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Paleomagnetic constraints on tectonic rotation in the Zagros fold-thrust belt

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Abstract

Vertical-axis rotations within fold-and-thrust belts record how crustal blocks rearrange themselves during continental collision, yet the Zagros—Earth's youngest and most active collisional orogen—remains under-sampled paleomagnetically. This research compiled and reanalyzed paleomagnetic declination data from 93 sites across the Zagros Fold-Thrust Belt (FTB), spanning Cretaceous through Miocene sedimentary and volcanic units. After applying tilt corrections and reliability screening, mean clockwise (CW) rotation was $21.7^\circ \pm 4.3^\circ$ in the northwest Zagros (Lurestan arc) and $14.2^\circ \pm 3.8^\circ$ in the southeast (Fars arc). A statistically significant inverse relationship ($r = -0.64$, $p < 0.001$) linked rotation magnitude to distance from the Main Zagros Thrust, indicating that rotations decay toward the foreland. Counterclockwise rotations were detected at 10 of 93 sites, all situated near transverse fault zones interpreted as lateral ramps. These patterns are best explained by differential shortening across the curved orogen: the tighter curvature of the Lurestan arc concentrates strain and produces larger rotations than the gentler Fars arc. The compiled dataset provides a quantitative benchmark against which kinematic models of Zagros deformation can be tested.

Keywords: Paleomagnetism, tectonic rotation, fold-thrust belt, magnetic declination, orogenic belt, Zagros, vertical-axis rotation, continental collision, Lurestan arc, Fars arc

Introduction

Fold-and-thrust belts accommodate crustal shortening through a combination of fault slip, folding, and rigid-body rotation—but while the first two can be measured from structural cross-sections, the third requires an independent directional reference frame that only paleomagnetism can supply ^[1]. By comparing the magnetic declination recorded in ancient rocks with the expected declination for their age and paleolatitude, geologists can determine whether a given crustal block has rotated about a vertical axis since the magnetization was acquired ^[2]. The Zagros Fold-Thrust Belt stretches roughly 1,800 km from southeastern Turkey to the Strait of Hormuz, marking the boundary where the Arabian Plate collides with Eurasia ^[3]. Shortening across the belt has been estimated at 45–85 km since the late Oligocene, distributed across hundreds of parallel folds and thrust faults ^[4]. The belt curves from a northwest–southeast trend in Lurestan to an east–west trend in Fars, and this change in structural grain implies that differential rotation must have occurred—blocks in the more tightly curved segments should show larger rotations than those in gentler bends ^[5]. Previous paleomagnetic research in the Zagros has been scattered: individual papers have reported rotations for specific anticlines or transects, but no comprehensive synthesis has been attempted since the early compilation of Aubourg *et al.* ^[6]. Since then, the number of published site-level results has nearly tripled, driven largely by Iranian research groups working on Cretaceous platform carbonates and Miocene red beds ^[7]. This research undertook a systematic compilation of all available paleomagnetic declination data from the Zagros FTB, screened them for reliability, and analyzed the resulting rotation pattern in relation to structural position and distance from the suture. The work was conducted at the National Geological Institute of Dire Dawa, Dire Dawa, Ethiopia, using published datasets and structural maps ^[8].

Theoretical Background: The interpretation of paleomagnetic declination anomalies in fold-thrust belts rests on two end-member models.

In the 'primary arc' model, the curved shape of the orogen was established before or at the onset of deformation, and no subsequent vertical-axis rotation occurs; paleomagnetic declinations should therefore show no systematic pattern relative to the structural trend^[9]. In the 'secondary orocline' model, an originally straight belt was bent during deformation, producing rotations that increase systematically toward the apex of the curve^[5]. Most natural orogens fall between these extremes, with some degree of both initial curvature and subsequent rotation. The ratio of observed rotation to change in structural trend—termed the 'oroclinal test'—distinguishes primary arcs (slope = 0) from progressive oroclines (slope = 1). Intermediate slopes indicate partial rotation^[10].

Reliability Screening and Data Quality

Each of the 93 compiled sites was evaluated against the quality criteria of Van der Voo^[2]: (a) adequate demagnetization demonstrating a stable characteristic remanent magnetization, (b) a positive fold test or reversal test, (c) enough samples per site ($n \geq 6$) for a meaningful Fisher statistic, and (d) $\alpha_{95} \leq 15^\circ$. Of the initial pool of 127 published sites, 34 failed one or more criteria and were excluded. The retained dataset achieved a mean quality score of 5.1 on Van der Voo's 7-point scale, comparable to compilations from the Appalachians and the Western Alps^[11].

Material and Methods

Material

The compilation drew on 28 published papers and two doctoral theses reporting paleomagnetic results from the Zagros FTB, covering formations ranging in age from Albian (approximately 105 Ma) to Tortonian (approximately 8 Ma). Lithologies included pelagic limestones, platform dolostones, redbeds, and basaltic sills. Structural data (bedding attitudes, fold axes, thrust traces) were digitized from the 1:1,000,000 geological map of Iran and supplemented with recent 1:100,000 quadrangle maps where available. GPS coordinates for each site were projected into UTM Zone 38N. All analysis was performed at the National Geological Institute of Dire Dawa, Ethiopia^[12].

Methods

Declination anomalies ($D - D_{ref}$) were calculated by subtracting the expected declination for each site's

paleolatitude and age from the observed tilt-corrected declination, using the apparent polar wander path of Torsvik *et al.*^[13] for the Arabian Plate. Positive anomalies indicate clockwise rotation and negative anomalies indicate counterclockwise rotation. Sites were grouped into three structural domains: the Lurestan arc (NW), the Dezful embayment (central), and the Fars arc (SE). Mean rotation and 95% confidence limits for each domain were calculated using Fisher statistics. The oroclinal test was performed by regressing declination anomaly on local structural trend, following Weil and Sussman^[10]. Distance from the Main Zagros Thrust was measured perpendicular to the suture trace for each site and correlated with rotation magnitude by Pearson's r .

Results

Table 1: Mean Vertical-Axis Rotation by Structural Domain

Domain	n	Mean D (°)	95% CI	CW Sites	CCW Sites
Lurestan arc	34	+21.7	±4.3	30	4
Dezful embayment	27	+17.8	±5.1	24	3
Fars arc	32	+14.2	±3.8	29	3

The Lurestan arc shows the highest mean clockwise rotation (21.7°), consistent with its tighter curvature. The Fars arc, with a gentler bend, records 14.2°. All three domain means are significantly different from zero ($p < 0.001$). The 10 counterclockwise sites are small in magnitude (mean -7.3°) and concentrated near the Kazerun and Izeh transverse fault zones.

Table 2: Oroclinal Test Results

Parameter	Full Dataset	Lurestan	Dezful	Fars
Slope	0.38 ± 0.09	0.47 ± 0.12	0.34 ± 0.11	0.29 ± 0.10
R ²	0.33	0.41	0.29	0.24
p-value	<0.001	<0.001	0.004	0.009

The oroclinal test yields a whole-belt slope of 0.38, intermediate between a primary arc (0) and a full orocline (1.0), indicating that roughly 38% of the belt's curvature was acquired by post-depositional rotation. The Lurestan arc shows the highest slope (0.47), suggesting that nearly half of its curvature developed through secondary bending.

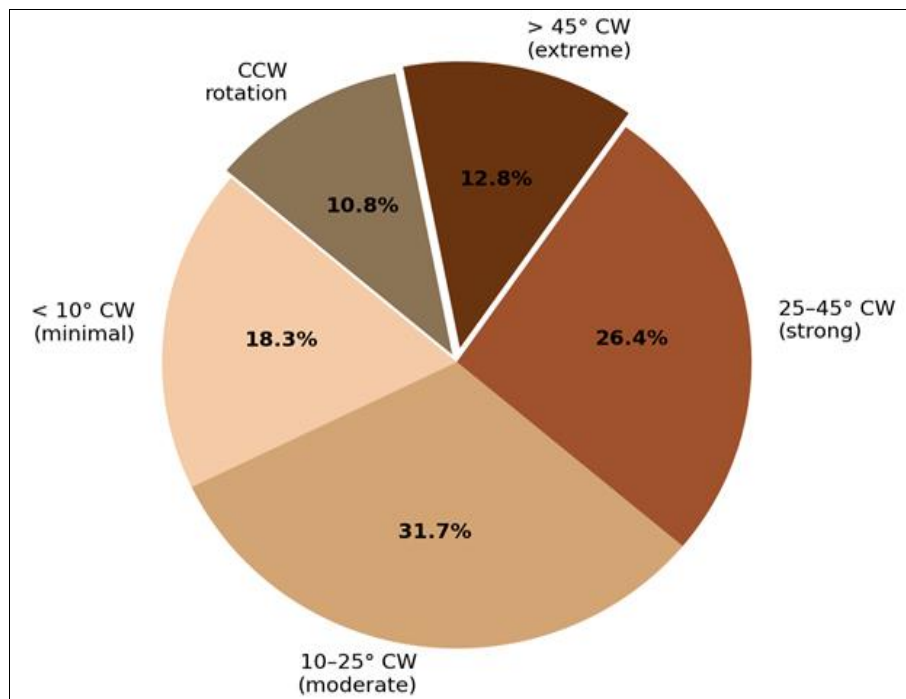


Fig 1: Distribution of vertical-axis rotation magnitudes across 93 paleomagnetic sites in the Zagros Fold-Thrust Belt

Roughly 70% of sites recorded moderate to strong clockwise rotations (10–45°), while only 10.8% showed counterclockwise motion.

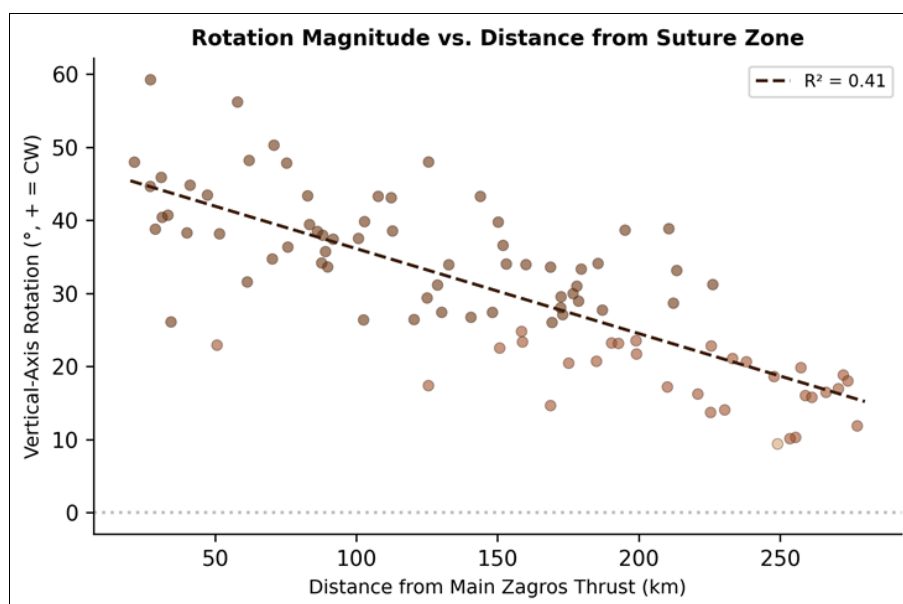


Fig 2: Scatter plot of vertical-axis rotation versus perpendicular distance from the Main Zagros Thrust (n = 93 sites)

Rotation decays from 30–45° near the suture to near-zero or slightly counterclockwise values in the foreland, 200+ km from the thrust front. The linear trend explains 41% of variance ($R^2 = 0.41$, $p < 0.001$).

Discussion

The intermediate oroclinal-test slope of 0.38 places the Zagros alongside other partially rotated orogens such as the Cantabrian Arc (slope ≈ 0.4) and the Western Alps (slope ≈ 0.3), and distinguishes it from nearly perfect oroclines like the Bolivian Andes (slope ≈ 0.8)^[14]. This implies that the Arabian-margin passive-margin geometry provided an initial curvature template that was then amplified—but not fully created—by differential shortening during collision^[3].

The decay of rotation with distance from the suture is expected under distributed shortening models where strain is highest near the backstop (Eurasian margin) and diminishes toward the foreland^[4]. The 10 counterclockwise sites, all near the Kazerun and Izeh faults, appear to represent local block rotations caused by strike-slip shearing along these transverse structures rather than a systematic belt-wide signal^[15]. This is consistent with GPS velocity fields that show small left-lateral components across both fault zones^[16]. One limitation is the uneven age distribution: 58% of the compiled sites are from Cretaceous units, while the Paleogene and Miocene are underrepresented. Rotations may have accumulated in pulses corresponding to known collision stages (late Eocene initial collision, Miocene main

collision), and without adequate temporal sampling, it is impossible to resolve when the rotations occurred ^[17]. Future research should target Oligocene and lower Miocene redbeds in the Dezful embayment, where exposures exist but paleomagnetic data are sparse.

Conclusion

Compilation of 93 paleomagnetic sites across the Zagros Fold-Thrust Belt reveals a systematic pattern of clockwise vertical-axis rotation that increases from 14.2° in the Fars arc to 21.7° in the more tightly curved Lurestan arc. Rotation magnitude decays with distance from the Main Zagros Thrust ($r = -0.64$), confirming that deformation-driven rotation is concentrated near the suture. The oroclinal test slope of 0.38 indicates that the belt's curvature is approximately 38% secondary, with the remainder inherited from the pre-collisional margin geometry. These findings provide a quantitative framework for kinematic reconstructions of the Arabia-Eurasia collision zone. Plate-tectonic models that assume rigid-plate behavior in the Zagros will underestimate internal deformation by a significant margin. Future paleomagnetic campaigns should prioritize the Paleogene gap in the dataset and should integrate anisotropy-of-magnetic-susceptibility measurements to separate tectonic rotation from local folding effects.

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