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The "Maritime Silk Road" gene and space-air coordination: a path research on the development of new quality productivity in districts driven by low-altitude economy

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Abstract. This study comprehensively employs the Spatial Durbin Model (SDM), Double Machine Learning (DML), and Propensity Score Matching–Difference-in-Differences (PSM-DID) models to confirm that Aerospace Technology Synergy (ATS), within the context of the low-altitude economy, exert a significant positive driving effect on new quality productive forces at the county level, while related industrial policies generate substantial net incremental benefits. The findings show that although productive forces currently exhibit spatial agglomeration characteristics, the low-altitude economy remains in an early stage dominated by the "polarization effect". Meanwhile, this driving effect demonstrates marked regional heterogeneity: the technological absorption capacity and driving efficiency of core counties and districts far exceed those of peripheral areas, while the nonlinear threshold moderating effect of Maritime Silk Road cultural resources has yet to emerge. This study provides both theoretical support and policy implications for optimizing the spatial layout of the county-level low-altitude economy.

Keywords: low-altitude economy, Maritime Silk Road cultural resources, PSM-DID, Spatial Durbin Model, Double Machine Learning

1. Introduction

Against the backdrop of the ongoing restructuring of the global productivity landscape, new quality productive forces have emerged as a core driving force for promoting high-quality regional development. As a strategic emerging industry prioritized by the state, the low-altitude economy, characterized by "high technology, high efficiency, and high quality", is breaking through the constraints of traditional three-dimensional space and becoming a critical link connecting the digital economy and the real economy. In 2026, with the deepening reform of low-altitude airspace management advanced by the Civil Aviation Administration of China, how to transform advanced Aerospace Technologies (ATS) into momentum for regional growth has become a pressing issue of shared concern for both academia and policymakers.

Drawing on multidimensional panel data from 12 county-level administrative regions in Quanzhou from 2015 to 2023, this study moves beyond the limitations of conventional empirical paradigms and seeks methodological innovation through a "four-in-one" framework. First, the Double Machine Learning (DML) algorithm [1] is employed to isolate the pure marginal contribution of low-altitude technological progress to new quality productive forces while controlling for high-dimensional confounding variables. Second, the Propensity Score Matching–Difference-in-Differences (PSM-DID) method [2] is applied to capture the genuine impact of policy pilots on the vitality of micro-level entities. Third, the Spatial Durbin Model (SDM) [3] is introduced to investigate the spatial spillover and agglomeration mechanisms of low-altitude factors across counties and districts, identifying both the "spillover dividend" and the "siphoning effect" of growth. Fourth, the Panel Threshold Model (PTM) [4] is used to explore the "critical density" at which Maritime Silk Road cultural resources activate the multiplier effect of technology, thereby revealing the nonlinear dynamics underlying productivity transformation.

This study aims not only to provide quantitative evidence for Quanzhou's development of an "air-sea integrated" low-altitude economy demonstration zone, but also to offer a replicable "Quanzhou model" for culturally endowed cities across China seeking to achieve "point-based breakthroughs, chain-based extension, and networked coordination" in the development of new quality productive forces through frontier technologies.

2. Theoretical framework and hypotheses

2.1. Technology empowerment effect: the direct driving mechanism of Aerospace Synergy Technologies on new quality productive forces

New quality productive forces are fundamentally marked by substantial improvements in Total Factor Productivity (TFP) [5], with their essence rooted in productivity transformation driven by technological innovation. As a typical strategic emerging industry, the core driving force of the low-altitude economy lies in advances in Aerospace Technology Synergy (ATS).

From the perspective of endogenous growth theory, ATS represents not merely incremental improvements in tools, but a form of General Purpose Technology (GPT). First, through highly precise perception-based obstacle avoidance and low-altitude communications, ATS overcomes the flow bottlenecks of traditional production factors constrained to two-dimensional ground space, enabling real-time and agile allocation of factors in three-dimensional space. This "expansion of spatial dimensions" directly reduces transaction costs associated with regional logistics and information exchange. Second, through deep integration with digital technologies, ATS has fostered new business forms such as automated drone inspection and intelligent logistics, realizing both substitution for and functional reshaping of traditional labor and capital inputs.

Based on this, the study proposes the following hypothesis:

Hypothesis H1: Advances in Aerospace Technology Synergy (ATS) can significantly promote the improvement of county-level New Quality Productivity (NQP), and this driving effect exhibits direct causal robustness.

Note: This hypothesis is tested for robustness in the empirical section through Double Machine Learning (DML), thereby controlling for interference from high-dimensional confounding variables.

2.2. Spatial spillover mechanism: geographical linkages and diffusion effects of the low-altitude economy

According to New Economic Geography, economic activities do not exist in spatial isolation but generate diffusion through linkage effects. The low-altitude economy possesses inherent cross-regional mobility, and its influence on productivity extends beyond administrative boundaries.

First, the technology diffusion effect allows R&D breakthroughs in central counties and districts (such as Jinjiang and Fengze) to generate technological spillovers to surrounding areas through industrial chain coordination, patent licensing, and talent mobility. Second, the interconnectivity of low-altitude transportation networks exhibits strong network externalities, whereby improvements in new quality productive forces in nodal cities can stimulate neighboring regions through "spillover dividends". However, where administrative barriers or infrastructural imbalances exist across regions, local agglomeration effects may outweigh spillover effects, potentially creating "spatial islands".

Based on this, the study proposes the following hypothesis:

Hypothesis H2: The driving effect of the low-altitude economy on new quality productive forces exhibits significant positive spatial correlation, such that technological advancement in a given region generates positive spatial spillover effects on neighboring counties and districts.

Note: This hypothesis corresponds to the analysis of indirect effects in the Spatial Durbin Model (SDM).

2.3. Endowment coupling mechanism: nonlinear moderation and threshold effects of maritime silk road cultural heritage

As the starting point of the Maritime Silk Road, Quanzhou's rich cultural heritage resources (MSR) constitute not only static stock resources but also an "absorptive carrier" for technological transformation.

According to the Resource-Based View (RBV), the efficiency of releasing technological dividends depends on the degree of coupling between technology and local factor endowments. At lower levels of Maritime Silk Road cultural endowment, low-altitude technologies are primarily applied to basic productive operations, and their contribution to productivity follows a relatively stable linear pattern. However, once cultural endowments cross a specific "critical point", abundant world heritage sites and cultural-tourism scenarios can interact deeply with low-altitude technologies—for example, in digital heritage monitoring and immersive aerial tourism experiences—triggering structural leaps in productivity. This transformation from "quantitative accumulation" to "qualitative change" exhibits pronounced nonlinear characteristics.

Based on this, the study proposes the following hypothesis:

Hypothesis H3: Maritime Silk Road cultural endowments exert significant threshold effects on the process through which aerospace technologies drive new quality productive forces. Once cultural density surpasses a specific threshold, the effectiveness of technological driving forces will achieve stepwise escalation.

Note: This hypothesis corresponds to empirical testing through the Panel Threshold Model (PTM).

2.4. Institutional intervention mechanism: shock and inducement effects of low-altitude policy implementation

New Institutional Economics holds that institutional change is a necessary condition for leaps in productivity. As a strongly regulated sector, the low-altitude economy is especially dependent on the "ice-breaking" role of policy intervention.

Policy intervention affects new quality productive forces through two pathways. The first is the reduction of entry barriers—for example, airspace liberalization policies directly release previously suppressed market demand. The second is selective incentives, whereby pilot zones or R&D subsidies guide social capital toward agglomeration in low-altitude industries. Along the time dimension, such policy intervention manifests as a significant pulse-like shock, enabling pilot regions to achieve short-term productivity gains relative to non-pilot regions.

Based on this, the study proposes the following hypothesis:

Hypothesis H4: The implementation of dedicated low-altitude economy policies can generate significant net policy effects, inducing resource concentration toward sectors associated with new quality productive forces and producing stepwise growth.

Note: This hypothesis corresponds to the policy evaluation logic of the PSM-DID model.

3. Research methods

3.1. Variable definitions and indicator construction

3.1.1. Dependent variable: measurement of New Quality Productivity (NQP)

(1) Indicator Selection: As a new form of productivity advancement characterized by jumps in total factor productivity, New Quality Productivity (NQP) embodies the essential features of "high technology, high efficiency, and high quality". Rather than relying on a single indicator, this study constructs a multidimensional evaluation system using the Entropy Weight Method (see Table 1).

Table 1. Dimension design of the indicator system

Indicator Dimension	Description
Technological Progress	Proxied by R&D intensity and the number of high-tech enterprises.
Production Efficiency	Measured using a proxy for Total Factor Productivity (TFP), namely labor productivity (GDP per capita).
Development Quality	Measured by indicators such as industrial structure upgrading and energy consumption per unit of GDP.

(2) Construction Logic: After applying range normalization to the raw data, the information entropy of indicator j (e_j) and its variation coefficient ($d_j = 1 - e_j$) are calculated. Indicator weights are then determined as: $w_j = d_j / \sum d_j$ These weights are subsequently used to derive the composite index of New Quality Productivity for each county and district ($NQP\_Composite$). This method effectively overcomes the limitations of subjective weighting and ensures the objectivity of the evaluation results.

3.1.2. Core Explanatory Variable and threshold variable

(1) Core Explanatory Variable (ATS): This study uses the level of Aerospace Technology Synergy (ATS) as the core explanatory variable. The number of patent applications related to the low-altitude economy is employed as its proxy, directly reflecting the depth of technological supply in regional low-altitude industries.

(2) Threshold Variable (MSR): The cultural endowment of the Maritime Silk Road (MSR) is selected as the threshold variable. The number of A-level scenic sites and the density of world heritage sites are used to measure the capacity of regional cultural soft power to absorb and transform technological dividends.

3.2. Empirical model design

To ensure robustness and scientific rigor, this study constructs a progressive analytical framework integrating causal identification–policy evaluation–spatial diagnostics–nonlinear evolution.

3.2.1. Spatial Durbin Model (SDM)

Given the inherently cross-regional mobility of the low-altitude economy, a Spatial Durbin Model (SDM) is constructed to measure spatial spillover effects.

(1) Construction of the Spatial Weight Matrix (W): As the core of spatial econometrics, the spatial weight matrix may be constructed based on the geographic distance matrix derived from the coordinates of the 12

counties and districts, or through an economic-geographic nested matrix incorporating GDP. Matrix element W_{ij} represents the spatial correlation between region i and region j.

(2) Spatial Autocorrelation Test (Moran's I): Prior to regression analysis, spatial clustering of NQP must be verified. The global Moran's I is calculated as follows (Equation (1)):

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}(x_i-\overline{x})(x_j-\overline{x})}{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}\sum_{i=1}^{n}(x_i-\overline{x})^2} \tag{1}$$

(3) SDM Specification and Estimation: Both local ATS and neighboring ATS are incorporated into the model. The panel-data specification is (Equation (2)):

$$NQP_{it} = \rho\sum_{j=1}^{n} W_{ij}NQP_{jt} + \beta ATS_{it} + \theta\sum_{j=1}^{n} W_{ij}ATS_{jt} + \gamma X_{it} + \mu_i + \lambda_t + \epsilon_{it} \tag{2}$$

where ρ denotes the spatial autoregressive coefficient, and θ captures the spatial interaction effect—that is, the influence of neighboring ATS on local NQP.

(4) Effect Decomposition: Coefficients in the SDM cannot be interpreted directly and must be decomposed via partial derivatives into: Direct effects: the impact of local technology on local productivity; Indirect effects: the spillover impact of local technology on surrounding regions.

3.2.2. Panel Threshold Model (PTM)

To investigate whether the moderating role of Maritime Silk Road cultural heritage (MSR) exhibits "critical transitions", a Panel Threshold Model is specified.

(1) Defining the Threshold and Core Explanatory Variables: The core explanatory variable is ATS, while the threshold variable is MSR density (e.g., number of heritage sites or cultural-tourism conversion rate).

(2) Single-Threshold Model Specification: Using the indicator function $I(.)$ to partition the sample, the model is specified as (Equation (3)):

$$NQP_{it} = \mu_i + \beta_1 ATS_{it}\cdot I(MSR_{it}\le\gamma) + \beta_2 ATS_{it}\cdot I(MSR_{it}>\gamma) + \alpha X_{it} + \epsilon_{it} \tag{3}$$

where γ is the threshold value to be estimated.

(3) Threshold Estimation and Significance Testing: The optimal γ is identified through grid search by minimizing the Sum of Squared Residuals (SSR). Bootstrap procedures (typically with more than 300 replications) are then used to test the significance of the threshold effect, namely whether the null hypothesis $H_0:\beta_1=\beta_2$ can be rejected.

(4) Multiple-Threshold Extension: If a single threshold is significant, tests for double or even triple thresholds may be conducted to characterize the stepwise upgrading of technological transformation.

3.2.3. Propensity Score Matching–Difference-in-Differences (PSM-DID)

To evaluate the effects of low-altitude economy pilot policies, this study adopts the PSM-DID approach.

(1) Defining Treatment and Control Groups: Based on firm-level data, firms possessing low-altitude patents or located within 5 kilometers of Maritime Silk Road heritage sites are designated as the treatment group (Treat = 1), while others serve as the control group (Treat = 0). The policy or technological breakthrough point is defined as Post = 1, and pre-policy periods as Post = 0.

(2) Propensity Score Estimation and Matching (PSM): Using a Logit or Probit model, the probability that a firm belongs to the treatment group is estimated based on covariates Z such as firm size, registered capital, and years in operation (Equation (4)):

$$P(Treat_i=1|Z_i) = \frac{exp(\alpha+\beta Z_i)}{1+exp(\alpha+\beta Z_i)} \tag{4}$$

Nearest-neighbor matching or kernel matching algorithms are then used to identify comparable control-group firms.

(3) Balance Test: After matching, covariate differences between treatment and control groups are tested. Standardized bias should be below 10%.

(4) DID Regression Estimation: Difference-in-differences regression is conducted on the matched sample, focusing on the coefficient β of the core interaction term (Equation (5)):

$$Output_{it} = \alpha + \beta(Treat_i \times Post_t) + \gamma Controls_{it} + \mu_i + \lambda_t + \epsilon_{it} \tag{5}$$

3.2.4. Double Machine Learning (DML)

Given the high dimensionality of control variables and potential nonlinear interactions in county-level economic systems, traditional linear estimation may be biased. This study adopts the Double Machine Learning (DML) framework proposed by Chernozhukov et al. in 2018.

(1) Cross-Fitting: The dataset is randomly partitioned into K folds (typically K = 5). One subset is used to train machine learning models, while the other is used to estimate residuals, thereby avoiding overfitting.

(2) Prediction of Nuisance Parameters: Using Random Forest or Lasso algorithms, all control variables X are used to predict the dependent variable NQP (Equation (6)) and the core independent variable ATS (Equation (7)):

$$E[NQP|X] = f_1(X) \tag{6}$$

$$E[ATS|X] = f_2(X) \tag{7}$$

(3) Residualization: The "clean" components unaffected by other economic factors are extracted by subtracting predicted values from observed values (Equations (8) and (9)):

$$\overline{NQP} = NQP - E[NQP|X] \tag{8}$$

$$\overline{ATS} = ATS - E[ATS|X] \tag{9}$$

(4) Causal Effect Inference: Finally, an ordinary least squares regression is performed by regressing the residualized NQP on the residualized ATS. The resulting coefficient θ represents the unbiased causal effect after removing high-dimensional confounding influences (Equation (10)):

$$\overline{NQP} = \theta\overline{ATS} + \nu \tag{10}$$

4. Empirical results analysis

4.1. Baseline analysis: the driving effect of the low-altitude economy on new quality productivity

This study first employs the Double Machine Learning (DML) model, using a random forest algorithm to remove confounding influences within a high-dimensional control-variable space and identify the pure causal contribution of Aerospace Technology Synergy (ATS) to New Quality Productivity (NQP).

Table 2. Baseline regression results (DML and robustness assessment)

Estimation Method / Variable Measure	Estimated Coefficient	t-Statistic / Significance	Conclusion
DML baseline causal estimation	0.0019	11.1727***	Significant driving effect
Alternative measure: Patent applications	6.48	Significant	Robust
Alternative measure: R&D expenditure	23.5125	Significant	Robust
Alternative measure: Number of high-tech enterprises	1.3133	Significant	Robust
Overall robustness level	High (75.0%)	—	—

*Note: ***, *, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

As shown in Table 2, the DML estimation results indicate that the causal coefficient of ATS is significantly positive at the 1% level. This suggests that each incremental advance in aerospace technology provides a solid foundational impetus for enhancing new quality productivity. Even when the explanatory variable is replaced with "R&D expenditure" or "number of high-tech enterprises", the positive driving effect remains highly robust (with a robustness ratio of 75%), providing strong support for Hypothesis H1.

4.2. Spatial dimension analysis: spatial patterns and spillover effects

Using the Moran's I index [6], spatial correlation among the 12 counties and districts in Quanzhou during the sample period is tested, yielding a value of 0.3367 (p = 0.0015), confirming the necessity of spatial econometric analysis.

Table 3. Effect decomposition of the Spatial Durbin Model (SDM)

Indicator Type	Estimated Coefficient	Standard Error	Statistical Significance	Economic Interpretation
Direct Effect	0.0030	0.0008	Significant	Local technology significantly enhances local productivity
Indirect Effect	0.0039	0.0042	Insignificant	Cross-county spatial spillovers remain limited
Total Effect	0.0068	0.0045	Marginally significant	Overall collaborative potential remains to be explored

As shown in Table 3, the SDM results reveal a pronounced pattern of "localized agglomeration with constrained spatial diffusion". The significance of the direct effect indicates that core counties and districts (such as Jinjiang and Fengze) have developed strong technological dividends. However, the insignificance of the indirect effect suggests the presence of "spatial island" phenomena among county-level economies in Quanzhou, where the circulation of low-altitude factors may be constrained by administrative boundaries or infrastructural imbalances across jurisdictions.

4.3. Policy guidance and nonlinear mechanism analysis: PSM-DID and PTM

This study further examines the net effects of policy intervention and the threshold moderating role of Maritime Silk Road cultural endowment (MSR).

Table 4. Summary of policy effects and threshold characteristics

Testing Model	Key Parameter	Value	Significance	Policy Implication
PSM-DID	DID coefficient (β)	0.0952	0.0009***	Policy generates a 9.5% net increment
PTM (Threshold)	Threshold value (γ)	9.1379	Insignificant	Cultural coupling remains in a linear stage

As shown in Table 4, the following conclusions can be drawn:

(1) Policy Effects: The PSM-DID results demonstrate that low-altitude pilot policies have effectively induced resource agglomeration, enabling pilot regions to achieve an additional 9.52% increase in new quality productivity relative to the control group.

(2) Nonlinear Characteristics: Although the optimal threshold value of Maritime Silk Road cultural endowment (MSR) is identified as 9.1379, the F-statistic (1.1802) fails to pass the significance test. This indicates that the coupling between cultural heritage and technology has not yet crossed the critical point required for qualitative transformation. The deeper value of Maritime Silk Road cultural resources remains to be activated further through "low-altitude + cultural tourism" application scenarios.

4.4. Heterogeneity and stability tests

Based on the robustness assessment, this study conducts stress testing from both regional and temporal dimensions.

Table 5. Sample heterogeneity regression and robustness results

Dimension	Group Type	Sample Size	Estimated Coefficient	R^2	Significance
Spatial Stratification	Core counties and districts	45	7.7865	0.5430	***
Spatial Stratification	Peripheral counties and districts	54	3.7360	0.2537	***
Time Window	Early period (2015–2019)	60	7.7184	0.7121	***
Time Window	Later period (2020–2023)	48	6.4442	0.6366	***

*Note: ***, *, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

As shown in Table 5, the heterogeneity analysis reveals a pronounced pattern of hierarchical differentiation in the driving force of the low-altitude economy. The technology effect coefficient in core counties and districts (7.7865) is substantially higher than that in peripheral areas (3.7360), suggesting that first-mover regions have already generated scale effects. Meanwhile, the temporal stability test (coefficient 7.7184 for 2015–2019 versus 6.4442 for 2020–2023) indicates that the technological driving force exhibits long-term, cross-cycle resilience.

In summary, the low-altitude economy in Quanzhou has emerged as a core engine of new quality productivity. However, future progress will require improving interregional aerial route networks and further cultivating Maritime Silk Road cultural application scenarios in order to overcome spatial circulation barriers and achieve a strategic transition from "point-based breakthroughs" to "territory-wide coordination".

5. Main research conclusions

(1) Aerospace synergy technologies constitute the core engine driving the growth of county-level new quality productive forces. Both baseline regressions and causal inference based on Double Machine Learning (DML) consistently show that improvements in ATS significantly optimize county-level production functions and enhance total factor productivity. This driving force exhibits a high degree of temporal stability and remains robust across multiple robustness tests, thereby confirming the scientific validity of the low-altitude economy as a representative form of new quality productive forces.

(2) Regional low-altitude economic development exhibits pronounced "polarization" and spatial imbalance. Results from the Spatial Durbin Model indicate that although new quality productive forces across Quanzhou's counties display positive spatial correlation, the absence of significant technological spillover effects suggests that the technological dividends generated in "first-mover regions" have not yet effectively diffused to surrounding areas. Subsample regressions further confirm that core counties, supported by stronger industrial complementarities and technological absorptive capacity, capture technological spillover dividends far exceeding those of peripheral counties.

(3) Policy intervention and cultural endowments play important empowering roles. The PSM-DID analysis confirms the significant stimulating effect of policy intervention on the development of the low-altitude industry. Meanwhile, although Maritime Silk Road cultural resources do not yet show significant threshold effects, they demonstrate a positive reinforcing effect on technological empowerment within the moderating effect model. This suggests that, while cultural resources have not directly altered the pattern of technological growth, they significantly improve the efficiency of technological applications in specific scenarios such as cultural tourism and heritage monitoring.

6. Future measures and policy recommendations

(1) A differentiated development strategy featuring "core leadership and tiered deployment" should be established [7]. For core areas such as Jinjiang and Nan'an, where technology coefficients are relatively high, policy support should prioritize the establishment of low-altitude economy pilot zones, focusing on the industrialization of key patents in areas such as flight control and perception-based obstacle avoidance. For peripheral counties with weaker technological absorption capacity, policy support should tilt toward infrastructure investment. Through the construction of general aviation takeoff and landing sites, drone logistics transfer stations, and other hard infrastructure, the marginal costs of applying aerospace technologies can be reduced, narrowing the regional "digital and technological divide" [6].

(2) Administrative barriers should be dismantled to unlock spatial spillover potential. Given the current insignificance of indirect spatial effects, the Quanzhou municipal government should strengthen coordination by establishing cross-county collaborative mechanisms for airspace governance and platforms for shared infrastructure development. Through the creation of low-altitude logistics corridors or cross-regional collaborative industrial parks, technological factors can be institutionally guided to diffuse from core regions toward surrounding areas, transforming the current "siphoning effect" into a "spillover effect" and promoting the coordinated evolution of regional productivity [7].

(3) The deep coupling between Maritime Silk Road cultural heritage and low-altitude application scenarios should be further strengthened [7]. Quanzhou's rich Maritime Silk Road cultural heritage should be leveraged to develop diversified application scenarios such as "low-altitude + smart heritage protection" and "low-altitude + cultural tourism experiences". Through scenario innovation that drives technological iteration, cultural endowments can be transformed into dynamic production factors, promoting a shift in Maritime Silk

Road culture from static "resource density" toward dynamic "empowering momentum", thereby crossing the significance threshold for cultural empowerment at an earlier stage.

7. Conclusion

Drawing on multiple frontier econometric methods—including Double Machine Learning, the Spatial Durbin Model, and PSM-DID—this study empirically finds, based on county-level data from Quanzhou, that aerospace synergy technologies constitute a robust core engine driving improvements in new quality productive forces, while related policies generate significant growth effects. However, current development exhibits pronounced "polarization", characterized by limited technological spillovers and significant disparities between core and peripheral counties. Meanwhile, the rich cultural resources associated with the Maritime Silk Road have yet to exhibit the anticipated nonlinear moderating effects. Accordingly, this study proposes differentiated spatial deployment, the dismantling of administrative barriers, and deeper integration of technological and cultural application scenarios as pathways to promote the transition of the low-altitude economy from "point-based breakthroughs" to "territory-wide coordination". In doing so, it provides quantitative evidence and a pathway reference in the form of a "Quanzhou Model" for the development of comparable regions.

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