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Fault-controlled magma pathways driving seismicity and eruption risk in Eastern Turkey

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Many oceanic and some continental transform faults host coupled tectonic shear and magmatism, complicating seismic and volcanic hazards. Here we integrate high-resolution seismic tomography and three-dimensional finite-element modelling to investigate fault–magma interactions along the eastern North Anatolian Fault Zone. Tomography reveals two shallow magma reservoirs beneath the Erzincan Basin and the Karlıova Triple Junction, characterised by high V_p/V_s (>1.85). The western reservoir is largely aseismic while the eastern reservoir has persistent seismicity. Time-dependent models demonstrate that right-lateral shear focuses tensile stresses around both reservoirs that encourage reservoir rupture and dyke injection. This stress concentration occurs even when the initial magma-generated excess pressure is zero, and may gradually expand towards the surface. Upward stress transfer is enhanced within the fractured damage zone, facilitating dyke propagation. The results may apply to many transform faults and are of great importance for evaluating the coupled earthquake–volcano hazards in such fault zones.

Magma accumulation and propagation through the continental crust can be strongly influenced by active fault zones. The fracture networks of these zones, particularly in the damage zones, provide sites of local minimum potential energy that, in accordance with Darcy's law, tend to collect available magma¹. Additionally, strike-slip faulting may promote magma accumulation and emplacement through pull-apart basins, extensional step-overs and crustal-scale anisotropies^{2,3}. Dyke propagation, partly facilitated by linking pre-existing fractures (primarily joints and other small fractures), is thus sensitive to fault-damage networks, especially in strike-slip systems^{4–6}. While inclined planes of dip-slip faults may arrest vertically propagating dykes⁷, strike-slip fault planes and damage zones are typically near-vertical, providing potential magma pathways – as are, indeed, observed in deeply eroded transform fault zones⁸. Although strike-parallel dykes are thus reported in transform faults, the precise interaction between faulting and magmatism remains poorly constrained. The North Anatolian Fault Zone (NAFZ), a major right-lateral strike-slip system bounding the Anatolian microplate, accommodates magma storage and ascent partly through transtensional basins and step-overs^{9,10}. Its eastern sector, intersecting the Arabia–Eurasia–Africa triple junction, is additionally affected by

ongoing shortening, lithospheric thinning and mantle upwelling^{11–13}. This region, spanning the Erzincan, Tunceli and Bingöl provinces, is among the most tectonically complex globally, with widespread magmatism and lithospheric stress along the NAFZ^{14,15}. Geochemical and geophysical evidence suggests that the magmatism primarily originates from the partial melting of a metasomatised lithospheric mantle facilitated by lithospheric thinning and transtension^{16,17}.

Field observations show that magma has repeatedly reached shallow crustal levels and the surface along this sector of the NAFZ, with Quaternary domes and feeder dykes (800–100 ka) aligned along Erzincan–Çağlayan and Adaklı–Nazımiye–Bingöl, coinciding with modelled stress concentrations. Quaternary volcanism in Eastern Anatolia is aligned with fault-bounded corridors that coincide with zones of ongoing crustal deformation. These corridors represent elongated crustal domains between overlapping fault strands where localised transtension promotes magma storage and vertical migration; in the Erzincan Basin, this corresponds to a releasing step-over within the NAFZ. Space-based geodesy (Interferometric Synthetic Aperture Radar (InSAR), The Global Positioning System (GPS), 2003–2022) data yields variable slip rates, with an increase from 16.3 ± 2.3 mm yr^{−1} near

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Erzincan to 24.0 ± 2.9 mm yr⁻¹ westward^{18–20}. Vertical velocities indicate an uplift of ~ 10 mm yr⁻¹ uplift in the western Erzincan Basin and comparable subsidence in the east. This is interpreted as magma accumulation and withdrawal beneath fault-controlled basins²¹.

Seismic tomography further indicates lithospheric segmentation linking mantle dynamics to crustal magmatism^{15,22,23}. Low-velocity anomalies and high V_p/V_s ratios in the upper crust are consistent with melt- and fluid-rich zones²⁴. Values of $V_p \leq 4.6$ km s⁻¹ and $V_p/V_s > 1.85$ are reported beneath the Karliova Triple Junction (KTJ) and the eastern NAFZ^{24–27}, suggesting partially molten environments. Similar features are found in other transform fault settings^{28,29}.

Understanding how magma reservoirs interact with fracture networks is critical for constraining combined seismic and volcanic hazards. While teleseismic tomography¹⁵ and magnetotellurics³⁰ have imaged partially molten lower crust along the NAFZ, the geometry of shallow reservoirs and their mechanical interaction with faults remain unclear.

Here we present the and integrated study of magma reservoirs and active faulting along the eastern NAFZ (Fig. 1). To this end, we employ a multidisciplinary approach that integrates local earthquake tomography with three-dimensional finite-element simulations to assess how observed low-velocity zones influence stress transfer along the NAFZ. By applying this approach, we identify two shallow magma reservoirs and show how their local stress fields generated by movement on the NAFZ encourages reservoir rupture and dyke injection and propagation. Furthermore, we demonstrate that these local stress fields may gradually expand towards the surface of the NAFZ. The results illuminate the magma-driven, shear-dominated corridor of Eastern Anatolia. This integrated approach enables direct comparison between imaged melt domains and modelled stress deformation fields.

Eastern Anatolia lies within the Arabia–Eurasia collision zone, where crustal shortening and thickening are superimposed on post-collisional volcanism. The eastern NAFZ, transitioning into the Karliova Triple Junction (KTJ), represents the principal surface expression of this

interaction. Here, the NAFZ merges with the left-lateral East Anatolian Fault and the Bitlis–Zagros Suture, forming a deforming crustal block at the convergence of three plates. The KTJ drives complex lithospheric interactions, leading to inversion, uplift, seismicity, and sustained volcanism over the past ~ 6 Myr.

The Erzincan Basin, situated along the eastern segment of the NAFZ, is a superimposed basin formed by right-lateral strike-slip motion along the Arabia–Eurasia plate boundary^{11,31} (Supplementary Fig. 1). Its evolution records alternating extension and subsidence, with secondary structures – particularly oblique and cross-cutting faults – focusing strain and controlling basin architecture^{24,32}.

Volcanism in this corridor is strongly fault-associated, in particular, within the Erzincan Basin and near the KTJ. Quaternary volcanic centres indicate persistent magma supply from an enriched lithospheric mantle, with ascent facilitated by intensely fractured and mechanically weak fault zones^{32,33}. The erupted products range from basaltic andesite to dacite, consistent with partial melting and fault-assisted ascent.

Geophysical data constrain subsurface structure. Regional tomography reveals low-velocity anomalies and high V_p/V_s ratios in the mid- to upper crust^{15,18,34}, interpreted as regions of partial melt or active magma storage. At crustal levels, local tomography study indicates V_p/V_s values exceeding 1.9 at depths of 4–6 km in the south eastern Erzincan Basin²⁴. Although initially attributed to fractured carbonates or fluids, these low-velocity, high V_p/V_s anomalies beneath fault-linked basins likely represent shallow magma bodies, given their spatial coincidence with crustal fault systems. Comparable patterns along other transform margins show that high V_p/V_s signatures often indicate magmatic intrusion zones^{35,36}.

Along the NAFZ, fourteen small-volume and phenocryst-rich volcanic domes – ranging compositionally from basaltic andesite to rhyolite – have been emplaced. Their K–Ar dates indicate ages between ~ 800 and 102 ka and the dome diameters are < 3 km^{26,37}. Amphibole megacrysts and hydrous phases record mid- to upper-crustal magma storage. Hence, geological and geophysical data indicate fluid transport through the crust driven by

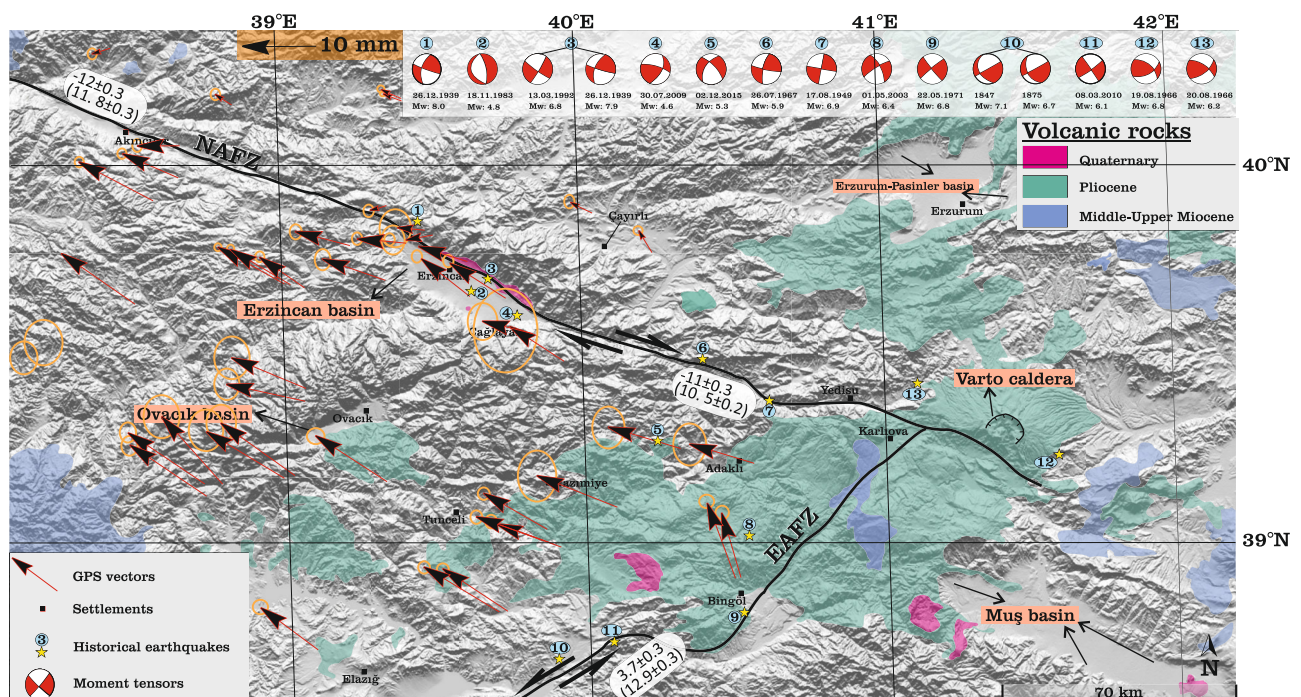


Fig. 1 | Tectonic and geophysical framework of Eastern Anatolia. Shaded relief map showing GPS velocity vectors (relative to Eurasia; 95% confidence ellipses) and historical moment tensor solutions (beach balls). Major active faults include the North Anatolian Fault Zone (NAFZ) and East Anatolian Fault Zone (EAFZ). Transensional basins and volcanic centres (for example, the Varto Caldera) are

marked. Yellow lines indicate locations of seismic tomography profiles (A–A', B–B'). Inset shows regional plate boundaries (Eurasia, Arabia and Africa) and westward motion of the Anatolian Block. Data sources: GPS from Özener et al.¹⁸; moment tensors from USGS; volcanic ages from Karaoğlu et al.¹⁷.

upwelling of asthenospheric mantle, with limited surface volcanism in the late Quaternary.

Results and discussions

Seismic tomography reveals dual magma reservoirs

Seismic tomography resolves two vertically extensive high V_p/V_s anomalies (> 1.85) beneath the Erzincan Basin and the KTJ, extending from ~ 5 km to 15 km depth, with elevated V_p/V_s values (> 1.80) persisting down to ~ 30 km (Supplementary Figs. 2–6). The larger western anomaly lies beneath the Erzincan Basin, coinciding with Cenozoic volcanic centres (Fig. 2). Vertical Sections 1 and 2 indicate maximum V_p/V_s values are concentrated within a discrete zone shallowing to ~ 5 –6 km, which we interpret as the uppermost melt-rich portion of the reservoir. Notably, seismicity is scarce within and immediately above this reservoir, suggesting ductile or melt-rich conditions. Below ~ 15 km depth, the anomaly continues with reduced amplitude, but lacks deep seismic clustering. Between ~ 20 and 30 km depth, a weaker but coherent high V_p/V_s (> 1.80) structure occurs northwest of the volcanic chain, potentially marking a lower crustal magma reservoir (Section 1 in Fig. 2). This structure extends laterally beneath a northern branch of the NAFZ, rather than beneath the main fault zone.

The coexistence of recent volcanic activity, elevated V_p/V_s ratios, and the absence of seismicity beneath the Erzincan Basin collectively suggest the presence of magma storage above ~ 15 km depth within the NAFZ,

particularly inside its damage zone. Elevated V_p/V_s values, low seismicity, and erupted product compositions all point to hot, low-viscosity magma stored above the brittle–ductile transition within a partially molten crystal mush, consistent with a thermally mature, melt-retaining system^{38,39}.

In contrast, the eastern high V_p/V_s anomaly beneath the KTJ coincides with intense seismicity from ~ 10 km to ~ 30 km depth. This persistence of seismicity likely reflects a lower melt fraction and cooler, more brittle host crust compared to the west, allowing stresses to be released seismically. No clear deep rooting is detected below 15 km. A tomographic cross-section parallel to the NAFZ (Section 1) outlines both magma reservoirs, vertically aligned with major fault strands at the base of transtensional fault segments (Fig. 1). A prominent cluster of deep seismicity near 30 km depth and intersects a laterally extensive V_p/V_s anomaly at ~ 15 km depth, a pattern suggesting lateral magma transport along mechanically weak crustal zones, comparable to other volcanic transform settings⁴⁰. The vertical Section 4 through the eastern anomaly (Fig. 2f) further illustrates its alignment with the NAFZ, supporting fault-controlled magma localization.

Numerical models demonstrate surface-reaching stress accumulation

Time-dependent finite-element simulations were utilised to examine the crustal stress response to magma chamber pressurisation and tectonic displacement over a 1,000-year period. Under baseline conditions

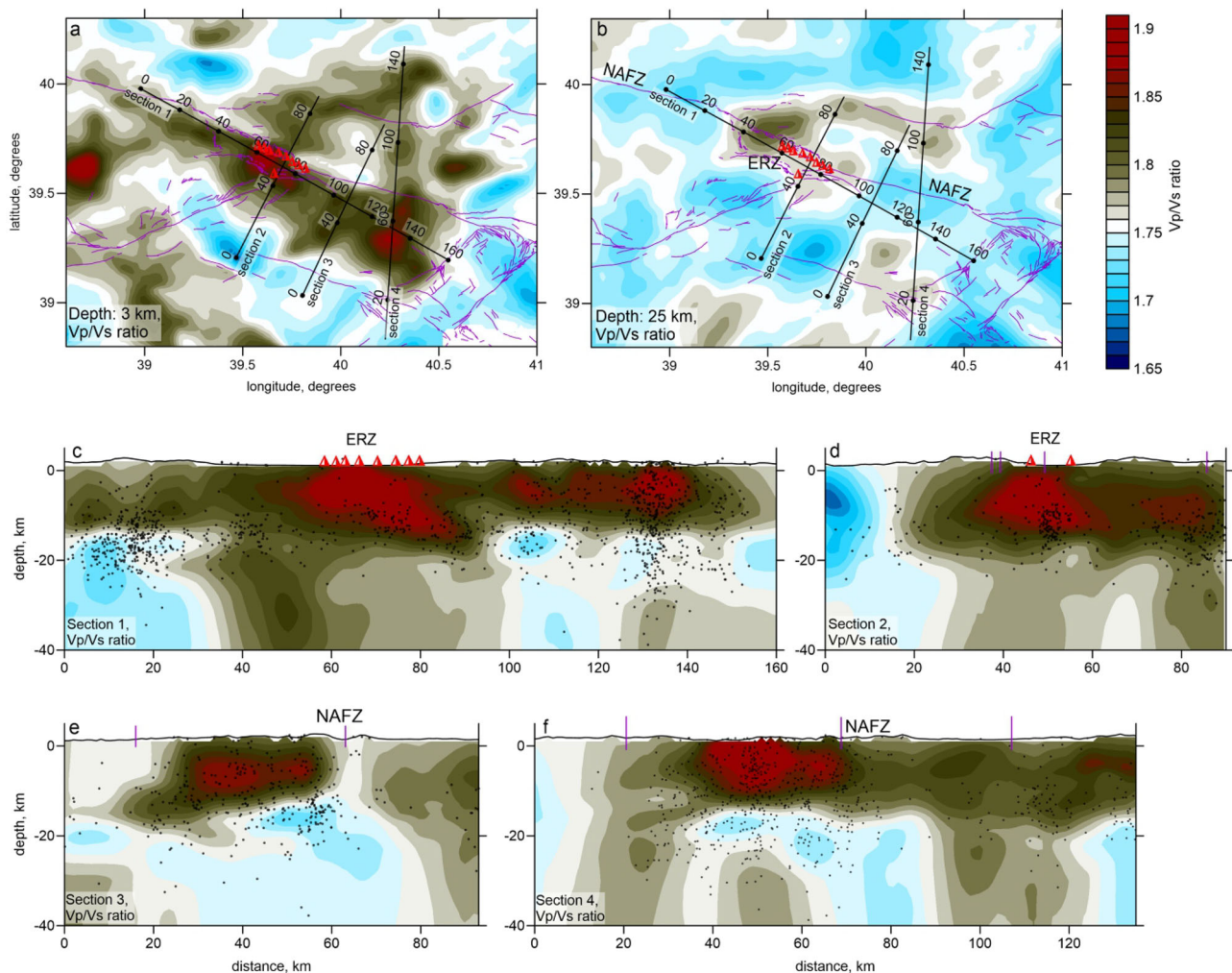


Fig. 2 | V_p/V_s ratio distribution derived from seismic tomography. **a, b** Two horizontal and **(c–f)** four vertical cross-sections show high V_p/V_s anomalies with the western and eastern crustal reservoirs highlighted at depths of ~ 5 –15 km. Pink lines denote mapped fault zones; red triangles mark Pliocene–Quaternary volcanic

centres in the Erzincan Basin (ERZ). Black dots indicate seismic events within 7 km of the vertical profiles. Vertical pink bars correspond to surface-traced faults. NAFZ North Anatolian Fault Zone.

(magmatic excess pressure, $MEP = 0$), stress migration is exclusively attributable right-lateral shear applied across the fault zone. Constant boundary displacements of $\pm 0.95 \text{ cm yr}^{-1}$ reproduce the long-term westward extrusion of the Anatolian block and generate deviatoric stress concentrations at reservoir margins and within the fault zone (Supplementary Fig. 7). In all of the scenarios that were tested, stress perturbations reached the surface within ~ 200 years, particularly above the western reservoir (Fig. 2; Supplementary Fig. 2). The Methods section provides a comprehensive overview of the full boundary conditions and material parameters (Supplementary Figs. 7 and 8).

Despite the absence of $MEP = 0 \text{ MPa}$, fault-displacement induced stresses generated at the reservoir roof were transmitted upward, increasing the likelihood of dyke initiation. This has direct implications for understanding magma mobility and forecasting eruption scenarios in tectonically stressed settings^{41,42}. This behaviour, controlled by differential shear along the NAFZ, is attributable to the continuous westward motion of the Anatolian block ($\sim 20 \text{ mm yr}^{-1}$). Sustained shear causes a progressive rotation of the principal stress axes, resulting in the tensile orientation of σ_3 above the reservoir roof, promoting reservoir rupture and dyke injection even without excess pressure. The larger, shallower western reservoir amplifies this stress rotation, producing higher tensile stress σ_3 for the same far-field loading and lowering the effective failure – and thereby dyke-injection – threshold^{1,7}. Consequently, regional strike-slip shear and westward extrusion alone can generate conditions favourable for dyke injection in such as fault-bounded magmatic system.

Concentration of the deviatoric shear within the NAFZ fault corridor further indicate that dyke injection is mechanically linked to the fault zone. The low-rigidity, highly fractured fault damage zone serves as a stress amplifier that focuses tensile failure upward. The tensile stresses, in turn, amplify any buoyancy-generated overpressure and the existing fractures (commonly vertical) in the damage zone encourage dyke propagation. This interpretation is consistent with tomographic evidence for fluid-rich, low-velocity domains above the western reservoir.

Under zero MEP conditions (lithostatic equilibrium), stress accumulation was most pronounced above the western reservoir during the first 400 years (Fig. 3). After 800 years, tensile stresses at the surface above this reservoir had increased to $\sim 2.4 \text{ MPa}$, despite the absence of magmatic excess pressure. These stress magnitudes imply that magma-reservoir rupture and dyke injection may occur even if there is no added magma to, and no magmatic excess pressure in, the reservoir. By contrast, the eastern reservoir displayed negligible stress amplification under these conditions (Fig. 3). With increasing MEP values ($1\text{--}5 \text{ MPa}$), however, stress concentrations developed around and above the eastern reservoir, indicating pressure-assisted failure there (Fig. 4; Supplementary Figs. 9–12). Magma storage several kilometres above the brittle–ductile transition likely reflects locally favourable regions for magma accumulation within the fault zone. Such regions may be related to releasing bends and step-overs as well as to local barriers to vertical magma transport. Such barriers may form in various ways in the crust^{1,2}. For the fault zones, such barriers may occur either in transpression or transtension zones, where the different mechanical properties of the fault rock together with the fault-zone shear loading may generate a local stress barrier. Additionally, the combination of volatile-rich magma and transient thermal softening may produce regions of local short-term ductile behaviour at shallower depths, reducing the local fault-zone permeability and promoting melt accumulation at $\sim 4\text{--}6 \text{ km}$ rather than at typical mid-crustal levels^{43,44}.

At the surface, in all scenarios with positive magmatic excess pressure ($MEP = 1\text{--}5 \text{ MPa}$), the minimum principal stress (σ_3) remained below MEP . However, the von Mises shear stress (τ)—representing the second invariant of deviatoric stress—consistently exceeds the applied MEP , reflecting the dominance of strike-slip kinematics along the NNAFZ. Shear loading therefore enhances rupture potential by progressively generating tensile stress concentrations, which over time may encourage dyke initiation. Since dykes form through extension–fracture failure (governed by, and with the dyke plane striking perpendicular to, σ_3) rather than shear-failure,

the elevated von Mises shear stress provides a critical context for assessing the likelihood of magma ascent. This indicates that shear stresses contribute to destabilizing the magma reservoir, increasing the potential for rupture of the reservoir roof or wall under tectonic (here transform fault) loading. Moreover, the gradual build-up of tensile stress due to sustained shear loading highlights an evolving failure potential that may culminate in dyke propagation.

Three-dimensional stress fields reveal strong contrasts between the two reservoirs. For MEP values of $1\text{--}5 \text{ MPa}$, σ_3 reached $\sim 34 \text{ MPa}$ and $\tau \sim 36 \text{ MPa}$ near the roof and walls (or flanks) of the western reservoir, whereas the eastern reservoir required higher MEP to attain comparable stress levels and remained mechanically more stable (Supplementary Figs. 7–10). The smaller σ_3 and τ difference around the east reservoir may reflect its geometry while shear stress amplification dominates in the west. The modelled stress pathways align with the NAFZ and the basin margins and reproduce the observed geodetic asymmetry—uplift in the west and subsidence in the east which supports the interpretation of shallow, magma bodies under stress concentration partly driving ongoing deformation¹⁴. These results demonstrate how structural inheritance modulates stress localisation, magma storage, and surface deformation in transform fault settings.

Asymmetric deformation linked to reservoir excess pressure thresholds

Numerical results indicate that stress propagation is governed not only by magma excess pressure within the reservoirs in the fault zone, but also by its coupling with the regional stress field and the inherited fault geometry. The findings of the numerical models, are corroborated by moment tensor solutions and historical seismicity records, which confirm right-lateral strike-slip dominance across the eastern NAFZ produces ground displacements up to 20 mm yr^{-1} (Fig. 1). Modelled excess pressure thresholds required for reservoir rupture and dyke initiation ($\sim 1\text{--}9 \text{ MPa}$)¹ are exceeded recurrently within the western reservoir, implying a high likelihood of shear-assisted mechanical failure and dyke injection under sustained tectonic loading.

The eastern reservoir remains comparatively stable under current loading conditions but could reach critical excess pressure levels so as to cause rupture and dyke injection should external tectonic loading or magma influx change (Figs. 2–4). Magma reservoirs (subject to excess pressure) beneath the Erzincan Basin plausibly explain the asymmetric vertical displacements identified by Weiss et al.¹⁴—uplift of $\sim 10 \text{ mm yr}^{-1}$ in the west and equivalent subsidence in the east—highlighting a magmatic contribution to differential crustal deformation along the NAFZ. Our simulations further show that stress migration occurs even at $MEP = 0$, emphasising that tectonic loading, not excess pressure, appear to be the primary driver. High V_p/V_s ratios (> 1.9) above both reservoirs are consistent with shallow partial-melt domains, which further enhance tensile failure and promote dyke propagation when combined with regional loading through fault movement. Taken together, these results elucidate the observed deformation asymmetry and highlight the sensitivity of fault-bounded magma systems to even modest variations in excess pressure.

Fault-controlled magma pathways in a transtensional regime

Our combined tomographic and numerical modelling results reveal a dynamic interplay between crustal-scale faulting and magma accumulation beneath the Erzincan Basin and the Karliova Triple Junction (KTJ) in Eastern Anatolia. The western reservoir, located adjacent to the North Anatolian Fault Zone (NAFZ), efficiently transmits tensile and shear stresses owing to inherited fault geometry (Fig. 3). The modelled stress concentrations at and above this reservoir exceeds failure thresholds for dyke propagation, suggesting it is mechanically primed for rupture under current conditions. This behaviour is consistent with InSAR and GPS measurements showing uplift above the western reservoir and subsidence to the east, reflecting the asymmetric stress field captured in the models.

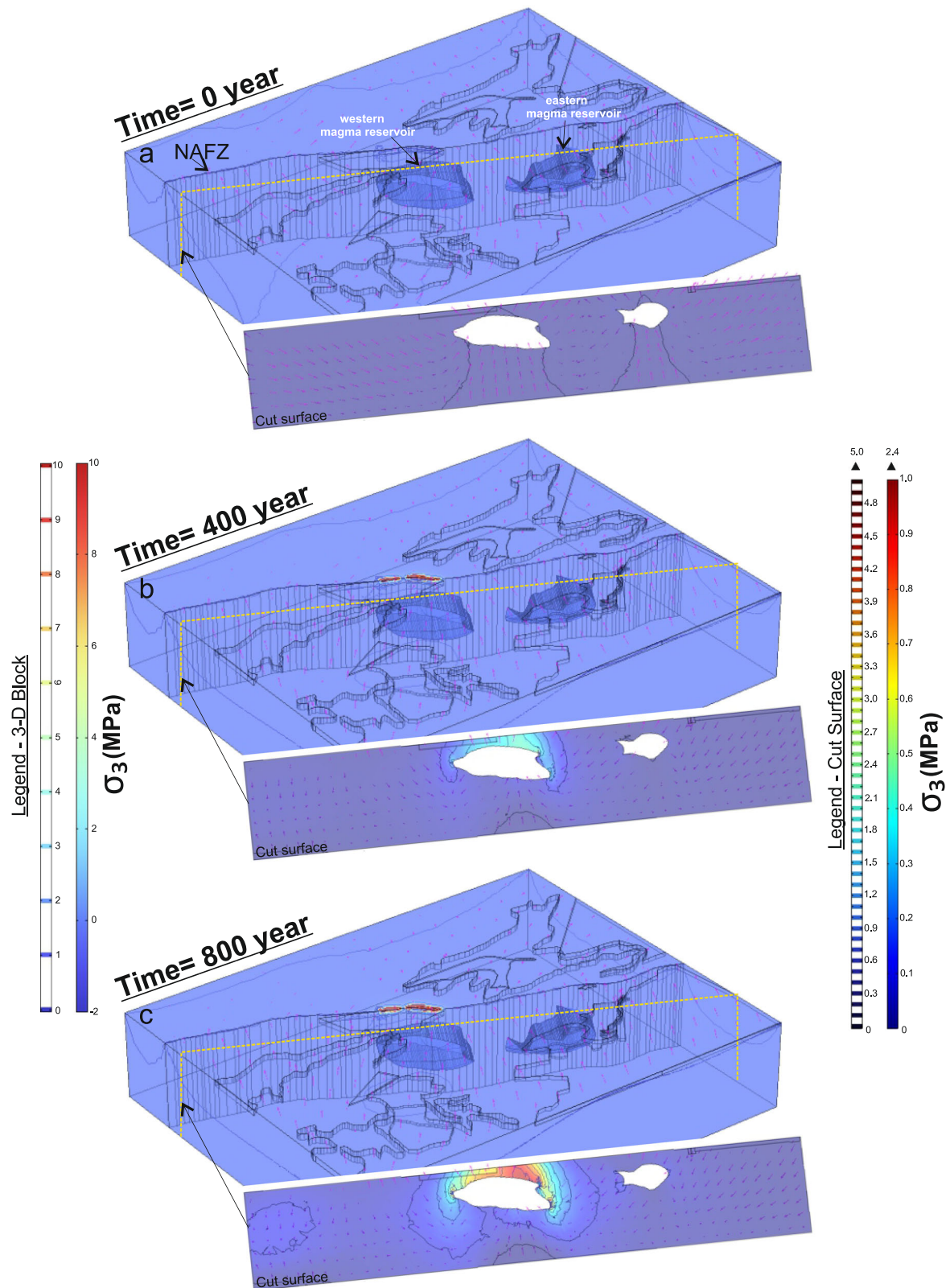


Fig. 3 | Minimum compressive (maximum tensile) principal stress, (σ_3) distributions for the two magma reservoirs under tectonic loading (MEP = 0 MPa). Front-facing cross-sections show σ_3 along the central cut plane of the model block.

Contour lines are referenced to maximum pressure values used in other scenarios. Red arrows denote the orientation of the intermediate principal stress (σ_2). Model geometry and dimensions are shown in Supplementary Fig. 1.

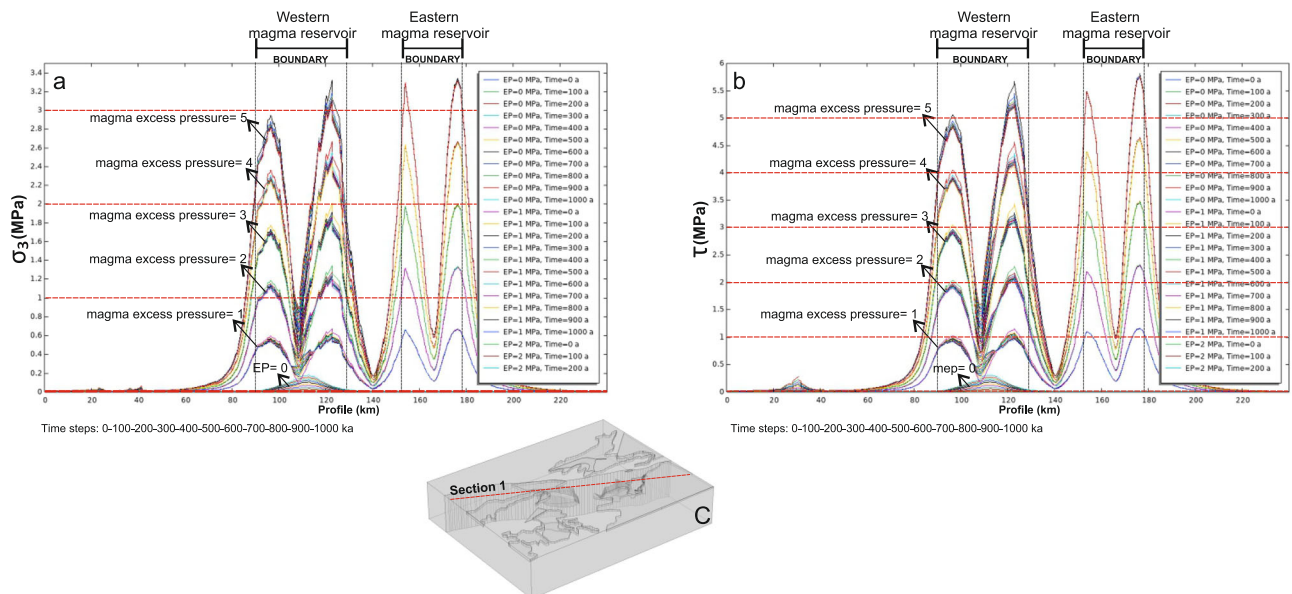


Fig. 4 | Surface stress distribution above the dual magma-reservoir system (Section 1). **a** Maximum principal tensile stress (σ_3) above the western reservoir remains below imposed excess pressure thresholds. **b** Von Mises shear stress (τ)

around the western reservoir margins exceeds critical failure levels after ~1,000 years. **c** Stress around the eastern reservoir remains below critical shear thresholds in most scenarios. Error bars show $\pm 1\sigma$ uncertainty from ensemble model runs ($n = 5$).

This structural configuration is comparable to magma–fault interactions along on-land oceanic transform fault systems, such as the Húsavík–Flátey Fault in North Iceland, where strike-slip kinematics are coupled with dike swarms and localised extensional structures^{43,38}. The Erzincan Basin exhibits similar patterns: asymmetric surface deformation differential melt accumulation and shear-driven stress partitioning across the fault.

The upward migration of stress in our simulations does not necessarily imply that magma rises to shallow crustal levels. As indicated above, at 5–15 km depth, rheological contrasts between the ductile mid-crust and the brittle upper crust, combined with near-surface stress rotation (resulting in stress barriers) and the absence of continuous conduits, partly dissipate relative tensile stresses before magma can ascend. This explains why models yield stress fields that reach the surface, whereas geodetic observations manifest solely as broad, low-amplitude deformation rather than the sharp uplift typical of shallow dyke intrusion^{45,46}. Overall, these results indicate that the observed deformation primarily depends on deep magmatic pressurisation coupled with regional shear, rather than active near-surface intrusion.

While our results highlight the importance of fault-controlled local stresses and pathways in guiding magma ascent, the primary role of regional stress fields, particularly in extensional regimes, in governing dyke propagation is well established^{1,48}. Fault zones may serve as pre-existing mechanical anisotropies that concentrate both shear and tensile stress and facilitate melt migration in general and through dyke propagation in particular. Our integrated approach, combining stress modelling with structural imaging, supports a hybrid mechanism in which both fault architecture and stress concentration contribute to magma emplacement along the NAFZ.

Magma migration and seismicity

Seismicity patterns, including lateral earthquake propagation from ~30 km to ~17 km depth, indicate magma transport guided by pre-existing mechanical boundaries. In the western reservoir, the transition from brittle seismic to aseismic behaviour coincides with high V_p/V_s anomalies, consistent with partially molten conditions (Fig. 2). A similar but weaker reduction in seismicity occurs within the eastern reservoir, where the overlying crust remains more brittle accommodates through fracturing.

Earthquake swarms beneath and around both reservoirs likely mark transient episodes of magma migration, in some cases linked with dyke propagation. Comparable seismicity above and below the western reservoir suggests interaction between melt and the surrounding crust. These clusters represent short-term fluctuations within a much longer-lived magmatic system; magma upwelling and migration beneath the Erzincan Basin and KJT has likely persisted since the inception of the NAFZ (~10 Ma).

Low-velocity and high- V_p/V_s domains with a similar rheological structure are found across Eastern Anatolia—particularly near Lake Van and the KJT^{47,49}. These domains consist of a ductile, melt-bearing lower crust overlain by a brittle, seismogenic upper crust. Seismo–geodetic analyses reveal strong NWW-directed strain accumulation toward the KJT⁵⁰, which matches the shear localisation resolved in our models. Continuous GNSS observations⁵¹ further document co- and pre-seismic deformation along the Erzincan–Karlöva corridor, coinciding with the zones of modelled maximum shear stress. Our tomographic results further align with the regional lithospheric structure. High V_p/V_s domains (≥ 1.85) beneath the Erzincan Basin and the KJT coincide with the thermally weakened, thin lithosphere imaged by Artemieva and Shulgin⁵². Their model indicates increased geotherms and lithospheric thicknesses of 55–70 km, which are favourable conditions for the partial melting of a metasomatised mantle and sustained mid- to upper-crustal melt storage. The shallow melt zones identified here are therefore consistent with the predicted thermal regime.

Together, these seismic, geodetic, and tomographic observations imply that present-day earthquake clusters represent only a snapshot of a long-lived melt-migration network. Their spatial coincidence with V_p/V_s gradients highlights persistent crustal melt pathways that vary in intensity but remain active over geological timescales. Although these fluctuations are unlikely to signal imminent eruption without additional precursors, they reinforce the role of the NAFZ as a first order structural regulator of magma ascent, storage, and associated potential volcanic activity.

Hazard implications for a magma-driven, shear-dominated corridor

The identification of active magma reservoirs beneath a historically active fault system carries profound implications for volcanic hazard assessment in Eastern Anatolia. The western reservoir beneath the Erzincan–Çağlayan area (Fig. 1), continuously approaches mechanical failure thresholds in our

models, even under baseline loading, indicating elevated potential for future unrest. As for the eastern reservoir beneath the Adaklı–Nazımiye–Bingöl region lacks Holocene surface volcanism, its partially molten state, coupled with ongoing seismicity and modelled overpressure indicates a non-negligible possibility of renewed eruptive activity. Geodetic observations⁵¹ documenting long-wavelength uplift in the west and subsidence in the east further support deep magmatic pressurisation interacting with right-lateral shear.

Fault-related volcanic systems such as the Dead Sea Fault Zone, the Husavik–Flatey Fault in Iceland, and oblique sectors of the East African Rift, similarly exhibit prolonged quiescence interrupted by sudden eruptive episodes^{39,53,54}. Our finding that tectonic shear-movement alone can initiate tensile stress and failure that promote dyke propagation—without the need for substantial excess magma pressure in the source reservoir—aligns with these analogues and emphasises the importance of fault-damage zones as composed of numerous small fractures that can be used for dykes to form part of their pathways, particularly if the fractures are vertical, as is common in the damage zones of strike-slip faults. The spatio-temporal evolution of strain and geophysical signatures along the Erzincan–Karlöva corridor resembles these settings. Our numerical simulations demonstrate that even moderate MEP values can accelerate stress focusing along inherited fault structures, enabling surface-reaching stress pathways within a few hundred years and encouraging dyke initiation and propagation.

Pressurised melts and fluids within the NAFZ system may further enhance its seismogenic potential through poro-elastic coupling, promoting unstable slip and amplify rupture^{55–57}. Thus, the Erzincan Basin functions not only a locus of tectonic strain accumulation but also as a magma-driven, shear-dominated fault corridor where crustal failure is intensified by magmatic processes. When considered together, these examples illustrate that fault-generated tensile stress concentration encouraging dike initiation is not unique to the eastern NAFZ. Rather it may represent a fundamental mechanism in transform and transtensional settings globally, where tectonic shear can largely govern stress concentration around reservoirs that allows for magma ascent even at low or zero initial excess-pressure conditions.

The Erzincan–Karlöva corridor also functions as a trans-crustal transfer zone linking the NAFZ and EAFZ, with the KTJ acting as a mechanical and magmatic node—consistent with the observed strain concentration and NWW-directed crustal flow toward the junction^{52,54}. This tectono-magmatic configuration closely resembles other major junctions such as Afar and Iceland, where plate-boundary linkages focus both shear and magmatism. These analogies highlight that the eastern NAFZ operates as an active volcano–seismo–tectonic corridor within the Arabia–Eurasia collision zone, shaped by the combined effects of right-lateral shear, deep melt supply, and crustal weakening.

These findings highlight the urgent need for integrated, real-time monitoring strategies for the Erzincan Basin and the Karlöva Triple Junction that combine geodetic, seismic, and gas-emission observations. Particular priority should be given to the Erzincan–Çağlayan area, where the western reservoir is mechanically unstable, and to the Adaklı–Nazımiye–Bingöl sector (Fig. 1) where the eastern reservoir could reawaken after prolonged quiescence. The Erzincan–Karlöva corridor therefore constitutes a high-hazard volcanic–seismotectonic domain requiring sustained multidisciplinary surveillance.

Methods

We combined local earthquake seismic tomography with three-dimensional, time-dependent finite-element stress modelling to characterise melt storage and fault–magma interactions beneath the Erzincan Basin and adjacent North Anatolian Fault Zone. Full details are provided in the Supplementary Figs. 1–12.

Seismic tomography

Local earthquake seismic tomography was employed to delineate the structure of the crust and upper mantle beneath Eastern Anatolia.

To investigate the crustal seismic structure of eastern Turkey, we analysed P- and S-wave arrival times from regional and local earthquakes recorded by permanent seismic stations (blue triangles in Supplementary Fig. 2). Data were selected within radii of 100 km (events) and 150 km (stations) from the area's centre (39.5°E, 39.7°N). To further select data for tomography, we used two criteria: (1) the number of picks per event should be equal or larger 8, and (2) the maximum residual after the step of source location should be smaller than 0.8 s. The final dataset comprised 3,072 events with 25,305 P- and 17,326 S-wave arrivals (mean 13.9 picks/event). Ray-path coverage and event distributions are shown in Supplementary Fig. 3. Stations and events were extended outside; however, the highest resolution was achieved in the area considered in this study.

For local earthquake tomography, we employed the LOTOS code⁵³, previously validated in regions with analogous observational geometries. While the algorithm's full description is available in prior studies, we highlight its key features and specify critical parameters.

The calculations begin with absolute source location determination using a grid-search method within a 1D reference velocity model. To optimise efficiency, we precomputed tabulated P- and S-wave travel times across a range of epicentral distances and focal depths. Sources were then relocated iteratively using a gradient method combined with a bending algorithm for 3D ray tracing, with this relocation stage repeated after each update of the 3D velocity model during inversion.

The 3D velocity structure was parameterized using nodes distributed adaptively based on ray coverage density. In map view, nodes were arranged in a regular 4 km grid only where ray density exceeded 10% of the average value. Vertical grid spacing varied inversely with ray density, with a minimum constraint of 2 km. To mitigate grid-orientation artefacts, we performed four independent inversions using grids rotated by 0°, 22°, 45°, and 66° respectively, then averaged the resulting models. The ray path distribution and node geometry are illustrated in Supplementary Fig. 2.

We performed the inversion using the LSQR algorithm with QR normalization⁵⁴, implementing both amplitude damping and smoothing constraints for stabilization. The regularization parameters were optimized through synthetic tests (described below), yielding values of 0.05 (damping) and 2 (smoothing) for P-wave data, and 0.2 and 6 for S-wave data respectively. The inversion solved simultaneously for: (1) V_p and V_s anomalies, (2) source coordinates (weight = 5), and (3) origin times (weight = 5).

Following each inversion, we interpolated the resulting V_p and V_s models onto a regular grid for use in subsequent source relocations. The process was repeated for five iterations, balancing computational efficiency with solution stability. This number of iterations was determined to provide optimal convergence while preventing overfitting, as verified through synthetic tests.

The 1D reference velocity model was defined at several depth levels and was linearly interpolated in between. The optimal velocity values were found after several complete runs of the full tomography procedure and recurrent updates of the starting model. Note that we updated only the P-wave velocities; the S-wave velocity in the starting model was calculated using a constant V_p/V_s ratio equal to 1.75. As a result, we obtained a model presented in Table 1, which provides an optimal balance of the positive and negative anomalies.

Results of tomographic inversion with experimental and synthetic data

One main results of this study are the tomographic models derived from seismic data inversion, which provide 3D distributions of P- and S-wave velocity anomalies (δV_p and δV_s) and the V_p/V_s ratio, calculated directly from the inverted V_p and V_s velocities. The validity of this approach is supported by synthetic tests (shown in Supplementary Figs. 5–6) and corroborated by prior studies using the same methodology. The resulting models are presented in horizontal sections (Supplementary Fig. 3) and vertical cross-sections (Supplementary Fig. 4), annotated with major tectonic features. For the main paper, we focus on the V_p/V_s ratio distribution (Supplementary Fig. 2), as this parameter most effectively identifies fluid-

Table 1 | Reference 1D distribution of P wave velocity used to calculate the main tomography model

Depth, km	V_p , km/s
–5	4.50
3	5.22
9	5.69
15	6.06
25	6.28
35	6.65
60	7.95

The S-wave velocity in the reference model is calculated based on a constant value of the $V_p/V_s = 1.75$.

saturated rocks and partial melt zones, critical for understanding magma storage and fault interactions in the North Anatolian Fault Zone.

The final P-wave (V_p) and S-wave (V_s) velocity models revealed prominent low-velocity zones associated with elevated V_p/V_s ratios (> 1.85), interpreted as regions of partial melt and fluid-saturated rocks. These features are most pronounced beneath the Erzincan Basin and the Karlova Triple Junction (KTJ), consistent with areas of known volcanic and tectonic activity.

To evaluate the spatial resolution of our tomography model, we conducted synthetic tests that accurately replicate our experimental inversion workflow. Using the identical source-receiver geometry from our final dataset, we generated a synthetic model by combining our reference 1D velocity model with prescribed 3D anomalies. Synthetic travel times were computed via 3D ray-tracing (bending algorithm) and then contaminated with realistic noise (0.1 s P-wave, 0.2 s S-wave Gaussian errors). We intentionally discarded the known source locations and performed complete event relocation using our standard inversion procedure, including the initial grid-search step. Through iterative parameter optimization, we achieved optimal recovery of the input structures, with these validated parameters subsequently applied to our experimental data inversion. This approach rigorously tests both the spatial resolution and the robustness of our inversion methodology under realistic observational conditions.

Supplementary Fig. 5 presents traditional checkerboard test results using alternating rectangular anomalies with predefined dimensions (30 km lateral size with 10 km intervals, and vertical polarity reversals between 15–20 km depth), featuring $\pm 8\%$ amplitude contrasts (opposite for P- and S-models to accentuate V_p/V_s variations). Supplementary Fig. 5 demonstrates successful recovery of these patterns, showing robust restoration of anomaly polarities at both 5 km and 25 km depths in horizontal views and vertical cross-sections, confirming the tomography's ability to resolve structural transitions in all directions with fair resolution.

In another test presented in Supplementary Fig. 6, we explore the capacity of tomography to recover free-shaped anomalies with realistic shapes. The velocity anomalies were defined in a set of polygonal prisms in certain depth intervals. The values of the P and S wave velocity anomalies as well as the corresponding values of the V_p/V_s ratio are indicated over each anomaly in Supplementary Fig. 6. In the considered model, the distinct anomalies were defined in two depth intervals. The recovery results show fair resolution capacity of the tomography inversion, and the obtained results look similar to the results of experimental data inversion.

The results of all synthetic tests - including both traditional checkerboard patterns and free-form anomaly reconstructions - consistently demonstrate our tomography inversion's robust capacity to recover velocity structures with dimensions and complexity comparable to the key features

discussed in the main article. This validation confirms that the imaged magma reservoirs (with lateral scales of 30–50 km) and their associated V_p/V_s anomalies are well-resolved features rather than inversion artefacts, providing confidence in our interpretations of melt distribution and fault-magma interactions.

Numerical modelling

To simulate the temporal evolution of stress and deformation induced by magma excess pressure and tectonic displacement (fault kinematics), we developed transient finite element models using COMSOL Multiphysics. These models incorporated stratigraphic layering, crustal rheology, and boundary conditions constrained by regional tectonics and geodetic data. Two shallow magma reservoirs were embedded at depths of 4–5 km, while displacement loading along the fault was explicitly imposed to capture fault-displacement induced stress concentration around the reservoirs and stress migration to the surface, even in scenarios where initial magma excess pressure in the reservoirs was set to zero.

Magma excess pressure (MEP) scenarios ranging from 0 to 5 MPa were applied to examine excess-pressure induced stress accumulation. The simulations evaluated the maximum tensile principal stress (σ_3) and von Mises shear stress (τ) fields across time and space, assessing their potential to trigger mechanical failure and, thereby, possibly encourage dyke injection and propagation. Boundary conditions included tectonic loading consistent with observed fault kinematics along the NAFZ.

To investigate the physical and geodynamic conditions of the paired magma reservoir system, various simulations were developed using the finite element software COMSOL Multiphysics 6.2 (www.comsol.com^{57–59}). These models incorporate two distinct crustal magma reservoirs, located to the west and east of the Erzincan Basin, extending from ~5 km depth to greater depths⁶⁰. Model geometries are constrained by field observations and analytical data from the Erzincan-Bingöl-Tunceli region (Supplementary Fig. 1).

The models are designed with two primary geometries, both hosted within a crustal domain measuring $288.5 \times 166.5 \text{ km}^2$ in surface area and extending to a depth of 40 km. The set-up includes two shallow magma reservoirs, each exhibiting irregular three-dimensional geometries approximating an ellipsoidal form. The left reservoir measures $48 \times 22 \times 20 \text{ km}$, while the right reservoir measures $48 \times 32 \times 14 \text{ km}$. The roofs of the western and eastern reservoirs were set at ~4 km and ~5 km, respectively, representing the shallow parts of the tomographically imaged melt columns that extend to the depth of ~15 km. These depths capture the brittle–ductile transition zone most sensitive to regional shear. Model-derived stress patterns indicate that stress concentration above the western reservoir primarily reflects its larger volume and its position beneath the broad, highly fractured fault damage zone, suggesting that chamber geometry and fault-zone rheology may exert stronger control than absolute depth (Supplementary Fig. 7).

The models are heterogeneous and anisotropic, incorporating five distinct horizontal mechanical layers, or stratigraphic units, constrained by regional geological and seismic studies⁵⁸ (Supplementary Fig. 8). The upper crust is primarily composed of limestone, metamorphic rocks, and massive gabbro, with laboratory-determined densities ranging from 2000 to 3300 kg/m^3 ¹.

The Young's modulus (E) for the stratigraphic layers (Supplementary Fig. 8) varies within a reasonable range for rock units at corresponding depths based on the region's geology, with values between 25 GPa and 45 GPa. A constant Poisson's ratio (ν) of 0.25 is applied¹, because this ratio does not vary across these rock types. Furthermore, a discrete, 30-metre-thick mechanically distinct layer has been identified along the fault plane, potentially influencing both the localisation of strain and the mechanical response of the surrounding crust during seismic and magmatic episodes. The fault zone is modelled as the most compliant unit, with Young's modulus and Poisson's ratio values set at 0.1 GPa and 0.33, respectively, based on data from active fault zones^{1,26,57}.

Governing equations for the model set-up

The “Solid Mechanics” interface in COMSOL solves the steady-state form of the equation of motion for linear elastic materials, expressed as:

$$0 = \nabla \cdot \mathbf{S} + \mathbf{F}_v \quad (1)$$

Here, $\nabla \cdot \mathbf{S}$ denotes the divergence of the second Piola-Kirchhoff stress tensor $\mathbf{S}$ which itself is a function of the strain tensor $\boldsymbol{\varepsilon}$, and $\mathbf{F}_v$ is the volume force vector acting on the material. The zero on the left-hand side indicates that, in the steady-state formulation, the net rate of change of stress within a given volume is zero. Further details of these terms are provided in Tabatabaian⁵⁷.

In the Solid Mechanics module of COMSOL Multiphysics, the transient behaviour of linear elastic materials is governed by the time-dependent form of the equation of motion, which explicitly for temporal changes in stress and deformation This is expressed as:

$$\rho \partial^2 \mathbf{u} / \partial t^2 = \nabla \cdot \boldsymbol{\sigma} + \mathbf{F}_v \quad (2)$$

where:

- ρ is the material density (kg/m^3),
- $\mathbf{u}$ is the displacement vector (m),
- t is time (s),
- $\boldsymbol{\sigma}$ is the Cauchy stress tensor (Pa), and
- $\mathbf{F}_v$ is the volume force vector (N/m^3).

Boundary conditions for transient analysis

For the transient analysis, the boundary conditions remain consistent with those defined for the steady-state problem. Tectonic loading was imposed through constant right-lateral shear applied along the lateral model boundaries, representing the long-term motion of the Anatolian block relative to Eurasia. Prescribed velocity values of $+0.95 \text{ cm yr}^{-1}$ (x -direction) and $+0.65 \text{ cm yr}^{-1}$ (y -direction) were applied to the northern block, while -0.95 cm yr^{-1} (x -direction) and $+0.65 \text{ cm yr}^{-1}$ (y -direction) were imposed on the southern block. These values reflect regional geodetic slip rates along the eastern NAFZ and were maintained throughout the full 1,000-year simulation period. Under MEP = 0 conditions, this tectonic shear is the sole driving force for stress redistribution within the model domain.

The upper horizontal boundary was treated as a free surface, incapable of transmitting shear stress. The lower boundary was assigned zero shear stress and zero normal strain, and the lateral boundaries were constrained using prescribed displacement/velocity fields to prevent rigid-body motion while allowing realistic tectonic deformation. The bottom surface was implemented as a roller boundary.

The displacement field $u(x, y, z, t)$ was solved as a time-dependent function to capture the temporal evolution of stress propagation within the crust. Magma reservoirs were represented as geometrically defined cavities based on seismic tomography, with magma excess pressure (MEP)—the pressure in excess of the lithostatic stress—varied between 0 and 5 MPa in separate scenarios (0–1–2–3–4–5 MPa; Supplementary Fig. 7)^{2,61–65}. This range is representative of shallow crustal storage zones close to the surface, where modest overpressure may exert significant influence on fault-zone stress fields. Flat topography was assumed, as its effect on near-surface stress distribution is negligible at the model scale. Stress variations therefore arise solely from tectonic loading, reservoir geometry, and contrasts in host-rock mechanical properties.

Model mesh

The predefined “extremely fine” mesh setting in COMSOL was implemented, using tetrahedral quadratic elements. This mesh configuration results in a maximum element size of 31.3 km, a minimum element size of 5.8 km, and a maximum element growth rate of 1.6. The total number of elements in the two-magma reservoirs/reservoir geometry models was 153,736. The curvature factor was set to 0.7, with a narrow-region resolution of 0.4.

Conclusions

The Erzincan Basin and Karlıova Triple Junction constitute a coupled seismic–magmatic system in which fault architecture critically governs magma storage, stress transfer, and surface deformation. Seismic tomography identifies two distinct crustal reservoirs: a thermally mature, partially molten western reservoir that is mechanically prone to rupture, and an eastern reservoir displaying a lower melt fraction where seismicity concentrates around its margins. Numerical models suggest that tectonic loading alone can drive stress migration from these reservoirs to the surface, with the western system persistently approaching failure thresholds and encouraging dyke injection even under initially zero reservoir excess pressure.

This integrated framework elucidates the pronounced asymmetry in vertical deformation across the NAFZ—uplift in the west and subsidence in the east, particularly in the Erzincan–Çağlayan segment, and highlights the tight coupling between right lateral shear, associated tensile stress concentration, and the potential for reservoir rupture and dyke injection. The resulting configuration enhances both seismic and volcanic hazards, reinforcing the need for integrated, real-time monitoring. Priority should be given to the mechanically unstable Erzincan–Çağlayan sector, where future unrest is most imminent, and to the Adaklı–Nazimiye–Bingöl region, where long-lived melt storage poses a latent but non-negligible hazard. Collectively, these insights establish the eastern NAFZ as a natural laboratory for understanding fault-guided magma ascent for assessing and its cascading implications for continental transform fault systems.

Data availability

The datasets used in this study are archived and publicly accessible via the Kandilli Observatory and Earthquake Research Institute (KOERI) phase-reading bulletins (http://www.koeri.boun.edu.tr/sismo/2/bultenler/aylik-bulten-faz-okumalari/faz_okumalari/) and the Disaster and Emergency Management Authority of Türkiye (AFAD) earthquake bulletin database (<https://deprem.afad.gov.tr/ddabulten>). Numerical modelling was performed using COMSOL Multiphysics (<https://www.comsol.com/>); the datasets and parameter values used for the simulations are described in the Methods section and are additionally summarised in Supplementary Figs. 7 and 8.

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References

- Gudmundsson, A. *Volcanotectonics*. Cambridge Univ. Press (2020).
- Gudmundsson, A. *Rock Fractures in Geological Processes* (Cambridge Univ. Press, 2011).
- Tibaldi, A. Structure of volcano plumbing systems: A review of multi-parametric effects. *J. Volcanol. Geotherm. Res.* **298**, 85–135 (2015).
- Gudmundsson, A., Brynjolfsson, S. & Jonsson, M. T. Structural analysis of a transform fault-rift zone junction in North Iceland. *Tectonophysics* **220**, 205–221 (1993).
- Fjäder, K., Gudmundsson, A. & Forslund, T. Dikes, minor faults and mineral veins associated with a transform fault in North Iceland. *J. Struct. Geol.* **16**, 109–119 (1994).
- Stuart, C., Völvi, T., Chastin, S., Gudmundsson, A. & Stefánsson, R. Indication of high pore-fluid pressures in a seismically-active fault zone. *Geophys. J. Int.* **151**, F1–F5 (2002).
- Gudmundsson, A. Propagation paths of fluid-driven fractures in layered and faulted rocks. *Geol. Mag.* **159**, 1978–2001 (2022).
- Gudmundsson, A. Stress fields associated with oceanic transform faults. *Earth Planet. Sci. Lett.* **136**, 603–614 (1995).
- Şengör, A. M. C. et al. The North Anatolian fault: a new look. *Annu. Rev. Earth Planet. Sci.* **33**, 37–112 (2005).
- Westaway, R. & Arger, J. Kinematics of the Malatya–Ovacik fault zone. *Geodinamica Acta* **14**, 103–131 (2001).

11. Şengör, A. M. C., Görür, N. & Şaroğlu, F. Strike-slip faulting and related basin formation in zones of tectonic escape: Turkey as a case study. In: Biddle, K. T. (Ed.), *Strike-slip Deformation, Basin Formation, and Sedimentation*, Soc. Econ. Paleontol. Spec. Publ. Editor. Christie-Blick, N. Oklahoma: Society of Economic Paleontologists and Mineralogists, Special Publication, pp. 227–264 (1985).
12. Reilinger, R. et al. GPS constraints on continental deformation in the Africa–Arabia–Eurasia collision zone. *J. Geophys. Res.* **111**, B05411 (2006).
13. Karaoğlu, Ö., Selçuk, A. S. & Gudmundsson, A. Tectonic controls on the Karlova triple junction (Turkey): implications for tectonic inversion and the initiation of volcanism. *Tectonophysics* **694**, 368–384 (2017).
14. Şengör, A. M. C. & Natal'in, B. A. Turcic-type orogeny and its role in the making of the continental crust. *Annu. Rev. Earth Planet. Sci.* **24**, 263–337 (1996).
15. Biryol, B. C., Beck, S. L., Zandt, G. & Özacar, A. A. Segmented African lithosphere beneath the Anatolian region inferred from teleseismic tomography. *Geophys. J. Int.* **184**, 1037–1057 (2011).
16. Pearce, J. A. et al. Genesis of collision volcanism in Eastern Anatolia, Turkey. *J. Volcanol. Geotherm. Res.* **44**, 189–229 (1990).
17. Karaoğlu, Ö. et al. Petrological evolution of Karlova-Varto volcanism (Eastern Turkey): Magma genesis in a transtensional triple-junction tectonic setting. *Lithos* **364**, 105524 (2020).
18. Özener, H. et al. Kinematics of the eastern part of the North Anatolian Fault Zone. *J. Geodyn.* **49**, 141–150 (2010).
19. Tatar, O. et al. Crustal deformation and kinematics of the Eastern Part of the North Anatolian Fault Zone from GPS measurements. *Tectonophysics* **518**, 55–62 (2012).
20. Aktuğ, B. et al. Deformation of Central Anatolia: GPS implications. *J. Geodyn.* **67**, 78–96 (2013).
21. Weiss, J. R. et al. High-resolution surface velocities and strain for Anatolia from Sentinel-1 InSAR and GNSS data. *Geophys. Res. Lett.* **47**, e2020GL087376 (2020).
22. Faccenna, C. et al. Mantle dynamics in the Mediterranean. *Rev. Geophys.* **52**, 283–332 (2014).
23. Confal, J. M. et al. Influence of upper mantle anisotropy on isotropic P-wave tomography images obtained in the Eastern Mediterranean region. *J. Geophys. Res. Solid Earth* **125**, e2019JB018559 (2020).
24. Kaypak, B. Three-dimensional VP and VP/VS structure of the upper crust in the Erzincan Basin (Eastern Turkey). *J. Geophys. Res.* **113**, B07307 (2008).
25. Ozer, C., Ozyazicioglu, M., Gok, E. & Polat, O. Imaging the crustal structure throughout the East Anatolian Fault Zone, Turkey, by local earthquake tomography. *Pure Appl. Geophys.* **176**, 2235–2261 (2019).
26. Karaoğlu, Ö., Browning, J., Salah, M. K., Elshaafi, A. & Gudmundsson, A. Depths of magma chambers at three volcanic provinces in the Karlova region of Eastern Turkey. *Bull. Volcanol.* **80**, 1–17 (2018).
27. Wang, H. et al. Isotropic and anisotropic P wave velocity structures of the crust and uppermost mantle beneath Turkey. *J. Geophys. Res. Solid Earth* **125**, e2020JB019566 (2020).
28. Jaxybulatov, K. et al. A large magmatic sill complex beneath the Toba caldera. *Science* **346**, 617–619 (2014).
29. Greenfield, T., White, R. S. & Roecker, S. The magmatic plumbing system of the Askja central volcano, Iceland. *J. Geophys. Res. Solid Earth* **121**, 7211–7229 (2016).
30. Türkoğlu, E., Unsworth, M. & Bulut, F. & Çağlar, İ. Crustal structure of the North Anatolian and East Anatolian fault systems from magnetotelluric data. *Phys. Earth Planet. Inter.* **241**, 1–14 (2015).
31. Barka, A. & Gülen, L. Strike-slip tectonics and basin formation in the Erzincan Basin. *Tectonophysics* **167**, 211–220 (1989).
32. Akpınar, Z. Erzincan Basin tectonic evolution from paleomagnetic and potential field data. PhD thesis, Cumhuriyet Univ., Sivas (2016).
33. Karslı, O. et al. Elemental and Sr–Nd–Pb isotopic geochemistry of Quaternary volcanism in the Erzincan Basin, Eastern Turkey: evaluation of basalt–lower crust interaction. *Lithos* **106**, 55–70 (2008).
34. Delph, J. R., Zandt, G. & Beck, S. L. A new approach to obtaining a 3D shear wave velocity model of the crust and upper mantle: An application to eastern Turkey. *Tectonophysics* **665**, 92–100 (2015).
35. Van Avendonk, H. J. A., Harding, A. J., Orcutt, J. A. & McClain, J. S. Contrast in crustal structure across the Clipperton transform fault from travel time tomography. *J. Geophys. Res. Solid Earth* **106**, 10961–10981 (2001).
36. Lees, J. M. Seismic tomography of magmatic systems. *J. Volcanol. Geotherm. Res.* **167**, 37–56 (2007).
37. Karslı, O. Pre-eruptive conditions revealed by mega- and phenocryst compositions from Quaternary Erzincan Volcanics, Eastern Turkey: insights into magma processes. *Geochemistry* **66**, 277–305 (2006).
38. Gregg, P. M., De Silva, S. L., Grosfils, E. B. & Parmigiani, J. P. Catastrophic caldera-forming eruptions: thermomechanics and implications for eruption triggering and maximum caldera dimensions on Earth. *J. Volcanol. Geotherm. Res.* **241**, 1–12 (2012).
39. Annen, C., Blundy, J. D., Leuthold, J. & Sparks, R. S. J. Construction and evolution of igneous bodies: towards an integrated perspective of crustal magmatism. *Lithos* **230**, 206–221 (2015).
40. Wright, T. J. et al. Geophysical constraints on the dynamics of spreading centres from rifting episodes on land. *Nat. Geosci.* **5**, 242–250 (2012).
41. Satow, C. et al. Eruptive activity of the Santorini volcano controlled by sea-level rise and fall. *Nat. Geosci.* **14**, 586–592 (2021).
42. Kavanagh, J. L., Menand, T. & Sparks, R. S. J. An experimental investigation of sill formation and propagation in layered elastic media. *Earth Planet. Sci. Lett.* **245**, 799–813 (2006).
43. Matthews, S. W. et al. A dynamic mid-crustal magma domain revealed by the 2023 to 2024 Sundhnúkgígur eruptions in Iceland. *Science* **386**, 309–314 (2024).
44. Bazargan, M. & Gudmundsson, A. Dike-induced stresses and displacements in layered volcanic zones. *J. Volcanol. Geotherm. Res.* **384**, 189–205 (2019).
45. Toker, M. & Şahin, Ş. Crustal Poisson's ratio tomography and velocity modeling across tectono-magmatic lake regions of Eastern Anatolia (Turkey): New geophysical constraints for crustal tectonics. *J. Geodyn.* **131**, 101651 (2019).
46. Bazargan, M. & Gudmundsson, A. Stresses and displacements in layered rocks induced by inclined (cone) sheets. *J. Volcanol. Geotherm. Res.* **401**, 106965 (2020).
47. Rivalta, E., Taisne, B., Bungler, A. P. & Katz, R. F. A review of mechanical models of dike propagation: Schools of thought, results and future directions. *Tectonophysics* **638**, 1–42 (2015).
48. Toker, M. & Şahin, Ş. Upper-to mid-crustal seismic attenuation structure above the mantle wedge in East Anatolia, Turkey: Imaging crustal scale segmentation and differentiation. *Phys. Earth Planet. Inter.* **329**, 106908 (2022).
49. Toker, M. & Pinar, A. New strain configuration of convergence in the Arabia–Eurasia collisional zone: A comprehensive analysis of large shear zones inferred from geodetic and seismic observations. *J. Asian Earth Sci.* **271**, 106235 (2024).
50. Dokukin, P., Güvenaltın, M. A., Kaftan, V. & Toker, M. Co- and pre-seismic crustal deformations related to large earthquakes between years of 2009 and 2023 using continuous CORS-TR GNSS observations in the Anatolian diagonal (Turkey). *Russ. J. Earth Sci.* **23**, 5005 (2023).
51. Artemieva, I. M. & Shulgin, A. Geodynamics of Anatolia: Lithosphere thermal structure and thickness. *Tectonics* **38**, 4465–4487 (2019).
52. Keir, D. et al. Lower crustal earthquakes near the Ethiopian rift induced by magmatic processes. *Geochem. Geophys. Geosyst.* **10**, Q0AB05 (2009).

53. Dal Zilio, L., Hegyi, B., Behr, W. & Gerya, T. Hydro-mechanical earthquake cycles in a poro-visco-elasto-plastic fluid-bearing fault structure. *Tectonophysics* **838**, 229516 (2022).
54. Koulakov, I. LOTOS code for local earthquake tomographic inversion: Benchmarks for testing tomographic algorithms. *Bull. Seismol. Soc. Am.* **99**, 194–214 (2009).
55. Paige, C. C. & Saunders, M. A. LSQR: An algorithm for sparse linear equations and sparse least squares. *ACM Trans. Math. Softw.* **8**, 43–71 (1983).
56. Zienkiewicz, O. C. The Finite Element Method (McGraw-Hill, 1979).
57. Deb, K. Optimization for Engineering Design: Algorithms and Examples. (Prentice-Hall, 2006).
58. Tabatabaian, M. COMSOL for Engineers (Mercury Learning & Information, 2014).
59. Karaoğlu, Ö., Bayer, Ö., Turgay, M. B. & Browning, J. Thermomechanical interactions between crustal magma chambers in complex tectonic environments: Insights from Eastern Turkey. *Tectonophysics* **793**, 228607 (2020).
60. Gudmundsson, A. Deflection of dykes into sills at discontinuities and magma-chamber formation. *Tectonophysics* **500**, 50–64 (2012).
61. Gaffney, E. S., Damjanac, B. & Valentine, G. A. Localization of volcanic deformation and rupture by heterogeneous host rocks. *J. Geophys. Res.* **112**, B09307 (2007).
62. Gudmundsson, A. How local stresses control magma-chamber ruptures, dyke injections, and eruptions in composite volcanoes. *Earth-Sci. Rev.* **79**, 1–31 (2006).
63. Hobé, A. et al. Tomographic and volcanotectonic control on the 2021–2023 Fagradalsfjall eruptions, Iceland. *Sci. Rep.* **15**, 16455 (2025).
64. Karaoglu, O., Browning, J., Bazargan, M. & Gudmundsson, A. Numerical modelling of triple-junction tectonics at Karliova, Eastern Turkey, with implications for regional magma transport. *Earth Planet. Sci. Lett.* **452**, 157–170 (2016).
65. Gerbault, M. Pressure conditions for dike propagation through heterogeneous crust. *J. Geophys. Res.* **117**, B05205 (2012).

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Author contributions

ÖK: designed the study, conducted field investigations, performed numerical modelling, and wrote the initial draft of the manuscript. IK: carried out the seismic tomography modelling, contributed to the tomography

sections of the manuscript, and assisted with editing. TE: collected and evaluated the earthquake dataset for seismic tomography, contributed to the tomography sections, and assisted with editing. MB: assisted with the numerical modelling and contributed to manuscript editing. AG: contributed to the interpretation of results, manuscript editing, and review. TG: contributed to the interpretation of results and manuscript review. LDZ: contributed to the interpretation of results and manuscript review.

Competing interests

The authors declare no competing financial interests. [Luca Dal Zilio] is an Editorial Board Member for Communications Earth & Environment, but was not involved in the editorial review of, nor the decision to publish this article.

Additional information

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