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Cross-Survey Analysis of Heterogeneous Aeromagnetic Data Reveals a Raw-Field Gradient-Reversal Anomaly at Uruana de Minas, Brazil

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Abstract

Aeromagnetic archives increasingly contain overlapping surveys acquired at different epochs, resolutions, flight geometries, and processing states, complicating the distinction between geological disagreement and different observational expressions of the same crustal structure. We analyze this problem through a targeted case at Uruana de Minas, Brazil, where the 2011 raw measured scalar total field has a median northward gradient of -1.555 nT/km in the observed target and $+0.963$ nT/km on the same 14 flight lines farther north, while IGRF remains positive ($+0.993$ and $+1.023$ nT/km, respectively); all 14 lines change sign before IGRF subtraction or derivative processing. With breakpoint position unconstrained, separate fits to all 14 lines recover the negative-to-positive turnover, whereas no tested external control reaches 14/14. An independent 2008 survey contains a compatible positive-negative-positive architecture; after common-support matching, Uruana ranks first among transition-bearing controls for both front proximity and signed-gradient agreement. Historical 1971-72 data retain a vertical-derivative sign boundary in 450/450 reconstruction variants and an opposed crustal residual, although total-field reversal fails. We use an operator-aware Cross-Survey Magnetic Persistence Framework (CSMPF) to organize the heterogeneous evidence; an analytic known-truth stress test illustrates why an unchanged source can reverse the scalar gradient at one support but not another. The primary empirical result is independent of that framework: the raw 2011 observations directly demonstrate a localized magnetic-gradient anomaly at Uruana de Minas.

Keywords: aeromagnetism; magnetic anomaly; gradient reversal; crustal magnetism; survey resolution; Uruana de Minas

1 Introduction

Aeromagnetic archives increasingly combine observations acquired decades apart under substantially different survey designs. Flight altitude, line spacing, sampling density, acquisition direction, sensor configuration, survey extent, and processing history alter the spatial frequencies and gradients recoverable from a survey. Legacy and modern surveys therefore need not reproduce identical magnetic maps even when they interrogate the same geology (Beamish and White, 2011). Sampling geometry and line spacing also condition the fidelity of short-wavelength anomalies and gradients (Saltus et al., 2026), while edge location can vary with height, source depth, source interference, and processing (Pilkington and Tschirhart, 2017).

Brazil illustrates the scale of this archive-level problem. Aerogeophysical surveying began nationally in the 1950s; the Serviço Geológico do Brasil reports 48 regional surveys conducted from 1971 to 2001, followed from 2004 by a higher-

resolution phase using 500-m flight-line spacing and 100-m flight altitude. By 2014, that phase alone covered approximately 3.7 million km², equivalent to 51% of Brazil and 86% of its crystalline basement (SGB, 2026c). Successive survey generations therefore coexist across a continental public archive with materially different spatial support, making cross-survey comparability a recurring archive-level problem rather than a peculiarity of a single locality.

Existing approaches solve related but different problems. Equivalent-source methods can transform or merge observations acquired at different altitudes or geometries (Gavazzi et al., 2020); multiscale derivatives track the persistence of magnetic edges as spatial scale changes (Lahti and Karinen, 2010); and legacy-versus-HiRES comparisons quantify differences in recoverable information content (Beamish and White, 2011). CSMPF addresses a distinct cross-survey inferential scope: whether a specific signed transition remains recoverable when scalar manifestations differ across surveys, and how to prevent high same-sign agreement from masquerading as persistence. We use the framework here as an analysis architecture rather than claiming independent prospective validation or replacement of established processing and interpretation methods.

Table 1 Position of CSMPF relative to established aeromagnetic approaches. The comparison identifies the inferential question addressed here; it does not imply that CSMPF replaces the established methods.

Approach	Primary purpose	Cross-survey treatment	Distinct inferential scope addressed here
Legacy vs high-resolution comparison (Beamish and White, 2011)	Quantify differences in information content and resolution	Compares survey generations	Whether a localized signed transition persists when scalar manifestations disagree
Equivalent-source integration (Gavazzi et al., 2020)	Transform, grid, and combine heterogeneous magnetic observations	Harmonizes observations into compatible representations	Whether independent surveys should be judged as recovering the same transition before merging
Multiscale magnetic edges (Lahti and Karinen, 2010)	Track edge persistence across continuation scale	Tests scale behavior of derived edges	How to condition cross-survey similarity on existence of the target topology
Edge-detector analysis (Pilkington and Tschirhart, 2017)	Locate geological contacts and assess detector limitations	Primarily interpretation within a survey/product	How to adjudicate operator-specific positive and negative results across survey generations
CSMPF (this study)	Organize evidence for persistence of a declared signed transition across heterogeneous surveys	Preserves survey realizations; matches support only for comparison	Transition existence, front proximity, and sign agreement considered in that order, with explicit negative results retained

For a meridional scalar-field gradient, we write conceptually

$$G_{obs} = G_{main} + G_{crust}.$$

If $G_{main} > 0$ and $G_{crust} < 0$, the crustal contribution can oppose the regional trend without reversing the measured total-field gradient. Scalar reversal requires the opposed contribution to be sufficiently expressed at the survey's effective support. Resolution, altitude, sampling, spatial support, and observation operator can therefore determine whether the same crustal transition appears as a derivative boundary, a negative-gradient domain, or a complete reversal of the scalar gradient.

To organize this situation, we use the Cross-Survey Magnetic Persistence Framework (CSMPF) as an ordered analysis architecture. It preserves surveys as separate realizations and evaluates raw-field existence, acquisition robustness checks, unconstrained transition topology, matched spatial support, main-field-crustal competition, directional information, and geological holdouts. As an internal logic stress test, we also examine an analytic known-truth example in which the crustal source is fixed exactly while only survey support changes. The benchmark is not fitted to the Uruana geometry or amplitudes and is not treated as independent empirical validation.

The analysis is applied to Uruana de Minas, northwestern Minas Gerais, Brazil. Uruana was examined as a targeted case during exploratory inspection of publicly available aeromagnetic coverage of the authors' home region; it was not selected through a blind regional screening procedure. The primary observation is therefore treated as a targeted discovery, while analyses developed subsequently are identified explicitly as robustness, descriptive, corroborative, or exploratory tests. Regionally, Uruana lies in the Rio Urucuia drainage region and within the broader western Sao Francisco cratonic-margin/foreland domain adjacent to the Brasilia Belt (Alkmim and Martins-Neto, 2012; Pimentel et al., 2011). The lithological contacts and structural geometries used in the geological holdout were taken from the 1:750,000 geological map of the Sao Francisco basin and its vector GIS layers published by the Servico Geologico do Brasil (Dias et al., 2024). The geological map was not used to select the magnetic target.

The empirical motivation is direct. In original 2011 flight-line data, all 14 usable lines have negative northward raw total-field gradients in the observed portion of a fixed 8-km Uruana target while the IGRF/main-field expectation is positive. In the paired same-line implementation, the median target gradient is -1.555 nT/km versus +0.993 nT/km for IGRF; the same 14 profiles become positive farther north (+0.963 nT/km) while IGRF remains positive (+1.023 nT/km). Thus every usable line contains the raw-field turnover before regional-field subtraction or derivative processing. We ask first whether this reversal can be directly demonstrated and spatially bounded strongly enough to document a localized magnetic-gradient anomaly, and second whether earlier and differently resolved surveys recover structurally compatible expressions without requiring scalar equality.

2 Methods

2.1 CSMPF observation model

For survey j ,

$$Y_j(x) = \mathcal{O}_j \left[K_j * \left(\mathbf{B}_{main}(x, t_j) + \mathbf{B}_{crust}(x) \right) \right] + \epsilon_j.$$

K_j represents spatial support, altitude, sampling, and gridding; $\mathcal{O}_j$ is the observation or processing operator. Persistence of the source does not require $Y_1(x) = Y_2(x)$. CSMPF instead tests whether a signed spatial transition remains recoverable after support and operator differences are considered.

2.2 Analytic known-truth benchmark

A dimensionless benchmark was defined independently of the Uruana amplitudes and geometry. The regional field is linear, $B_{main}(x) = x$, such that $G_{main} = 1$. A fixed crustal contribution is

$$B_{crust}(x) = -A \exp(-x^2/2),$$

with $A = 3.3$. Its derivative has a known negative-to-positive transition at $x = 0$. A Gaussian survey-support kernel of standard deviation s gives

$$G_{crust,s}(x) = \frac{Ax}{(1+s^2)^{3/2}} \exp \left[-\frac{x^2}{2(1+s^2)} \right].$$

The maximum competition ratio is

$$R_s = \frac{Ae^{-1/2}}{1+s^2}.$$

For fine support $s=1/6$, $R \approx 1.95 > 1$ and the total gradient becomes negative over a finite interval. For coarse support $s=2$, $R \approx 0.40 < 1$ and the total gradient remains positive everywhere, although the same signed crustal transition persists. Exact Gaussian-kernel composition makes the matched-support front distance $D=0$ and sign agreement $C=1$. A deliberately local 27-combination sensitivity family varying A , fine support, and coarse support preserves the fine-reversal/coarse-nonreversal regime in 27/27 combinations (Online Resource 1; Online Resource 2). The benchmark is an analytic demonstration of the observability problem, not an empirical validation and not a fit to Uruana.

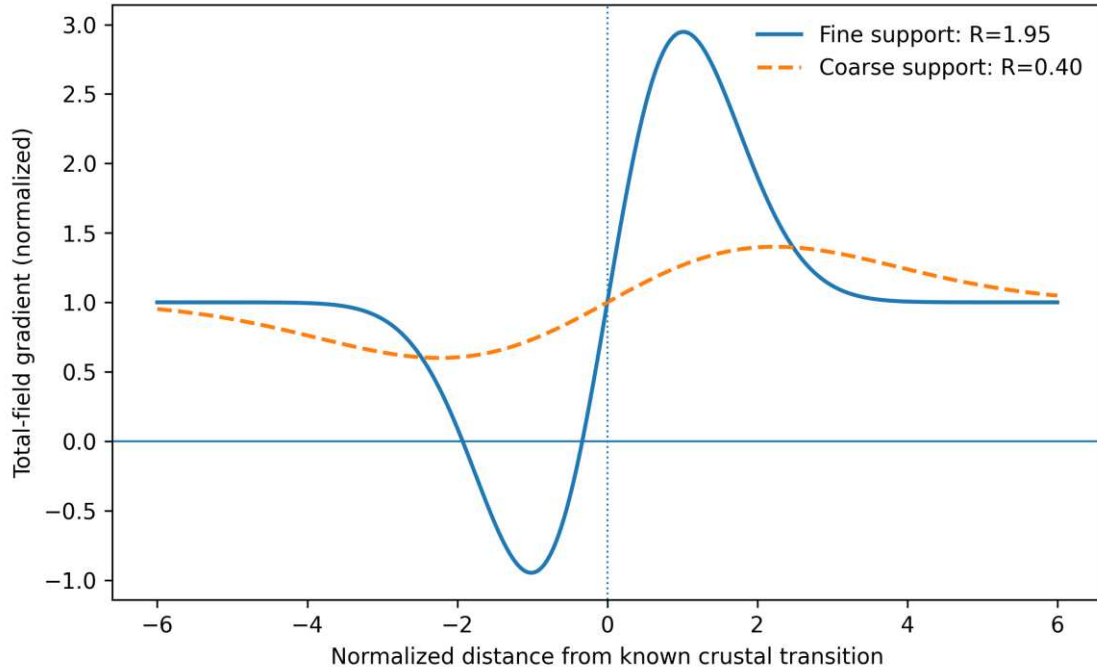


Fig. 1 Synthetic known-truth benchmark. An identical fixed crustal source is observed at fine and coarse spatial support. The fine realization enters $R > 1$ and exhibits total-gradient reversal, while the coarse realization remains $R < 1$. The known signed crustal transition remains at $x = 0$.

2.3 Raw-field existence and same-line controls

For 2011 Project 3087, raw total-field observations from Mag-3087.XYZ were aggregated into 250-m northing bins to limit high-frequency along-track pseudoreplication. A line was retained when at least five bins (at least 1 km of observed support) occurred inside the actually observed northern cap of the fixed 8-km target. Fourteen N-S lines meet this rule. The primary statistic is the line-wise northward slope of raw total field, compared with the IGRF-14 main-field expectation (Beggan et al., 2026). Each retained line is also compared with itself farther north, eliminating between-line zero offsets. As post-discovery robustness checks, the frozen target/control geometry was also evaluated in the supplied Project 3087 magnetic-stage channels MAGCOM, MAGCOR, MAGNIV, and MAGMIC and in the accompanying GPSALT, BARO, ALTURA, and MDT channels. A four-phase 250-m bin-origin sensitivity and a pairwise-median slope sensitivity were used only to expose operator dependence; neither redefines the primary MAGBRU statistic (Online Resource 2).

2.4 Acquisition robustness checks and unconstrained transition fronts

The retained lines are divided by acquisition heading and date. Control-band start and width were varied after discovery as post-discovery robustness checks. For unconstrained transition recovery, each line is fit with two linear segments separated by a free breakpoint; the best breakpoint is selected before the signs of the segment gradients are inspected. The target topology is a negative pre-breakpoint slope followed by a positive post-breakpoint slope.

2.5 Transition-existence criterion and common-support cross-survey comparison

For survey j at common support L , signed local gradient is $S_{j,L}(x) = \text{sgn}[G_{j,L}(x)]$. Sign agreement is

$$C(L) = \frac{1}{N_L} \sum_i \mathbf{1}[S_{1,L}(x_i) = S_{2,L}(x_i)].$$

Independent transition-front separation is $D(L) = |b_{1,L} - b_{2,L}|$. Similarity is evaluated only after the target signed transition exists, because uniform same-sign domains can yield $C = 1$ without containing the anomaly.

2.6 Historical reconstruction and resolution stress

Historical Project 1009 PGW values are IGRF-reduced residuals acquired in 1971-72. Because the local historical lines are approximately E-W, the 2011 within-line N-S derivative cannot be reproduced exactly; meridional trends are estimated between line summaries within fixed longitude corridors. Historical first-vertical-derivative structure was reconstructed over a 450-member family spanning interpolation, grid spacing, detrending, upward continuation, and local-window support. Separately, the 2011 signal was low-pass filtered and quantized to test whether historical resolution alone could erase the scalar reversal.

2.7 Modern model-scale sensitivity

WMM, WMMHR, and IGRF outputs were evaluated at epoch 2026.61644. WMMHR2025 (NOAA National Centers for Environmental Information and British Geological Survey, 2024) and EMM2017 (NOAA National Centers for Environmental Information, 2019) were used in the model-scale sensitivity analysis. A controlled scale-addition experiment adds static EMM2017 degrees 134-790 to the contemporary WMMHR baseline. This hybrid is not an official NOAA 2026 model; it is used only to test how smaller-scale crustal content changes gradient sign and directional information.

2.8 Geological holdout and negative controls

Magnetic target definition preceded geological-map inspection. Geological contacts and the Sao Domingos structure were subsequently examined as holdouts. Bouguer gravity and a full 2-D gradient-angle test were retained as explicit negative controls, and an earlier ~43-degree directional hypothesis was not retained as evidence after regional specificity testing.

2.9 Data provenance, verification, and computational assistance

The empirical analyses use public third-party upstream archives rather than privately acquired field measurements. The 2011 measurements derive from SGB Project 3087 (Area 19 - Formoso - Buritis - Lagoa Grande), the historical data from SGB Project 1009 (Projeto Aerogeofísico Convenio Brasil-Alemanha), and the 2008 data from ANP Project 0032 Sao Francisco (ANP, 2008; SGB, 2026a, 2026b). Exact project and file identifiers are listed in Online Resource 2. Machine-readable derived tables preserve the 14 individual 2011 target-line gradients, the 14 same-line target/north-control pairs with heading and date, mirrored controls, the full 450-member historical reconstruction family, matched-resolution outputs, modern-model vectors, and geological-control summaries. A deterministic verification script recomputes the principal reported summaries from these tables.

ChatGPT (OpenAI; accessed August 2026) was used as an interactive computational and editorial assistant for analysis-code drafting and debugging, organization of analysis plans and reproducibility audits, and language editing. The authors defined the scientific questions and inferential decisions, reviewed the code and outputs, and checked the numerical results through deterministic reruns, machine-readable derived tables, and source/audit checks. No AI-generated images are included. The authors take full responsibility for the submitted work.

3 Results

3.1 Direct raw-field reversal in 2011

Within the observed target cap, all 14 retained flight lines have negative raw northward slopes while their corresponding IGRF gradients are positive. In the paired same-line implementation used throughout the main text, the median target raw slope is -1.554762 nT/km and the median IGRF slope is +0.992857 nT/km. Thus raw-gradient reversal relative to the broad main-field expectation occurs on 14/14 lines before IGRF subtraction or derivative processing. An earlier target-only aggregation gives -1.649644 nT/km versus +0.998354 nT/km and the same 14/14 sign result; the small difference in medians reflects support implementation rather than claim status and is documented in Online Resource 1.

Each of the same 14 lines was compared with itself in a northern control. The target median raw slope is -1.554762 nT/km (14/14 negative); the 16-20 km northern control median is +0.962614 nT/km (14/14 positive). The paired north-

minus-target change is positive on 14/14 lines, median +2.577798 nT/km, minimum +0.549080 nT/km. IGRF remains positive in both zones (+0.992857 and +1.022984 nT/km, respectively).

Channel sensitivity supports, but does not replace, the primary raw-field result. In the supplied MAGMIC channel, the same exact target/control implementation gives 14/14 negative target slopes and 14/14 positive northern slopes (median -1.660952 and +1.164173 nT/km); all paired north-minus-target changes are positive (median +2.542801 nT/km; minimum +0.675563 nT/km). A separate reconstruction directly from Mag-3087.XYZ retains 14/14 target-negative and 14/14 north-positive raw-point OLS slopes in MAGBRU, MAGCOM, MAGCOR, MAGNIV, and MAGMIC. Across four shifted 250-m bin phases, MAGCOM, MAGNIV, and MAGMIC retain 14/14 in both zones at every phase; MAGBRU and MAGCOR are 13/14 target-negative at one 125-m shift and 14/14 at the other three, while all northern controls remain 14/14 positive. The accompanying height/topography channels do not reproduce a universal target sign: positive-slope counts are 13/14 for GPSALT and BARO, 4/14 for ALTURA, and 10/14 for MDT at every tested phase (Online Resource 2).

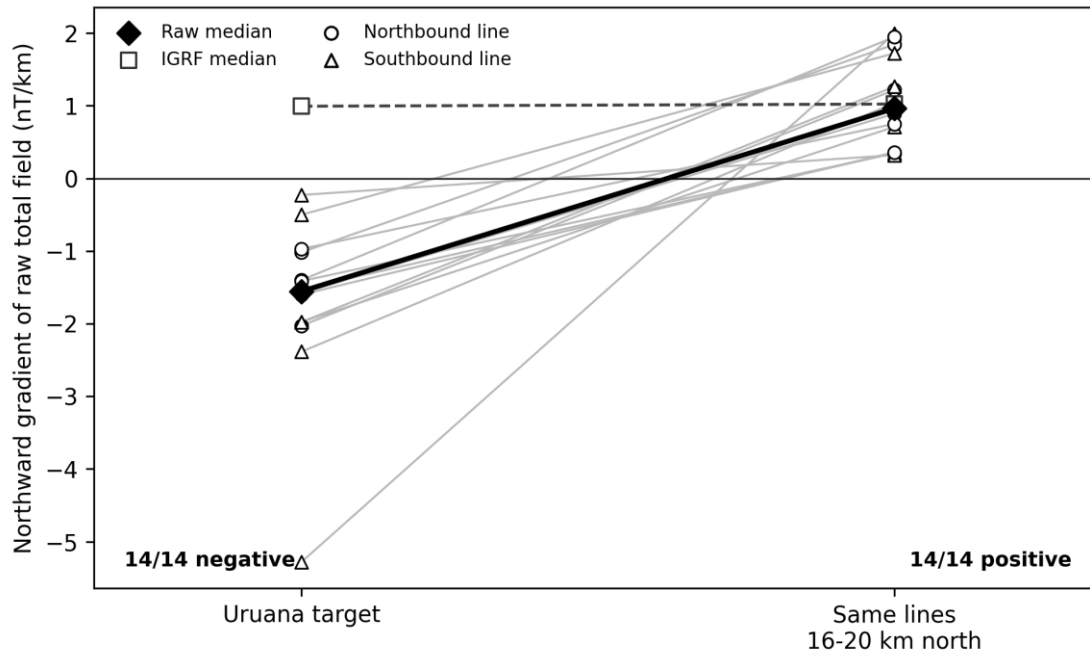


Fig. 2 Model-free 2011 same-line reversal. Thin lines connect the target and northern-control raw slopes for each of 14 individual flight lines; circles and triangles denote northbound and southbound acquisitions. Every raw line changes from negative to positive, while the IGRF medians (open squares) remain positive in both zones. Filled diamonds show the raw medians.

The 14 lines split into seven northbound and seven southbound acquisitions. Northbound medians change from -1.414 to +0.890 nT/km and southbound medians from -1.976 to +1.036 nT/km. The relation is preserved across acquisition dates 27, 28, and 30 May 2011. From a 16-km control start, every tested control width from 4 to 12 km gives positive raw slopes on 14/14 lines.

3.2 Unconstrained breakpoint recovery and spatial controls

When breakpoint position is left free, the 14 lines are fitted separately and all select the negative-to-positive topology. Breakpoints span approximately 16.25-20.50 km north of Uruana, with median 18.50 km and dispersion ~1.23 km. Median pre-transition slope is approximately -0.55 nT/km and post-transition slope approximately +2.98 nT/km. The topology remains 14/14 for aggregation bins of 125, 250, 500, 750, and 1000 m and multiple minimum-support rules. The recovered breakpoint marks the northern termination of the negative-gradient domain; it is not the location at which the Uruana anomaly is defined.

Applying the same algorithm to matched blocks yields 14/14 at Uruana and a maximum of 9/14 among tested external controls. In an earlier mirrored non-overlapping audit, Uruana also ranked 1/12 for raw inversion fraction and 1/12 for most-negative median raw gradient. These ranks are descriptive robustness rather than preregistered probabilities.

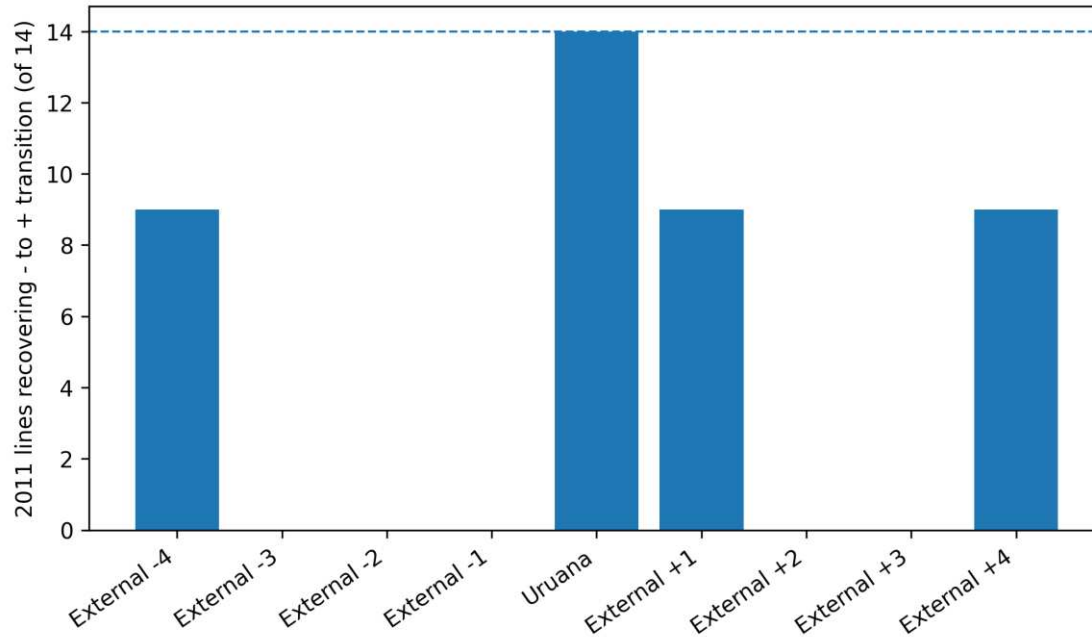


Fig. 3 2011 unconstrained transition-front coherence across matched control blocks. Uruana is the only tested block reaching 14/14; controls are descriptive robustness rather than preregistered inferential tests.

3.3 Independent 2008 turnover and matched-support convergence

The independent 2008 1.5-km grid gives raw northward gradients of +0.842, -1.632, +2.217, and +3.113 nT/km across successive 0-8, 8-16, 16-24, and 24-32 km northern intervals. After diurnal correction the signs persist (+0.810, -1.679, +2.136, +2.771 nT/km), yielding a robust + to - to + architecture.

After bringing 2011 to the same 1.5-km support, the 2008 northern - to + fronts occur at approximately 15.58, 15.50, and 15.34 km for 3-, 5-, and 7-cell windows, while the corresponding 2011 fronts occur at 14.34, 13.99, and 14.08 km. Front separations are therefore ~1.2-1.5 km. Signed-gradient agreement rises from ~84.2% to ~88.2% to ~100% across the primary 3-, 5-, and 7-cell representations; 7-cell sensitivity variants remain ~93.3-100%.

Among five tested blocks carrying comparable transitions at all three supports, Uruana has $D_{med}=1.254$ km and $C_{mean}=0.908$. The strongest external competitor, 16 km east, has $D_{med}=1.354$ km and $C_{mean}=0.881$; remaining controls are weaker. Uruana ranks 1/5 for both metrics.

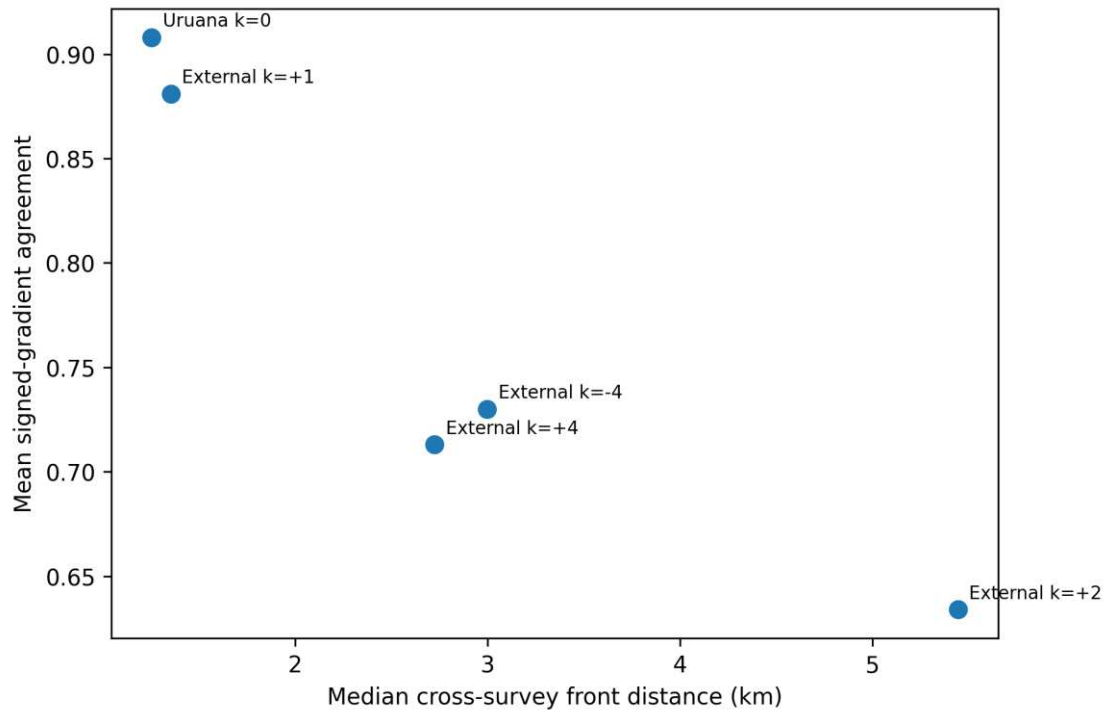


Fig. 4 Cross-survey transition-bearing controls. Uruana has the smallest median 2008-2011 transition-front separation and largest mean signed-gradient agreement among the five tested blocks carrying comparable transitions across all three supports.

A control 16 km west can achieve 100% sign agreement but has 0/14 target transitions in raw 2011 lines. This real false positive demonstrates why transition existence must precede similarity scoring.

3.4 Historical persistence with scalar-reversal failure

Across 1971-72 reconstruction dates and corridor widths, the IGRF meridional gradient is +1.356 to +1.373 nT/km, the PGW crustal residual gradient is -0.356 to -0.233 nT/km, and the reconstructed total remains +1.000 to +1.144 nT/km. Direct historical replication of the 2011 scalar reversal therefore fails.

However, all 450 historical 1DV reconstruction variants retain a zero crossing within 8 km of the fixed city centre. Nearest-zero distance ranges from 0.005 to 6.864 km, median 2.375 km. The wide-support 450/450 family is not point-localizing: shifting the centre 16 km east also gives 450/450. Local historical representation is more selective, and a regional exploratory audit found 0/276 controls simultaneously matching Uruana's zero proximity and sign balance.

A simple resolution-only explanation for the historical scalar FAIL is rejected. Applying a ~2-km low-pass to 2011 leaves 14/14 lines inverted; adding 2.5-nT residual quantization also leaves 14/14. Even an extreme 6-km low-pass plus quantization retains 11/14.

3.5 Main-field competition and modern scale-addition

Descriptive competition ratios are approximately $R=0.17-0.26$ for 1971-72, $R\sim 0.86$ for 2008, and $R\sim 2.63$ for the 2011 observed cap. These are observability descriptors, not a temporal crustal-strength series.

At the coarse 2026 model scale, WMM, IGRF, and WMMHR all predict positive northward total-field gradients; WMMHR therefore fails to reproduce the 2011 scalar inversion. Adding EMM2017 degrees 134-790 changes the modeled crustal F-gradient increment from +0.179723 to -0.333653 nT/km while the hybrid total gradient remains +0.808092 nT/km. The fine hybrid suppresses the main gradient by ~29.2% and has $R\sim 0.292$.

The signed inclination-gradient perturbation changes from -2.354 arcsec/km for WMMHR-WMM to -4.542 arcsec/km for the final hybrid-minus-WMM, preserving direction while approximately doubling. Across four supported N-S tracks, both the fine-scale scalar contribution and inclination-gradient perturbation are negative in 4/4 tracks.

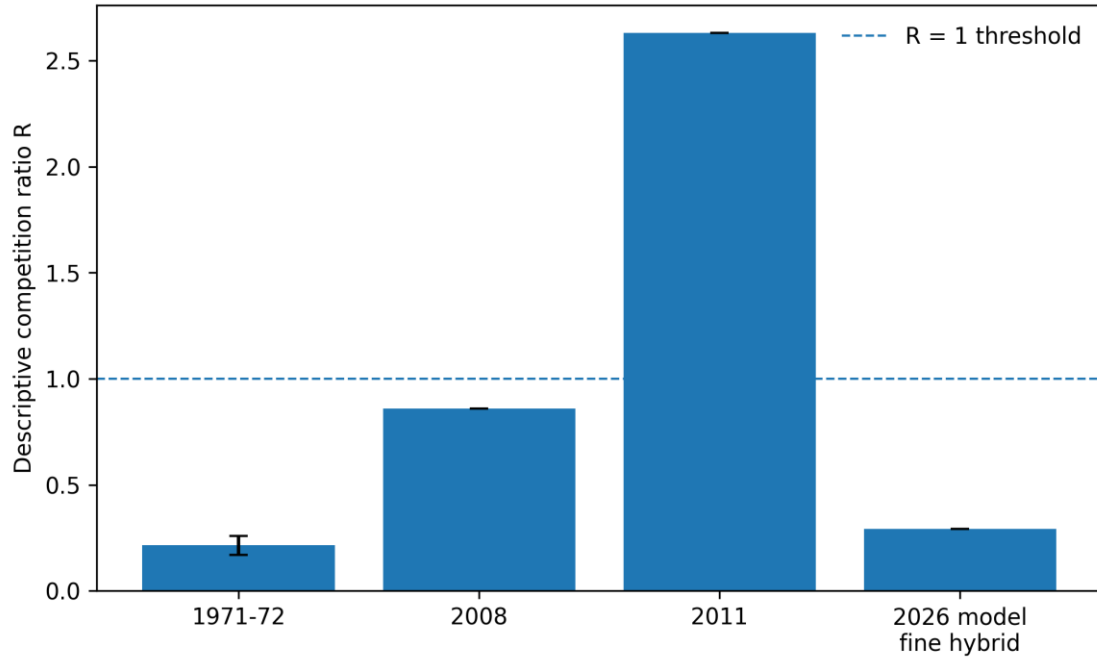


Fig. 5 Descriptive competition ratio across survey/model realizations. $R = 1$ marks the threshold at which an opposed crustal contribution can overcome the main-field gradient in the scalar observable. Values are not interpreted as a temporal crustal-strength series.

3.6 Geological holdout and explicit failures

The magnetically selected anchor lies ~30.7 m in GIS coordinate distance from the mapped Serra de Santa Helena-Lagoa do Jacare contact in the SGB Sao Francisco basin geological GIS (Dias et al., 2024). Given the 1:750,000 scale of the source map, this sub-100-m separation is interpreted only as a proximity statistic within the control audit, not as metric registration accuracy of the mapped contact. Among 1,195 non-overlapping controls, one matches or exceeds both magnetic and geological proximity thresholds; this is exploratory cross-domain corroboration, not a confirmatory probability.

The mapped exposed-to-concealed Sao Domingos transition lies ~8.113 km from Uruana. A 2008 E-W production line crosses ~86 m from this transition and records a raw step of 13.426 nT; an independent N-S tie-line acquired ~63 days earlier crosses the same structural sector ~1.35 km from the transition and records 7.110 nT. Both increase toward the same northeastern side.

Bouguer gravity does not reproduce the localized magnetic behavior and is retained as a negative cross-domain result. A full 2-D gradient-angle comparison is likewise non-discriminating and is not promoted. The earlier ~43-degree directional observation is not retained as evidence because comparable orientations are not rare regionally.

4 Discussion

4.1 What is demonstrated

Reversal of a weak regional magnetic gradient is not by itself unusual in crustal magnetic data. The distinguishing observation at Uruana is the complete same-line coherence of the turnover, its persistence across opposing flight directions and acquisition dates, its recovery without a prescribed breakpoint, its contrast with matched controls, and its

cross-survey correspondence. The strongest site-specific inference does not require residual construction, 1DV, geology, or modern models: the raw measured total field itself has a negative northward gradient in the observed Uruana target and a positive gradient farther north on every one of 14 usable flight lines, while the broad main-field expectation remains positive. We therefore consider the following formulation supported: a localized magnetic-gradient anomaly is present in the Uruana de Minas sector, characterized by reversal of the meridional gradient of the measured scalar total magnetic field relative to the regional main-field expectation.

This is not a geomagnetic polarity reversal, reversal of the complete magnetic vector, or reversal of the terrestrial main field.

4.2 Why topology is the more stable cross-survey object

The 1971-72, 2008, and 2011 surveys do not show identical scalar realizations. That is expected from the established effects of line spacing, altitude, sampling, and information content (Beamish and White, 2011; Pilkington and Tschirhart, 2017; Saltus et al., 2026). The matched-support result indicates that the more stable object is the signed transition architecture rather than amplitude equality. This complements, rather than replaces, equivalent-source integration and multiscale edge methods (Gavazzi et al., 2020; Lahti and Karinen, 2010).

4.3 A nested, finite-width turnover architecture

The total evidence is more consistent with a nested structure than with an infinitesimal point anomaly: a broader crustal domain contains a turnover zone, within which the Uruana sector exhibits the highest tested transition coherence. The 2008 + to - to + topology suggests a finite-width negative-gradient band, while the matched 2008-2011 northern fronts converge to within ~1-1.5 km. The proximity of the Sao Domingos structural transition provides geological context but does not establish causation.

4.4 Why failures strengthen the inference boundary

The analysis is not constructed to make every Uruana-related test reproduce the target. Historical total-field reversal is absent; broad-support historical localization is non-unique; full 2-D gradient reversal is non-discriminating; WMMHR does not reproduce the total-field inversion; gravity does not reproduce the localized magnetic response; and the ~43-degree directional hypothesis is not retained. These outcomes constrain the central result to what the data directly demonstrate: a localized meridional gradient reversal of the measured scalar total field, embedded in a broader persistent signed-gradient structure. Whether this non-discriminating 2-D behavior reflects genuine source anisotropy or anisotropy of the effective sampling cannot be resolved from the available scalar line data. The northward derivative is densely constrained within the N-S flight lines, whereas the eastward derivative is inferred across line spacing and therefore depends more strongly on line-to-line levelling and gridding, consistent with known sampling constraints on horizontal-gradient recovery (Saltus et al., 2026). Reciprocal vector traverses in both directions would separate these possibilities directly.

4.5 General methodological implication

The analytic benchmark and the empirical false-positive control identify the same safeguard: similarity metrics should be evaluated only after confirming existence of the structural object whose persistence is being claimed. Prior work explains why legacy and high-resolution surveys can differ in information content (Beamish and White, 2011), how heterogeneous observations can be transformed or combined (Gavazzi et al., 2020), and how magnetic edges behave across scale (Lahti and Karinen, 2010; Pilkington and Tschirhart, 2017). CSMPF addresses a different decision problem: whether a declared signed transition remains persistent when one survey crosses the scalar-reversal threshold and another does not. An unchanged source can cross $R=1$ solely because support changes, while a uniform same-sign domain can yield perfect agreement without containing a turnover. In this application, CSMPF distinguishes scalar replication from conditioned signed-topological persistence.

5 Limitations and prospective test

The 2011 survey does not cover the entire fixed 8-km circle; direct inference is restricted to the observed northern cap. The demonstrated quantity is $\partial F/\partial N$, not direct reversal of vector Z or inclination. Several regional-control statistics were developed after discovery and are therefore treated as descriptive robustness checks rather than preregistered p -values. Historical Project 1009 data are digitized/reprocessed rather than equivalent raw profiles. Modern WMMHR/EMM experiments are model sensitivities, not 2026 local measurements, and EMM can inherit legacy aeromagnetic compilations. CSMPF was formalized during analysis of the Uruana evidence rather than prospectively validated on an independent field case. The analytic known-truth benchmark tests the internal logic of the framework but does not constitute independent empirical validation. A pre-specified application to an unrelated pair of heterogeneous surveys would provide the appropriate framework-level transferability test. The post-discovery operator sensitivity also shows that the exact 14/14 MAGBRU count belongs to the frozen primary OLS/binning implementation rather than to every possible bin origin or slope estimator: one of four shifted 250-m bin phases gives 13/14 target-negative MAGBRU slopes, and pairwise-median slopes can likewise give 13/14 in shifted phases. Because some target lines contain only 5-8 bins, multivariable northing-plus-height fits are ill-conditioned on the weakest lines and are not used to claim an altitude-corrected 14/14 result. These sensitivity boundaries are retained explicitly; the primary fixed-operator result and the multi-channel target-to-north turnover are unchanged.

A post-discovery exploratory source-depth sensitivity audit was also performed rather than assigning a depth from a single preferred estimator (Online Resource 2). Radially averaged 2008 grid power spectra (Spector and Grant, 1970) repeatedly recover a shallow apparent ensemble scale of approximately 1.5-2.2 km across the tested local windows and detrending choices, but this scale is not source-specific. Euler solutions vary materially with structural index, analysis window, and upward continuation, consistent with known instability of structural-index and depth estimates (Florio et al., 2014), while 2011 profile spectral estimates vary with spatial and wavelength window. Source-specific profile-width fits at the mapped Sao Domingos crossing were likewise not stable. We therefore do not assign a unique causative-body depth or geometry from the present data.

The decisive site-specific prospective experiment is a new local vector survey measuring X , Y , Z , and F across the fixed geometry with reciprocal traverses and coverage of both the Uruana sector and the independently recovered northern front. A separate application to an unrelated pair of heterogeneous aeromagnetic surveys, with the analysis rules fixed before opening that case, would provide an external test of the framework's transferability.

6 Conclusions

The original 2011 flight-line observations directly demonstrate a localized magnetic-gradient anomaly at Uruana de Minas. The raw measured scalar total magnetic field has a northward gradient opposite to the positive main-field expectation on all 14 usable lines, before IGRF subtraction and before derivative processing. The same lines change from negative in the target to positive farther north; opposite headings, multiple acquisition dates, unconstrained breakpoints, and spatial controls retain the result.

Independent 2008 data recover a compatible turnover architecture, and matched spatial support places Uruana first among tested transition-bearing blocks for both front proximity and signed-gradient agreement. Historical 1971-72 data do not reproduce the scalar reversal but retain an opposed crustal residual and a robust derivative sign boundary. Modern model-scale experiments similarly show that smaller-scale crustal content can become oppositional without producing total-field reversal.

The resulting inference is specific: **Uruana de Minas hosts a localized magnetic-gradient anomaly whose strongest directly measured expression is a reversal of the meridional gradient of the raw scalar total magnetic field.** More generally, cross-survey persistence should be evaluated through conditioned signed spatial topology after accounting for survey support, acquisition geometry, main-field competition, and observation operator, rather than by requiring equality of scalar anomaly maps.

Statements and Declarations

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Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Author contributions

Conceptualization: Lucas Giovani Ribeiro. Methodology: Lucas Giovani Ribeiro, Marcos André Simonssini. Software: Lucas Giovani Ribeiro. Validation: Marcos André Simonssini. Formal analysis: Lucas Giovani Ribeiro, Marcos André Simonssini. Investigation: Lucas Giovani Ribeiro, Marcos André Simonssini. Data curation: Lucas Giovani Ribeiro. Visualization: Lucas Giovani Ribeiro. Writing - original draft: Lucas Giovani Ribeiro. Writing - review and editing: Lucas Giovani Ribeiro, Marcos André Simonssini. Both authors read and approved the final manuscript.

Data availability

All primary empirical data originate from public Brazilian geophysical archives of the Serviço Geológico do Brasil and Agência Nacional do Petróleo, Gas Natural e Biocombustíveis, together with public NOAA/NCEI geomagnetic models. Large upstream survey archives are not redistributed. Online Resource 2 supplies exact source identifiers, versioned audit outputs, machine-readable line-level and control-level derived tables, the complete 450-member historical reconstruction table, model-sensitivity tables, figure-source data, the Project 3087 channel/bin-phase/height sensitivity tables, and verification scripts.

Code availability

Online Resource 2 contains the analytic benchmark script and a deterministic verification script that recomputes the principal reported summary statistics from the supplied machine-readable derived tables. It also contains a streaming Project 3087 script that accepts the original public Mag-3087.XYZ file, or the archive containing it, and regenerates the added channel/bin-phase/height sensitivity tables. The principal verification script does not replace preprocessing of all large upstream public survey archives; it provides a transparent check of the numerical claims carried from the derived data into the manuscript, while the new 2011 sensitivity script closes the upstream-to-derived path for that robustness analysis.

References

- Agência Nacional do Petróleo, Gas Natural e Biocombustíveis (ANP) (2008) Acervo de dados técnicos não sísmicos: Projeto 0032 São Francisco. ANP, Brazil.
- Alkmim FF, Martins-Neto MA (2012) Proterozoic first-order sedimentary sequences of the São Francisco craton, eastern Brazil. *Mar Pet Geol* 33:127-139. <https://doi.org/10.1016/j.marpetgeo.2011.08.011>
- Beamish D, White JC (2011) Aeromagnetic data in the UK: a study of the information content of baseline and modern surveys across Anglesey, North Wales. *Geophys J Int* 184:171-190. <https://doi.org/10.1111/j.1365-246X.2010.04852.x>
- Beggan CD et al. (2026) International geomagnetic reference field: the fourteenth generation. *Earth Planets Space* 78:127. <https://doi.org/10.1186/s40623-025-02360-0>
- Dias PHA, Brito DC, Silva MA, Barros RA, Matos CA, Reis C, Meira M, Silva WS (2024) Mapa geológico da bacia do São Francisco. Serviço Geológico do Brasil, Belo Horizonte. Scale 1:750,000.
- Florio G, Fedi M, Pasteka R (2014) On the estimation of the structural index from low-pass filtered magnetic data. *Geophysics* 79:J67-J80. <https://doi.org/10.1190/GEO2013-0421.1>

395 Gavazzi B, Bertrand L, Munsch M, Mercier de Lepinay J, Diraison M, Geraud Y (2020) On the use of aeromagnetism
396 for geological interpretation: 1. Comparison of scalar and vector magnetometers for aeromagnetic surveys and an
397 equivalent source interpolator for combining, gridding, and transforming fixed-altitude and draping data sets. *J Geophys*
398 *Res Solid Earth* 125:e2019JB018870. <https://doi.org/10.1029/2019JB018870>

399 Lahti I, Karinen T (2010) Tilt derivative multiscale edges of magnetic data. *Lead Edge* 29:24-29.
400 <https://doi.org/10.1190/1.3284049>

401 NOAA National Centers for Environmental Information (2019) Enhanced Magnetic Model 2017 (EMM2017).
402 NOAA/NCEI geomagnetic model archive.

403 NOAA National Centers for Environmental Information, British Geological Survey (2024) World Magnetic Model
404 High Resolution 2025 (WMMHR2025). <https://doi.org/10.25921/qb1c-vn52>

405 Pilkington M, Tschirhart V (2017) Practical considerations in the use of edge detectors for geologic mapping using
406 magnetic data. *Geophysics* 82:J1-J8. <https://doi.org/10.1190/geo2016-0364.1>

407 Pimentel MM, Rodrigues JB, DellaGiustina MES, Junges S, Matteini M, Armstrong R (2011) The tectonic evolution of
408 the Neoproterozoic Brasilia Belt, central Brazil, based on SHRIMP and LA-ICPMS U-Pb sedimentary provenance data:
409 a review. *J S Am Earth Sci* 31:345-357. <https://doi.org/10.1016/j.jsames.2011.02.011>

410 Saltus RW, Chulliat A, Blakely RJ (2026) Evaluation of aliasing in aeromagnetic surveys - update to Reid 1980
411 analysis. *Earth Space Sci* 13:e2025EA004336. <https://doi.org/10.1029/2025EA004336>

412 Servico Geologico do Brasil (SGB) (2026a) GeoSGB public aerogeophysical data: Project 3087 - Area 19 - Formoso -
413 Buritis - Lagoa Grande. <https://geosgb.sgb.gov.br/downloads/>. Accessed 14 Aug 2026.

414 Servico Geologico do Brasil (SGB) (2026b) GeoSGB public aerogeophysical data: Project 1009 - Projeto Aerogeofisico
415 Convenio Brasil-Alemanha. <https://geosgb.sgb.gov.br/downloads/>. Accessed 14 Aug 2026.

416 Servico Geologico do Brasil (SGB) (2026c) Aerogeofisica. Ministerio de Minas e Energia, Brazil.
417 <https://www.sgb.gov.br/aerogeofisica>. Accessed 18 Aug 2026.

418 Spector A, Grant FS (1970) Statistical models for interpreting aeromagnetic data. *Geophysics* 35:293-302.
419 <https://doi.org/10.1190/1.1440092>

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