, a positional effect, or an unmodeled physical process.

The heterogeneity evidence therefore weakens the claim that the corner behaved as a perfectly uniform specimen. It does not independently overturn the medieval date.

15. Quantitative Carbon Mass Balance: What It Does and Does Not Exclude

A central requirement of any contamination hypothesis is quantitative adequacy. Suppose, for the sake of argument, that the original linen were about 1,920 radiocarbon years old in 1950, while the tested carbon appeared about 650 radiocarbon years old. With radiocarbon activity $A/A0 = \exp(-t/8267)$, the respective activities are approximately 0.793 and 0.924. If f is the fraction of truly modern carbon, $0.793(1 - f) + 1.000f = 0.924$, giving f approximately 0.63.

This result is substantially larger than the fifteen-to-twenty-percent figure sometimes quoted. Fifteen or twenty percent modern carbon would not move first-century linen into the thirteenth or

fourteenth century. If the contaminant itself were medieval rather than modern, an even larger fraction would generally be required.

Ordinary surface dust, oils, smoke, or microbial material are therefore inadequate unless present in massive amounts and resistant to all pretreatments. A visible or invisible medieval reweave could supply a large young-carbon fraction only if it constituted much of the analyzed yarn; the retained Arizona fragments match the principal cloth structurally and reveal no such bulk replacement [1]. Surface conservation coatings, candle smoke, and handling oils generally represent too little mass and should be reduced by pretreatment. The 1532 fire could deposit soot, but soot derived from old fuel would not necessarily be modern and widespread thermal exposure would not readily explain a corner-specific age. Microbial growth sufficient to contribute most of the carbon would imply extensive biomass or fiber replacement that has not been demonstrated.

The approximately 63% calculation therefore imposes a severe burden on additive contamination models. It should not, however, be generalized to every possible explanation of a young radiocarbon age. In particular, neutron-induced production of carbon-14 changes isotopic abundance without requiring 63% of the sample mass to be replaced by young organic carbon. That possibility requires a separate nuclear and spectroscopic analysis.

> ***"The approximately 63% calculation imposes a severe burden on additive contamination models."***

16. Neutron Irradiation as an Isotope-Production Hypothesis

Shortly after the 1988 dating, Phillips proposed in Nature that neutron irradiation could increase the carbon-14 content of the Shroud and therefore make an older cloth appear radiocarbon-younger [19]. Two nuclear pathways are relevant in principle: neutron capture by carbon-13 can yield carbon-14, and the reaction 14N(n,p)14C can produce carbon-14 from nitrogen associated with the textile or its impurities. Phillips estimated that an integrated thermal-neutron fluence of the order of 2×10^{16} neutrons cm^{-2} could, under his assumptions, create an apparent age shift of the required order. He also emphasized testable consequences, including spatial variation in the carbon-isotope ratio and production of other activation products.

The hypothesis immediately attracted a strong criticism from Hedges, who argued that no plausible physical mechanism had been demonstrated for the required neutron source and that a dose matching the medieval date appeared highly fine-tuned [20]. Those objections remain important. A nuclear reaction that is physically possible is not thereby shown to have occurred on the Shroud.

Later authors have developed spatial neutron-transport models and have argued that non-uniform irradiation could produce gradients in apparent carbon age [22]. Such models are highly assumption-dependent: they require a source geometry, neutron spectrum, flux, duration, linen composition, surrounding materials, and capture cross-sections. They should therefore be evaluated by predictions that are independent of the 1988 date used to tune the model.

The scientific significance of neutron irradiation is consequently narrow but real. It is a quantitatively different explanation from contamination, it makes spatial and material predictions, and it can in principle be tested. The appropriate question is not whether neutron irradiation is currently proven - it is not - but whether the Shroud displays independent physical signatures compatible with a neutron dose large enough to affect radiocarbon dating.

17. Experimental Linen Irradiation and Non-Destructive Testing

Barta, Fernández-Álvarez, and Ruiz-Navas [21] irradiated eight modern linen samples with increasing neutron and gamma doses, reaching a total dose of 166 kGy, and then examined the fabrics with techniques selected for potential application to cultural-heritage textiles. Ultraviolet luminescence increased markedly with dose. ATR-FTIR spectra showed radiation-related chemical trends, including changes associated with carbonyl formation, while the fluorescence background in Raman spectroscopy intensified with dose. The authors found NMR less useful for dose detection because of the intrinsic heterogeneity of natural linen.

Of particular relevance, the study proposed an ATR-FTIR-based neutron-irradiation index derived from spectral ratios and reported a correlation with irradiation dose in the experimental set. The authors explicitly framed such methods as a way to search for a radiation-dose gradient on a large linen cloth without destructive sampling [21]. A subsequent study examining heating and neutron irradiation in relation to FTIR linen dating likewise proposed a non-destructive FTIR test specifically to evaluate whether the Turin Shroud experienced neutron irradiation [23].

These experiments do not demonstrate that the Shroud was irradiated. The test linen is modern; the reactor exposure includes neutron and gamma components; dose rate and spectrum may differ radically from any historical event; natural aging, fire, water, conservation, and oxidation can also modify cellulose spectra; and textile heterogeneity increases uncertainty. Any application to the Shroud must therefore use calibrated controls that separately model thermal aging, the 1532 fire, water exposure, ultraviolet history, gamma radiation, neutron spectrum, and dose.

Nevertheless, the work changes the status of the neutron hypothesis from a purely retrospective explanation to a directly testable one. Before new destructive radiocarbon sampling is considered, the cloth can first be mapped non-destructively for radiation-sensitive spectroscopic features. A reproducible spatial gradient matching an independently specified neutron-transport prediction would increase the hypothesis's credibility; a null result obtained with a validated detection threshold would constrain or potentially exclude the dose range required to shift the carbon date.

18. Repair and Localized Alteration

The evidence now argues strongly against the simplest invisible-mending claim: that the Arizona sample was wholly a visibly different patch. Textile specialists selected the area, and the retained fragments match the principal cloth structurally and show no obvious repair [1].

The study's scale does not exclude every localized alteration, such as reweaving with closely matched yarn, addition of original-style fibers, or a transition zone outside the retained fragments. Such models, however, must account for the large carbon fraction required by an additive-contamination explanation and should predict detectable transitions in weave, chemistry, or isotopes.

The dating problem should therefore not rest on an unspecified repair. It requires direct mapping of the entire original sampling region and comparison with distant cloth regions.

19. Cellulose-Aging Evidence

De Caro and colleagues applied wide-angle X-ray scattering to one Shroud fiber sample approximately 0.5 x 1 mm, reportedly taken near the Raes/radiocarbon region. Their comparison set comprised a small series of historically or radiocarbon-dated linen samples spanning antiquity to recent centuries; four reference profiles were emphasized in the published comparison, and the Shroud profile most closely resembled a Masada linen dated to 55-74 CE [12].

A subsequent environmental model examined long-term temperature and relative-humidity effects. The authors argued that the observed degradation could fit roughly two millennia if the cloth experienced average secular conditions around 20.0-22.5 C with correlated relative humidity of approximately 75-55% during its undocumented history. To reconcile the same degradation with only seven centuries, their model required long-term temperatures close to extreme terrestrial values [13].

These results deserve attention because they are physically independent of radiocarbon measurement. Their limitations are substantial: WAXS dating of linen remains preliminary and is not an established archaeological dating standard; the calibration series is small; independent blind validation against large known-age textile collections has not been reported; the exact provenance and chain of custody of the tested Shroud fiber have been questioned; and cellulose degradation depends strongly on temperature, humidity, oxidation, fire, water, radiation, and conservation history.

The addition of irradiation studies makes one further point important: cellulose-based aging proxies should be calibrated against neutron and gamma exposure as well as heat and humidity. Otherwise, a spectroscopic or structural change caused partly by irradiation could be misread as natural aging, or vice versa [21,23]. WAXS therefore remains preliminary discordant evidence requiring replication on securely documented fibers in independent laboratories.

20. Alternative Chronological and Provenance Models

The evidence need not be reduced to a binary choice between approximately 30 CE Judaea and fourteenth-century Europe. Additional models include a Roman or late-antique cloth later used for the image, a Byzantine textile, an early-medieval cloth, a first-century imported luxury textile

manufactured outside Judaea, a mostly ancient linen with localized later intervention, or a wholly medieval cloth made in a specialized European or non-European workshop.

Barta-Gil's provenance analysis makes the geographic dimension especially important [17]. A first-century cloth present in Jerusalem could, in principle, have been woven elsewhere in the Roman trade network, including regions connected through Egypt and the Indian Ocean. Conversely, a medieval date does not automatically identify western European manufacture.

The present textile evidence cannot discriminate confidently among all these possibilities. Its strongest conclusion is exclusionary: no demonstrated textile characteristic requires fourteenth-century European technology, but no textile characteristic directly fixes the cloth in the first century either.

21. Relation of the Linen to the Wider Shroud Question

This paper deliberately excludes detailed analysis of the body image, bloodstains, and historical provenance. That scope protects the textile argument from circular reasoning, but it also limits the conclusion.

An ancient linen could theoretically receive a later image, and a medieval linen could bear image properties that remain difficult to reproduce. Likewise, neutron irradiation has sometimes been proposed as both a radiocarbon-altering process and part of an image-formation mechanism; the present paper does not assume that the two questions must have a common cause. Authentication of the Shroud requires integration of textile chronology with image chemistry, blood sequencing, forensic anatomy, documentary history, and any independently testable radiation evidence.

The age and provenance of the cloth are necessary but not sufficient for identifying the artifact.

22. Comparative Assessment

The first-century eastern Mediterranean model is materially plausible. Flax, manual spinning, Z-twist traditions, trade in high-value textiles, and complex weaving all existed before the Middle Ages. The seam comparison, Indo-Roman textile trade, and preliminary cellulose-aging evidence add contextual compatibility [9,12,17,18]. The model's weaknesses are the absence of a direct first-century linen parallel matching the Shroud's full structure and the need to explain the medieval radiocarbon concentration.

The medieval model has direct chronological support from three AMS laboratories and an experimentally favored treadle-loom explanation [5,7]. Its weaknesses are single-region radiocarbon sampling, reported statistical heterogeneity, the absence of an established close contemporary linen parallel, and discordant supplementary aging measurements.

The neutron model addresses a specific weakness of ordinary contamination explanations: it can increase carbon-14 without replacing most of the sample mass. Its weaknesses are more fundamental

at present: no neutron exposure of the Shroud has been demonstrated, the required source and dose history are unresolved, and predicted collateral signatures have not been comprehensively measured. The recent irradiation studies are important chiefly because they provide a route to falsification or corroboration [21,23].

The evidential balance is therefore asymmetric. The medieval AMS result remains the strongest direct measurement. The ancient case is broader but indirect, while the neutron mechanism is testable but unconfirmed. A decisive advance requires measurements that are geographically distributed and methodologically independent.

23. Testable Predictions

A homogeneous medieval-origin model predicts that samples from distant regions, after rigorous cellulose isolation, should converge on a medieval age and show no systematic whole-cloth isotope gradient.

An ancient-origin model with a locally altered radiocarbon corner predicts substantial regional isotope differences and chemical or structural evidence explaining the younger corner carbon. An imported first-century luxury-textile model predicts no necessary local Judaean manufacturing signature; instead, comparative fiber, twist, trace-fiber, and construction data should fit at least one documented eastern Mediterranean or Indo-Roman production tradition.

A medieval-loom model predicts that the characteristic weave and defect architecture will be reproduced reliably on four-shaft treadle systems and not on plausible ancient alternatives. An ancient-technology model predicts successful single-layer reproduction on at least one loom configuration that can be securely documented for antiquity or for a first-century-connected production region.

A neutron-irradiation model predicts more than an anomalous carbon date. Depending on the proposed source geometry, it predicts spatially varying irradiation signatures across the cloth. Non-destructive ultraviolet, ATR-FTIR, and Raman measurements should therefore be mapped at high spatial density and compared with a pre-registered neutron-transport model rather than fitted after measurement [21-23]. If the dose required to shift the carbon date is above the experimentally calibrated detection threshold, absence of the predicted spectroscopic pattern would count against the model. If a reproducible pattern is found, follow-up isotope measurements could test for carbon-14 gradients and, where analytically and ethically feasible, activation products proposed in the early neutron literature [19].

WAXS replication should test multiple documented Shroud fibers and dated controls under blinded conditions, including irradiated and heat-treated linen controls. Agreement across independent laboratories would determine whether cellulose degradation deserves significant chronological weight.

24. Recommended Research Program

A decisive program should proceed in stages, beginning with methods that do not remove material.

Phase 1 - Whole-cloth non-destructive mapping. Following the strategy developed by Barta, Fernández-Álvarez, and Ruiz-Navas [21] and extended in subsequent FTIR work [23], investigators should map ultraviolet luminescence, ATR-FTIR spectral ratios, Raman spectra and fluorescence background across a predefined grid. The radiocarbon corner, opposite end, central frontal and dorsal regions, side strip, scorched areas, water-stain margins, image regions, and non-image background should be included. Instrument settings, environmental conditions, spot size, calibration standards, and raw spectra should be published. The analysis plan should be registered before unblinding spatial labels.

The spectroscopic calibration library should contain untreated modern linen; thermally aged linen; linen exposed to humidity/water cycling; gamma-only controls; neutron-irradiated linen across multiple spectra and dose rates; and, if ethically obtainable, securely dated archaeological linen. This is necessary because radiation-sensitive spectral changes are not automatically radiation-specific. The proposed irradiation index should be validated for repeatability, inter-instrument transfer, and discrimination from heat and natural aging before it is interpreted on the Shroud.

Phase 2 - Textile and provenance mapping. The full weave should be digitally mapped at thread level, including herringbone reversals, defects, knots, replacements, density changes, selvages, and seam structures. Experimental weavers should test warp-weighted, vertical two-beam, manually controlled horizontal, pit/treadle, and four-shaft treadle looms using identical yarn specifications. The comparative archaeological set should deliberately include Roman Egypt, the Levant, Late Antique/Byzantine textiles, medieval Europe, and South Asian/Indo-Roman material relevant to Barta-Gil's provenance model [17,18].

Phase 3 - Minimal geographically distributed sampling, only if authorized. If ecclesiastical custodians and conservators permit destructive testing, micro-samples should be taken from the original corner, the opposite end, a central region, the side strip, and areas with distinct conservation histories. Sampling should be independently supervised and fully documented. Coded specimens should be sent blind to multiple AMS laboratories. Adjacent fibers should undergo conventional cleaning, solvent extraction, and alpha-cellulose isolation; pretreatment yields and removed fractions should be retained and analyzed.

Before destruction, every sampled point should receive the non-destructive measurements used in Phase 1. This creates a direct bridge between spectroscopic maps and isotope results. If a neutron-gradient signature were observed, the radiocarbon sampling design should be capable of distinguishing the predicted spatial pattern from a simple edge repair or contamination gradient.

All raw measurements, images, spectra, laboratory protocols, calibration files, neutron-transport assumptions, and statistical code should be released. The central scientific objective is not to favor an ancient or medieval conclusion but to create a dataset in which competing models make different, pre-specified predictions.

25. Conclusion

The 2026 Arizona-fragment study confirms that retained radiocarbon fragments are genuine Shroud linen and finds no visible repair or significant surface contamination in the small region examined [1]. These results substantially weaken a simple foreign-patch explanation.

The 1988 radiocarbon result remains the strongest direct evidence for medieval chronology. Any first-century hypothesis must explain concordant medieval measurements from genuine cloth. Quantitative mass balance shows that ordinary additive contamination by modern carbon would need to constitute roughly sixty percent of the analyzed carbon to produce the observed shift, making vague contamination scenarios inadequate.

That calculation, however, does not exclude every mechanism capable of altering a radiocarbon age. Neutron irradiation is conceptually different because it proposes in-situ generation of additional carbon-14. The hypothesis is not established, and the required historical source remains unresolved, but it is no longer scientifically useful to dismiss it solely by invoking the mass fraction required for modern contamination. Controlled experiments have shown that irradiated linen develops measurable changes in ultraviolet luminescence, ATR-FTIR, and Raman response, creating a non-destructive route for testing whether the Shroud carries a compatible spatial radiation signature [21,23].

The textile itself contains no feature conclusively demonstrated to be exclusive to fourteenth-century Europe. Z-spinning and complex twills predate the Middle Ages. Olsen's work favors a treadle loom, but the date and geographic distribution of relevant horizontal multi-shaft loom technologies require broader comparison. Barta-Gil's 2025 provenance analysis further shows that India and the Indo-Roman trade sphere deserve explicit consideration rather than restricting the ancient comparison to local Judaean burial cloths [17]. First-century Z-spun Indian cotton recovered at Berenike independently demonstrates that Indian textiles reached the Roman Red Sea world [18]. This does not prove Indian manufacture of the Shroud, but it strengthens the plausibility of long-distance textile procurement.

The scientifically defensible conclusion is therefore narrower than an authentication claim. The Turin Shroud linen remains materially compatible with an ancient eastern Mediterranean context, potentially including an imported luxury textile, but the textile evidence does not prove that origin. The medieval radiocarbon chronology is not a complete whole-cloth demonstration until geographic representativeness is tested, while the ancient hypothesis cannot prevail without a quantitatively adequate explanation of the sampled corner. The next research priority should be a transparent, whole-cloth, non-destructive spectroscopic mapping campaign - explicitly including the neutron-irradiation tests proposed by Barta and colleagues - followed, if warranted and authorized, by minimal geographically distributed radiocarbon testing.

> ***"The scientifically defensible conclusion is narrower than an authentication claim."***

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