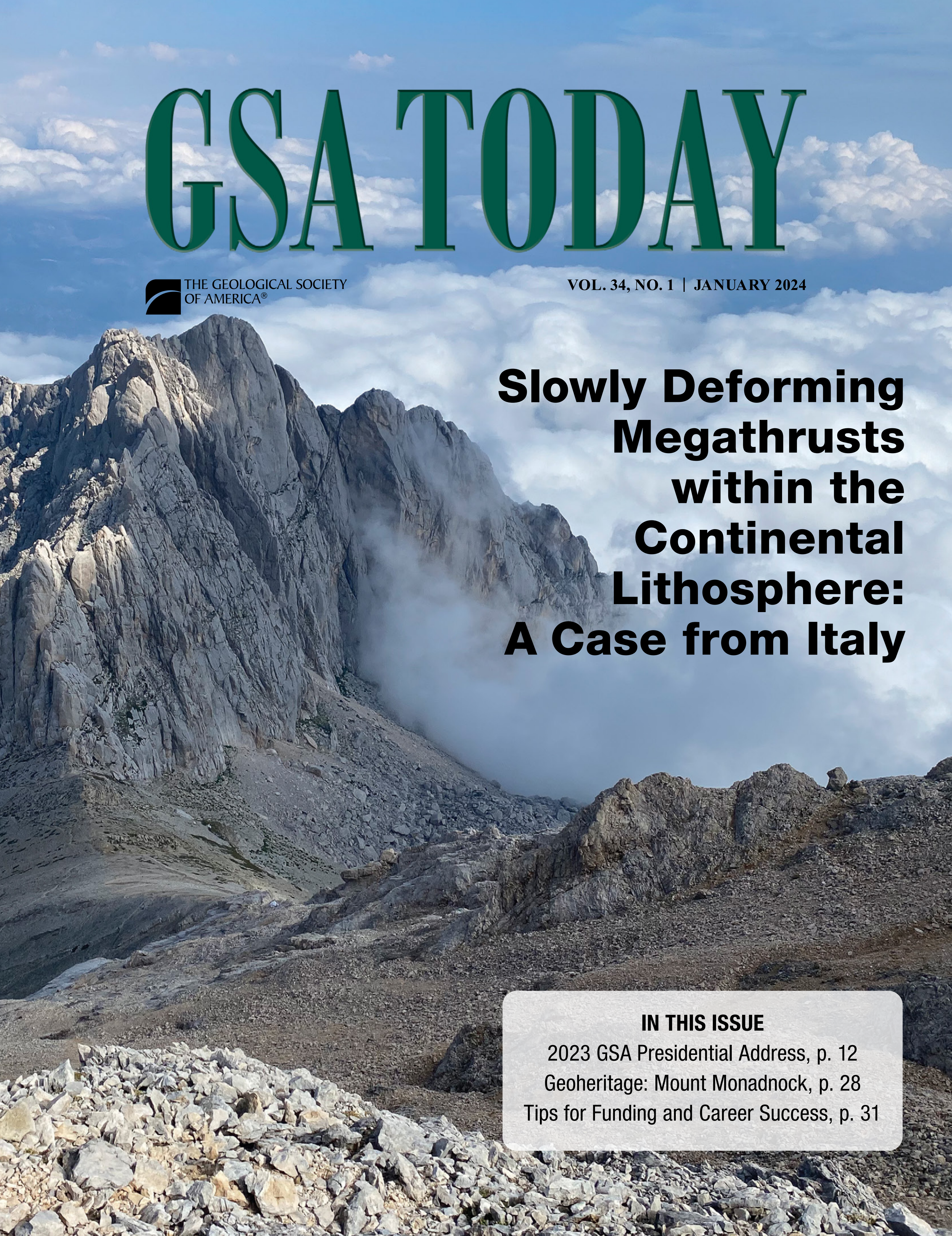

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Slowly Deforming Megathrusts within the Continental Lithosphere: A Case from Italy

IN THIS ISSUE

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Slowly Deforming Megathrusts within the Continental Lithosphere: A Case from Italy

Giusy Lavecchia, Federico Pietrolungo, Simone Bello, Donato Talone, Claudia Pandolfi, Carlo Andrenacci, Andrea Carducci, and *Rita de Nardis,** DiSPuTer, Università G. d'Annunzio Chieti-Pescara, 66100 Chieti, Italy; and CRUST, Centro InteRUniversitario per l'analisi Sismotettonica Tridimensionale, 66100 Chieti, Italy

ABSTRACT

The Late Pliocene–Quaternary Outer Thrust System of the Apennine-Maghrebides fold-and-thrust belt extends ~2000 km from northern Italy to Sicily. Its northernmost arc is seismically active and represents a test case to study geometries and seismogenesis of slowly deforming megathrusts developed within the continental lithosphere. Two distinct SW-dipping reverse shear zones (T1 and T2) in the Outer Thrust System of eastern Central Italy have been recently unveiled thanks to geological and integrated seismological information. These shear zones penetrate the Adria continental lithosphere to a maximum depth of ~60 km, with an outward convex shape associated with an outward-diverging radial pattern.

This paper presents new constraints on the megathrusts' geometry in light of a novel microseismic catalog (from 2009–2022) specifically focused on the compressional volume. Further details in the reconstruction of T1 and T2 are derived from a recent compressional seismic sequence (November 2022, M_W 5.5) located in the Adriatic offshore. It activated the outermost T1 upper crustal segment with pure compressional kinematics and illuminated T2 at lower crustal depths. We integrate geological sections, seismic lines, serial hypocentral cross sections, and focal mechanisms to build a detailed nonplanar 3-D model of the thrusts involved. In addition, we build Coulomb stress scenarios for analyzing the possibility of the static interplay between the upper crust T1 segment activated by the 2022 sequence and the underlying T2 crust segment. The overall results may be relevant for assessing seismic hazards in areas with multi-depth active structures and for gaining insights into plate tectonic dynamics.

INTRODUCTION

Megathrusts are reverse shear planes along subduction boundaries that can cause giant earthquakes ($M_W \geq 8.5$; Calais et al., 2016; Sippl et al., 2021). They are characterized by a long subduction zone with thick trench sediments, which promotes extensive lateral rupture propagation (Brizzi et al., 2018). While typically found in subduction zones, potentially seismogenic megathrusts can also develop within the continental lithosphere. We may consider two end-members: (1) highly deforming structures, such as the Himalayan collisional belt with thrust associated with strong upper crust earthquakes (e.g., 2015 Gorkha event, M_W 7.8; Elliott et al., 2016); and (2) slowly deforming continental regions (SDCR), such as the Mongolian region of the North China Craton, with long periods of seismic quiescence (Bollinger et al., 2021) or the Outer Thrust System (OTS) of Italy at the front of the Miocene to Quaternary Apennine-Maghrebides compressional belt, with moderate multi-depth earthquake activity (de Nardis et al., 2022).

The OTS is located within the active circum-Mediterranean contractional domain, which includes various fold-and-thrust systems, such as the southern Alps, Apennine-Maghrebides, Betics, and Dinarides-Hellenides. Seismogenic compression predominates at crustal depths (<35–40 km; Figs. 1A and 1B) but is also present within the uppermost mantle (35–70 km).

In central Italy, the basal thrust of the Adriatic fold-and-thrust belt is a known intra-continental shear zone that propagates at a low angle across the continental crust up to ~35 km beneath the Apennines (ABT in Lavecchia et al., 2003). The typical ABT thick-skinned style is well revealed by the CROP-03 near-vertical reflection profile (Pauselli et al., 2006). A blind lithospheric-scale megathrust sited beneath the ABT has been recently unveiled within the lower crust and upper mantle (25–60 km; de Nardis et al., 2022; Figs. 1C and 1D). Both thrusts, here referred to as T1 and T2, exhibit reverse-type microseismicity and minor thrust and strike-slip sequences with moderate historical and instrumental earthquakes (up to M_W 6.0–6.5; Rovida et al., 2022).

In November 2022, a moderate thrust sequence (M_W 5.5) activated the outermost upper crust splay of T1 offshore of Pesaro (Fig. 1B). This sequence, here called Bice after the name of the nearest deep drilling well (Progetto ViDEPI, 2016), is noteworthy for several reasons. First, it activated a previously aseismic T1 segment, providing new geometric and kinematic constraints. Second, it occurred where long-term deformation can be well reconstructed using available geological information. Finally, the Bice sequence illuminated T1 at depths of ~6–10 km and the underlying T2 portion at depths of ~20–25 km, suggesting the possibility of concurrent activity between the two thrusts.

In this paper, the fault releasing the Bice sequence was identified using seismic lines and seismicity data. A high-quality microseismic earthquake catalog for 2009–2022 (see Data Set S1 in the Supplemental Material[1]) was compiled to better constrain the geometry of T1 and T2. Coulomb scenarios of static stress propagation were also

[1]Supplemental Material. Figures S1–S8: Additional seismic activity models. Data Set S1: Catalog of high-quality hypocenter data. Please visit https://doi.org/10.1130/GSAT.S.24645996.v1 to access the supplemental material, and contact editing@geosociety.org with any questions.

* rita.denardis@unich.it

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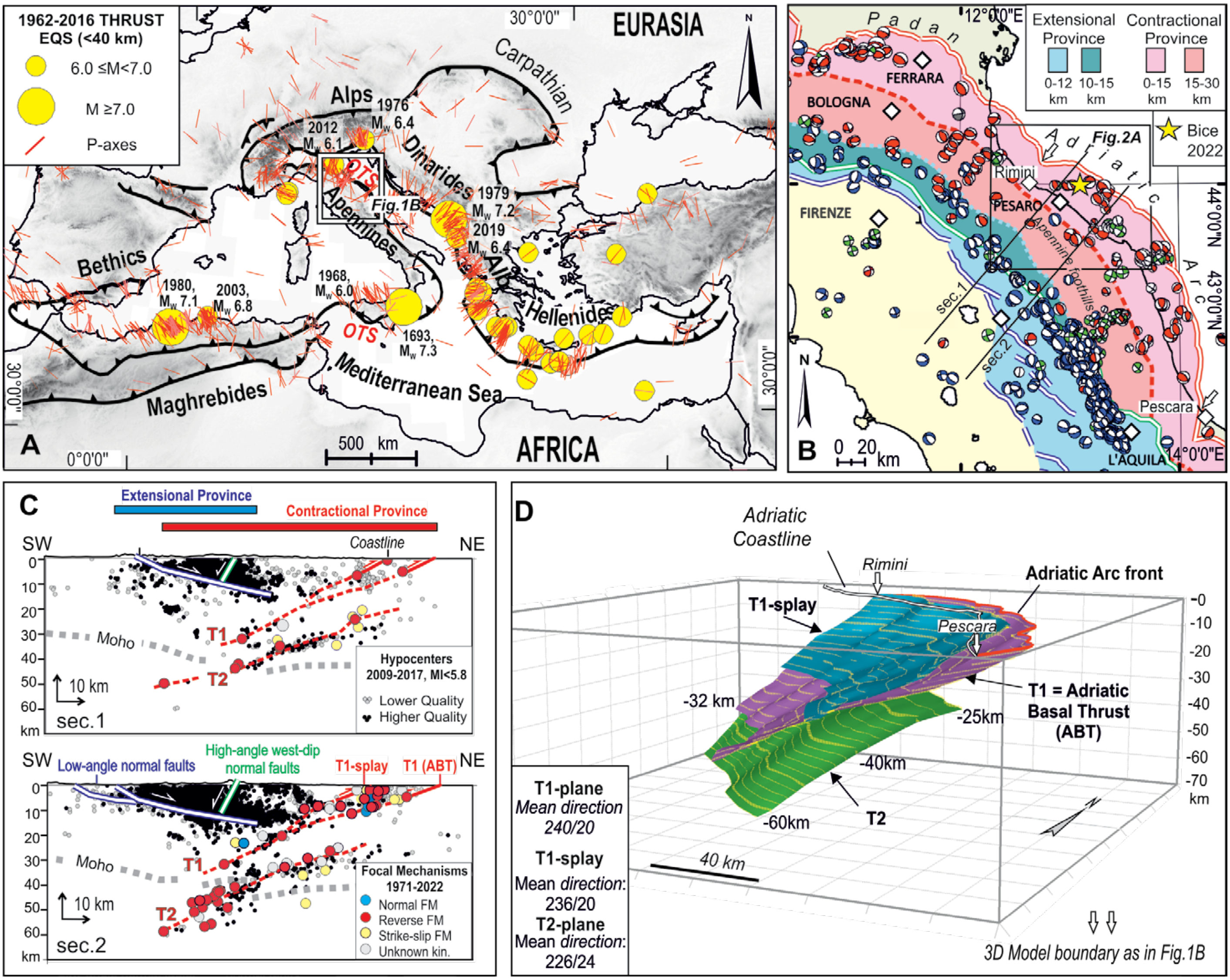

Figure 1. Seismotectonic framework. (A) Circum-Mediterranean crustal thrust earthquakes (World Stress Map database, Heidbach et al., 2018). (B) Seismotectonic provinces and focal mechanisms 1971–2022, depth <40 km (updated after Lavecchia et al., 2021). (C) Hypocentral sections with focal mechanisms and interpolated fault traces (dashed red lines), after de Nardis et al. (2022; projection semi width = 20 km, traces in Fig. 1B). (D) 3-D fault model of T1 and T2 megathrusts from de Nardis et al. (2022).

employed to investigate the hypothesis of interconnected activity between T1 and T2.

REGIONAL SEISMOTECTONIC FRAMEWORK

Late Pliocene–Quaternary active contraction in peninsular Italy is observed along with the OTS, which extends ~2500 km from the Padan region to Sicily (Fig. 1A). Along-strike, the OTS is characterized by two second-order major outer convex arcs: the NNE-to-ENE–verging northern Padan-Adriatic Arc and the SE-to-S–verging southern Ionian-Sicilian arc, linked by a linear segment in the southern Apennines (Petricca et al., 2019; Lavecchia et al., 2021). A similar arcuate pattern, at least to the base of the crust, is well depicted from the Moho contour-depth map, highlighting a deep connection between shallow and deep arcuate features (Cassinis et al., 2003). The Padan-Adriatic arc is organized in several third-order arcuate outer convex fold-and-thrust belts (e.g., Livani et al., 2018; Tibaldi et al., 2023). The central one, referred to as the Adriatic Arc, extends from Rimini offshore to Pescara for ~250 km (Fig. 1B). Perpendicular to strike, the Adriatic Arc is organized in two near-parallel and eastward rejuvenating, largely blind, major fold-and-thrust domains (Fig. S1A in the Supplemental Material). The internal domain is late Pliocene to Quaternary in age; it develops at the hanging wall of a regional inner splay of T1 (hereinafter T1-splay) and runs along and close to the Marche-Adriatic coastline. The external domain is Quaternary in age; it develops at the T1 hanging wall and runs entirely offshore, several kilometers east of the coastline.

Geological slip rates in the order of a few mm/yr characterized the Padan-Adriatic Arc in late Pliocene to early Pleistocene times, with a slip-rate deceleration to a few hundredths of mm/yr since Calabrian times (~1.0–1.5 m.y.; Maesano et al., 2015; Gunderson et al., 2018; Panara et al., 2021). Geodetic velocities show that present shortening occurs both beneath the Apennine Mountains range front at a rate of ~3 mm/yr

(Bennett et al., 2012) and along the Apennine frontal thrusts in a SW-NE direction at rates of 1.5–2.5 mm/yr, decreasing to ~0.5 mm/yr, corresponding to the outermost structures (Pezzo et al., 2020).

Available regional seismotectonic zonations (DISS Working Group, 2021; Lavecchia et al., 2021) highlight the ongoing contractional activity that occurs at upper-crustal depth within the Padan-Adriatic Province and deepens westward, reaching lower crust depths beneath the Apennine foothills (Figs. 1B and S1A). The fold structures are locally displaced by N-S right-lateral and E-W left-lateral strike-slip faults, splaying from the common basal detachment and functional to accommodate local arcuate shapes. The strike-slip deformation is synkinematic with the compressional one under a common near-horizontal SW-NE–shortening direction (de Nardis et al., 2022). Historical and instrumental seismic activity never exceeds M_W ~6.0–6.5 (Rovida et al., 2022; Latorre et al., 2023), with seismological strain rate values in the order of a few hundredths of mm/yr (Visini et al., 2010).

As during the whole Neogene–Quaternary history of outward migration of the Tyrrhenian-Apennine system, the ongoing contractional deformation is contemporaneous with near coaxial extension in the rear along the axis of the Apennine Mountains (Picotti and Pazzaglia, 2008; Barchi, 2010). The Extensional Province is characterized by a system of en-echelon, east-dipping, low-angle faults that propagate to depths of ~15 km and by synthetic and antithetic high-angle faults responsible for moderate to large earthquakes (M_W up to ~7.0; e.g., Trippetta et al., 2019; Lavecchia et al., 2021).

EARTHQUAKE DATA

The Bice Sequence

The Bice epicentral area is located ~35 km offshore Pesaro, within the external fold-and-thrust domain at the T1 hanging wall (Figs. 2A and S1A). Although largely blind, the geometry of such a system is well known at shallow depths (<5–6 km) because of the large number of commercial seismic lines

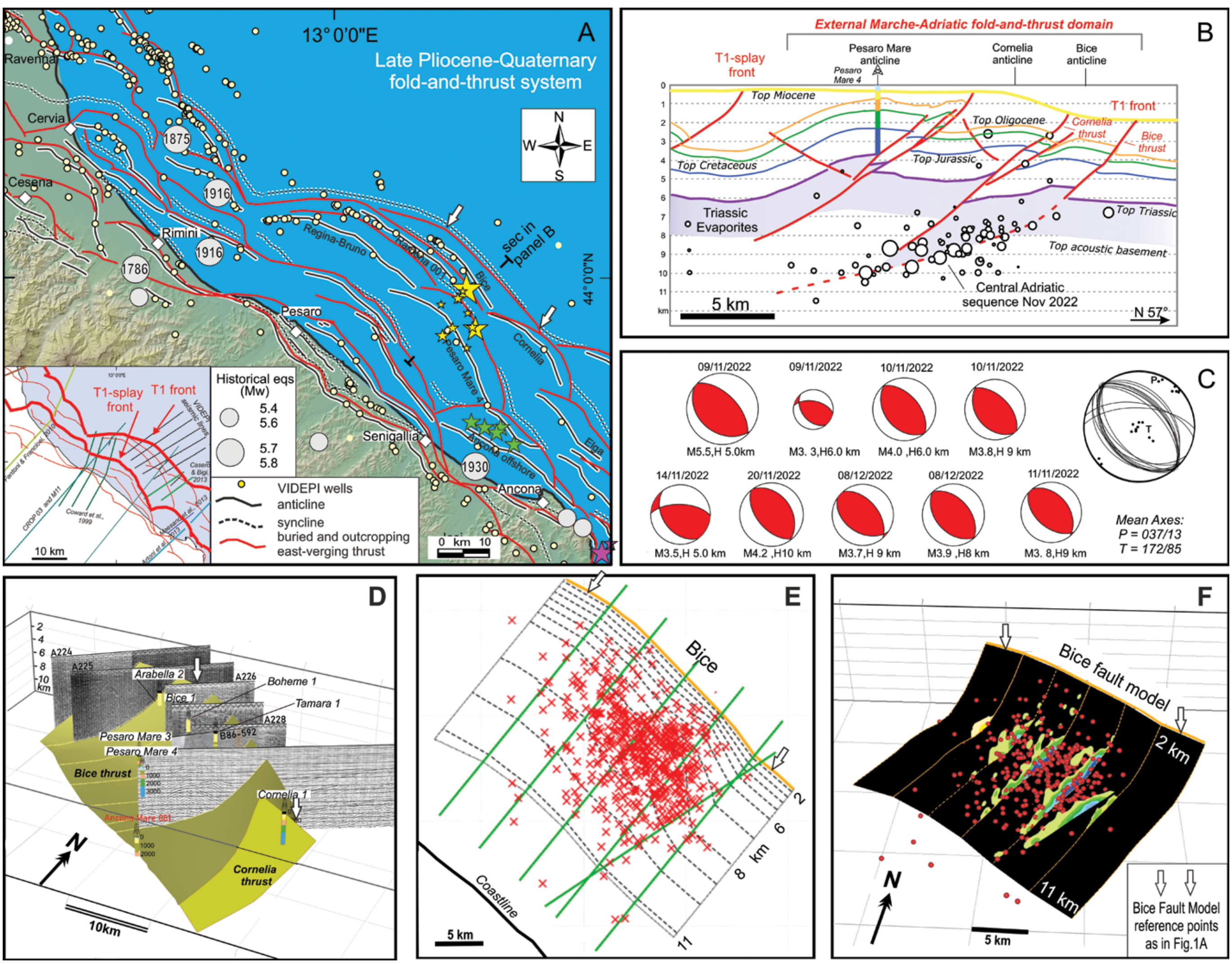

Figure 2. Tectonic framework and 3-D fault model of the Bice seismic sequence. (A) Marche-Adriatic late Pliocene–Quaternary fold-and-thrust system with historical earthquakes (Rovida et al., 2022) and major instrumental events (Bice 2022 = yellow stars: M_L 3.8–5.5 from http://terremoti.ingv.it/; Ancona 1972 = green stars: M_L 4.6–4.8; Ancona 2013 = purple stars: M_L 5.1 and 4.5). (B) Interpretative geological section (after Casero and Bigi, 2013) with Bice hypocenters in section view (semi-width 2.5 km). (C) Bice Time Domain Moment Tensor (TDMT) focal solutions from http://terremoti.ingv.it/. (D) 3-D view of ViDEPI seismic lines, Bice, and Cornelia thrust surfaces. (E) Bice epicentral distribution (9 November 2022–25 December 2022, 1.0 ≤M_L ≤5.5, depths ≤11 km) with traces of hypocentral serial sections and depth contour lines of the Bice fault model. (F) Bice 3-D-fault model with earthquake density contours projected along the sections (green lines in Fig. 2E). More details are in Figs. S2, S3, and S4 (see text footnote 1).

and boreholes available since the 1960s for oil exploration (e.g., Casero and Bigi, 2013).

The sequence started on 9 November 2022 with two major offshore events (M_W 5.5 and 5.2) enucleated within 1 min ~8 km away in map view (Figs. 2A and S2). The sequence ended on 15 January 2023 (http://terremoti.ingv.it/; Fig. S2). During the first ten days, ~395 earthquakes occurred ($0.9 \leq M_l \leq 4.0$), identifying a SW-dipping low-angle (~20°) seismogenic volume at depths between ~6–7 and 10–11 km (Fig. 2B).

During the overall time interval of the Bice sequence and within the same epicentral area, the Istituto Nazionale di Geofisica e Vulcanologia (INGV) seismic network also recorded background seismic activity at depths of 20–30 km ($1.0 \leq M_l \leq 2.8$; Fig. S2). The focal mechanisms of the sequence were almost pure dip-slip with an average SW-NE near-horizontal average P-axis (Fig. 2C), consistent with the ~N040 max horizontal stress direction calculated from breakouts (Montone and Mariucci, 2023).

The Megathrust Seismicity

The geometry of the T1 and T2 megathrusts, first outlined by de Nardis et al. (2022; Fig. 1D), is here further constrained and detailed in light of a novel compilation of high-quality data recorded by the Central Eastern Italy Seismometric Network (ReSIICO; Cattaneo et al., 2019) in the time interval from 2 August 2009 to 30 September 2022. The seismic events, having $0.0 \leq M_l \leq 5.8$ and depths <60 km, were recorded with good coverage by 103 seismic ReSIICO stations integrated with the Italian seismic network (RSN). The events were relocated using the probabilistic nonlinear global search inversion approach of Lomax et al. (2000). Methodologies for relocation and quality of the seismic data are described in de Nardis et al. (2022).

From the 2009–2022 data set**,** we selected a sub–data set of events located within a SW-dipping crustal volume between 10 km at the roof of T1 and 10 km at the bed of T2.

Such a novel microseismic catalog, representative of the lithospheric scale compressional seismogenic volume associated with the OTS of Central Italy, is made available in the Supplemental Material (Data Set S1; Figs. 3A and S5). It includes 9632 earthquakes with $-0.6 \leq M_W \leq 4.8$ and depths 0–60 km. Formal vertical and horizontal errors are <2 km for ~92% of the data (see Fig. S5). For the same hypocentral volume, we extracted the corresponding focal mechanisms associated with either T1 and T2 from de Nardis et al. (2022) and integrated them with focal mechanisms from Mariucci and Montone (2020; Fig. S1B). The stress tensor inversion is represented in Figure 3B.

METHODS

A nonplanar fault model of the seismogenic structures activated by the Bice sequence (Fig. 2) is built with a multistep methodological approach (e.g., Bello et al., 2021; Tibaldi et al., 2023), integrating geological and geophysical data. Considering available geological maps and sections, seismic lines, and boreholes available from the literature and imported into an ArcGIS project (Fig. S3), we performed the following steps:

1. Updated the fold-and-thrust structural map (Fig. 2A) and elaborated an interpretive geologic section across the hypocentral area (Fig. 2B);
2. Selected transversal and longitudinal seismic lines from the ViDEPI database and used them to interpret the section view geometry of the Bice thrust and of the neighboring Cornelia thrust (https://www.videpi.com; Figs. 2D and S4);
3. Computed the kernel density estimation of the Bice seismic events projected along seven 10 km-spaced cross sections perpendicular to the structural trends by applying the Silverman (1986) kernel function (Fig. 2F); and
4. Interpolated the Bice thrust near-surface trace, the Bice fault traces, identified on the seismic lines (Fig. S3) and from the hypocentral distributions (Fig. 2), and built a 3-D nonplanar fault model (Figs. 2D, 2E, and 2F).

In addition, to validate the T1 and T2 megathrust geometries constrained from seismological data with independent information (Fig. 3), we projected the earthquake data along the trace of the onshore CROP-03 and offshore MS16 near-vertical seismic profiles (Fig. 4A) and verified their correspondence with identifiable thrust reflectors.

We also performed possible Coulomb stress transfer scenarios from a hypothetical

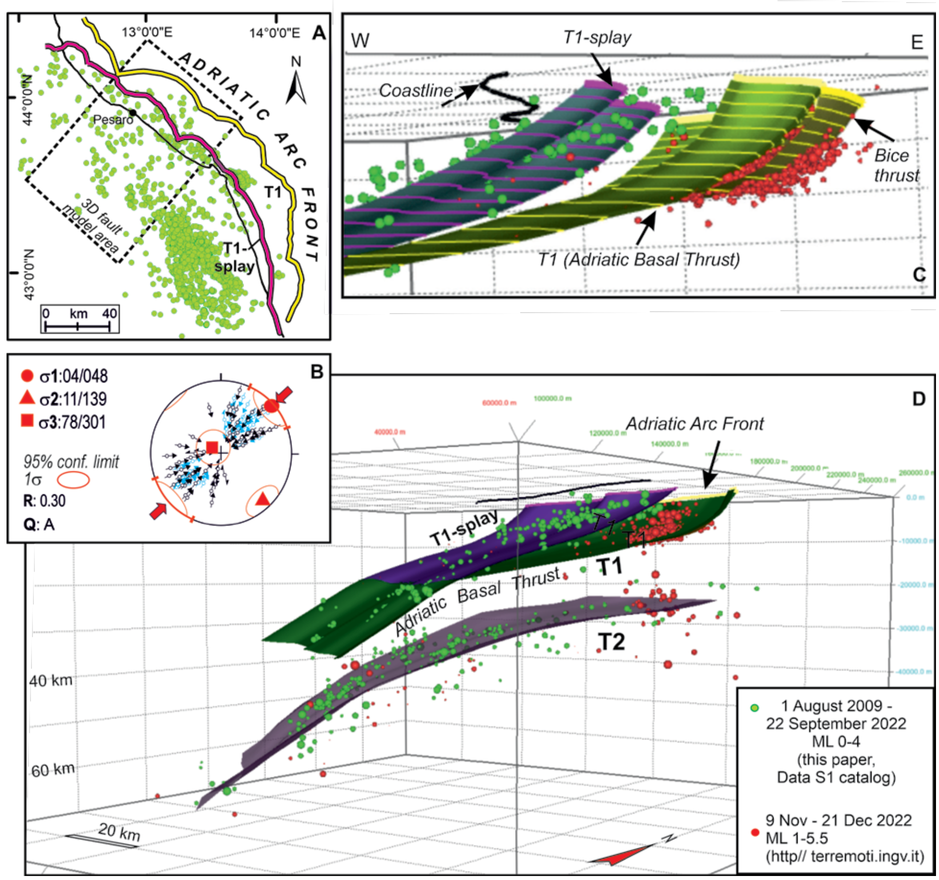

Figure 3. Updated 3-D seismotectonic fault model of T1 and T2 megathrusts and T1-splays. (A) OTS_EQS Catalog (2009–2022, Fig. S5) with a selection of events (green) associated with T1 and T2. (B) Stress tensor from focal mechanisms associated with T1 and T2 (from de Nardis et al., 2022). (C, D) 3-D view from SE of T1 and T2 with a zoom on Bice thrust and T1-splay. Geometric and kinematic parameters in Fig. S7 (see text footnote 1).

earthquake occurring on T1. We simulated an M_W 6.2 event nucleated at upper-crustal depths on the T1, given that it is considered responsible for historical and instrumental thrust earthquakes at upper- and lower-crustal depths, with equivalent M up to 6.0–6.5 (e.g., Rovida et al., 2022; Fig. S1). We used Coulomb code 3.4 (Lin and Stein, 2004), considering a bull's-eye slip distribution on the fault plane, and computed the imparted stress on the surrounding faults. We assumed the average geometry parameters retrieved by Bice and T1 fault models here reconstructed (220° striking, 22° dipping finite faults; Fig. 3C). Specifically, we consider a source ~14-km-long and 7-km-wide (downdip width), as suggested by the scaling law for events of such magnitude (Wells and Coppersmith, 1994). Furthermore, we assumed a friction coefficient (μ) of 0.4. Finally, we analyzed the results considering the stress changes for four simulated seismic sources at different depths (Fig. S7).

RESULTS

The Bice 3-D Fault Model

The style reconstructed for the structures hosting the Bice sequence is typical of a fault-propagation-fold system and consists of three en-echelon buckle folds with underlying thrusts (Pesaro Mare, Cornelia, and Bice) detaching on a SW-dipping basal detachment (Fig. 2B). The latter propagates with staircase trajectories from the Permian–Triassic basement (10–15 km depth) up to near-surface depths and represents the outermost upper-crust splay of the T1 megathrust.

In map-view, the Bice thrust trace can be identified for an along-strike extent of ~30 km in the NW-SE direction; southward, it converges with the Cornelia right-lateral en-echelon thrust (Figs. 2A and S3E). In section-view and 3-D-view, a listric Bice geometry is evident, with an average dip angle of ~40° from near surface to a depth of 7 km and ~20° at seismogenic depths, from 7 to 11 km (Figs. 2B and 2E).

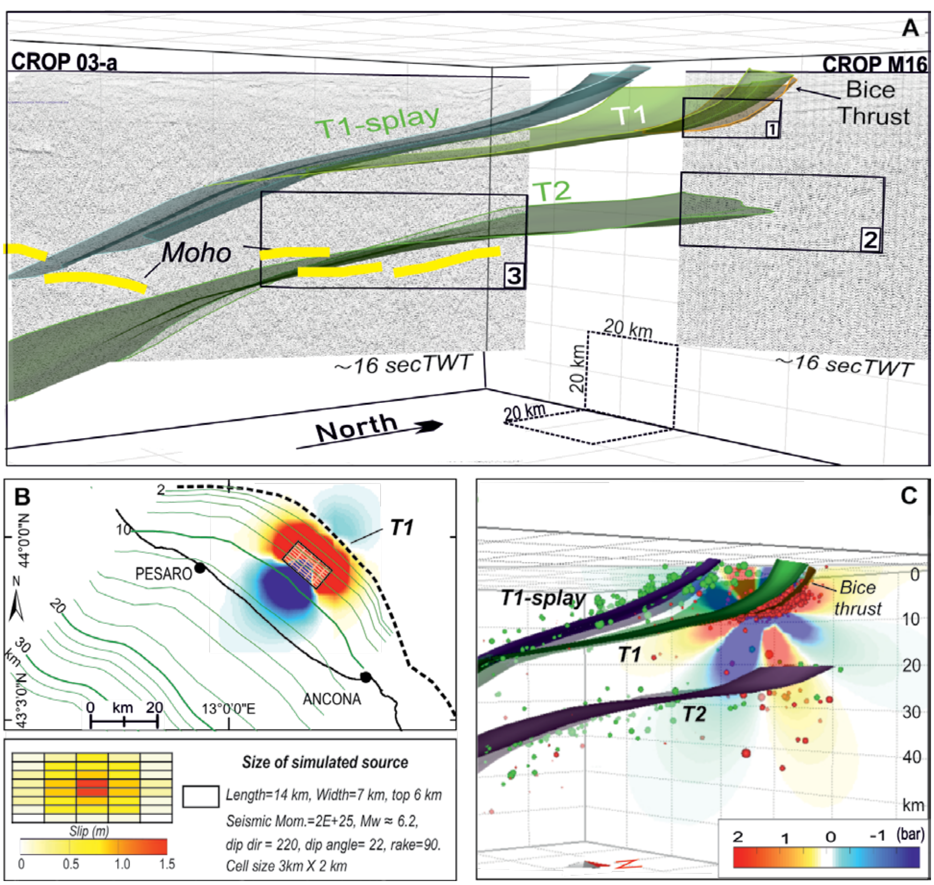

Figure 4. Near-vertical seismic lines across T1 and T2 and Coulomb stress scenario for a thrust earthquake nucleated on T1, near the Bice fault. (A) Near-vertical seismic profiles across the earthquake-constrained fault models (https://www.videpi.com/videpi/crop/crop.asp; details 1, 2, and 3 in Fig. S6). (B, C) Map- and section-view Coulomb stress simulation for a M_W 6.2 event (Coulomb code 3.4; Lin and Stein, 2004) (other scenarios in Fig. S8). The colored dots legend of panel C is the same as in Figure 3D.

The central and southern portion of the Bice thrust, for a length of ~20 km, released most of the events of the November 2022 aftershock sequence; nonetheless, the intermediate Cornelia thrust was subordinately activated in its northernmost portion overlapping with Bice (Figs. 2A, 2B, and S4). The main event (M_W 5.5) nucleated on the Bice thrust; the second one (M_W 5.2) was at the intersection between Bice and Cornelia.

Whereas the Cornelia thrust was known in the previous reconstructions (Casero and Bigi, 2013) and highlighted in recent ones (Maesano et al., 2023), the seismogenic role of the Bice thrust has been underevaluated. This structure is especially interesting from a seismic hazard point of view because it intercepts two deep extraction wells (Bice 1, 4322 m, and Tamara 1, 3216 m; Fig. 1A), reopening the triggered and induced seismicity question (Lavecchia et al., 2015).

The Megathrust Fault Models

The hypocentral distribution from Data Set S1 helps reinforce the megathrust images in de Nardis et al. (2022), with additional information relevant to structural interpretation.

The T1 and T1-splay hypocentral distribution present a bimodal pattern with events mainly located at upper crust (0–8 km) and middle crust (13–22 km) depths. The regional T1-splay branches from T1 at a consistent depth of ~20 km and represents the basal detachment of the internal fold-and-thrust domain of the Adriatic Arc, T1 being the basal detachment of the external fold-and-thrust domain of the Adriatic Arc (Figs. S1A and 3). T2 is continuously illuminated from middle crust to upper mantle depths (~20–60 km) for an along-strike extent of at least 250 km.

The 3-D megathrust models revised in this paper focus on the northern sector of the Adriatic where the Bice sequence was released (Fig. 3). The green hypocenters in Figure 3 refer to Data Set S1; the red ones are extracted from the INGV list of earthquakes (http://terremoti.ingv.it) during the time interval of the Bice sequence activity (1 November–25 December 2022; Fig. 3). Clustered events from Data Set S1 and the Bice seismic sequence contemporaneously nucleated on T1 and T2 (Figs. S2 and S5).

The earthquake-constrained T1 and T2 megathrust surfaces (Fig. 3) fit well with the geometries highlighted along the trace of the CROP-03 and MS16 seismic profiles (Fig. 4A). In particular, the upper and lower crust T2 segments fit well with thrust deformation evident in the CROP-03 seismic line at Moho depths (35 km) and in the MS16 seismic line within the upper part of the lower crust (20–25 km; Fig. 4A). Details are given in Figure S6, and parametric data are given in Figure S7.

Scenarios of Fault Interaction

The coexistence of T1, T1-splay, and T2 at different depths within the same lithospheric volume and under the same stress field raises questions about potential stress interaction during an ongoing seismic sequence. Starting from the reconstructed 3-D fault models, we investigate the likelihood of static stress interactions among the above structures (Figs. 4 and S7).

Modeled Coulomb stress scenarios show that slip on T1 increases the stress on nearby zones, both along the dip and perpendicular to the dip (Figs. 4C and S8). Therefore, it can trigger secondary slip at lower depths and can be responsible for broadly off-fault aftershock activity on T2, as observed during the Bice sequence (Fig. 3D). Conversely, lateral Coulomb stress transfer from T1 toward T1-splay does not appear to be triggered in the here-modeled scenarios, suggesting that T1 and T1-splay act independently (Fig. S8).

DISCUSSION AND CONCLUSIONS

In this paper, we provide further insights into the geometric multi-scale complexities of slowly deforming continental regions (SDCR) with a case study from the orogenic belt of eastern Central Italy. Most often, SDCR geometries remain controversial, because it is possible to infer them only after large earthquakes, either through earthquake data or surface seismic deformation (Bollinger et al., 2021; Laporte et al., 2021). The seismic activity is widely spread across the rock volume and is thought to result from transient stress perturbations or changes in fault strength, which lead to the release of accumulated strain within the prestressed lithosphere (Calais et al., 2016). In the Italian case, the regional stress driving the compressional deformation since the late Pliocene (Lavecchia et al., 1994) is still active (de Nardis et al., 2022), and the microseismicity occurs around distinct shear planes, specifically T1 and T2.

T1 and T2 represent an uncommon example of a double reverse shear zone at lithospheric depths, because such configurations are commonly imaged at intermediate depths in subduction zones. Their reconstructed 3-D configuration allows us to speculate on points that may be essential to reduce uncertainties in seismic hazard assessment (Pandolfi et al., 2023): (1) strain partitioning, (2) vertical stress triggering, and (3) seismogenic potential at the outer Apennine front.

1. The coexistence in the Adriatic continental lithosphere of two multi-depth megathrusts may imply a strain partitioning on the two structures, thus slowing individual seismogenic deformation rates. In such a frame, the observed slowdown of the compressional rate at the T1 hanging wall since the middle Pleistocene might be the result of the underlying growth of the T2 blind structure, which is too deep to modify the surface strain rate field (Picotti and Pazzaglia, 2008; Gunderson et al., 2018).
2. The interconnected T1 and T2 seismic activity shows rare evidence of vertical stress transfer between fault structures at different crustal depths during moderate earthquakes (M_W 5.5–6.5). Highlighted cases of vertical stress interaction are usually associated with strong earthquakes (e.g., 2016 M_W 7.8 Kaikōura earthquake in New Zealand; Lanza et al., 2019), whereas stress triggering during moderate earthquakes mainly develops along strike or dip of segmented structures (e.g., 2016 M_W 5.9 thrust Menyuan Earthquake in the Qilian Orogen of China; Zhang et al., 2020).
3. In the past 2000 yr, only a few events in the Adriatic Arc area reached M_W ~6.0, occurring both near the coast (e.g., Senigallia in 1930, M_W 5.8) and more internally (e.g., Fabriano in 1741, M_W 6.2; Rovida et al., 2022). Based on the analysis of attenuation curves and an empirical law relating epicentral intensity to depth and magnitude, the Fabriano earthquake has been deepened to ~35 km (see Fig. S1A for epicenteral location), with an increase in magnitude up to M_W 6.3–6.4 (Sbarra et al., 2022). With the new hypocentral coordinates, the event falls on T2, raising the issue of the seismogenic role of T2. Furthermore, because SDCR have long seismic cycles that may last thousands of years (Bollinger et al., 2021), we cannot exclude the occurrence in the past or future of highly destructive events, such as, for example, the 1693 earthquake offshore eastern Sicily (M_W 7.3; 60,000 casualties; Rovida et al., 2022), which might be associated with a Sicilian segment of the OTS (Fig. 1A; Petricca et al., 2019).

The knowledge of structural complexities at a 3-D scale and their analysis in terms of strain partitioning and stress transfer is especially relevant in slowly deforming intra-continental regions as they may help to reveal more complex, unexpected, and even highly seismogenic scenarios with evident implications for seismic hazard assessments, as well as for a deeper understanding of geodynamic processes.

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