



OPEN Trench sediment heterogeneity controls accretion mechanisms in subduction zone

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Trench basins related to an almost entirely subducted oceanic lithosphere are filled by deposits sourced from either the passive continental margin or the accretionary wedge. They also include large-scale submarine landslides often triggered by the inherited rough topography of the subducting plate. This mechanism provides the deposition of material by mass-transport processes from the wedge to the trench, resulting in highly heterogeneous trench sedimentation. The role of the mass-transport deposits in the accretion mechanisms, as well as their influence on seismic behaviour at the plate interface is difficult to assess in the active trenches, because of their limited accessibility. This study reports on a well-preserved fossil trench-fill sequence exposed in the Northern Apennines. A multidisciplinary survey including fieldwork, stratigraphy, biostratigraphy, geochemistry, and zircon provenance, allows reconstructing the anatomy of these deposits. The heterogeneities derived by distinct sediment packages made of mass-transport deposits and deep-sea turbidites reflect a setting with two feeding source areas: the accretionary wedge and the continental margin, respectively. Alongside the roughness of the subducting plate, this deposits association favours coherent underplating processes developed at depth. Such accretion mechanisms, linked to thrust faults at the base of the wedge, can generate both major earthquakes and new mass movements, reinforcing the complex role of trench-fill processes in subduction dynamics.

Keywords Trench, Heterogeneous sedimentation, Subduction, Landslide-induced seismicity, Northern Apennines

In the convergent margins, the continuous subduction of oceanic lithosphere generally leads to development of an accretionary wedge, a morpho-tectonic structure where slices of ophiolites and deep-sea sediments are scraped off from the subducting plate and stored along the edge of the over-riding plate^{1–5}. The accretionary wedges are the most world-wide dynamic environments, where tectonics and sedimentation interplay between each other. In this frame, the sediments lying on the subducting oceanic plate, generally represented by pelagic, hemipelagic deposits and deep-sea turbidites, the latter able to fill the trench, can be accreted at the front of the accretionary wedge, or transferred at its base. These processes led to a continuous growth of the prism be achieved by underplating of entire crustal section (i.e., coherent underplating) or by integrating dismembered rocks (i.e., diffuse underplating^{6–9}). The material previously transferred into the accretionary wedges can be redeposited on the subducting plate by tectonic erosion, mainly triggered from the underthrusting of plates with a rugged morphology^{10–12}. This complex interplay between sedimentation and tectonics, typical of sediment-dominated subductions, produces large volume of Mass Transport Deposits (MTDs), a generic term referring to rocks derived from a rapid mobilization and deposition of sediments, partly lithified sediments and rock clasts in the trench that occurs by slope failure and gravitational deformation in the form of submarine landslides^{13–15}. Different types of MTDs may occur in the same depositional setting as complex sedimentary associations, that generally consist of debris flows and slide deposits interfingering with slumped muds and turbidites. According to Festa et al.¹⁶, medium to giant (10 to > 1000 km²) MTDs with a heterogeneous internal fabric when involved in a subduction zone may strongly modify the physical behaviour of subducted materials¹⁷, thus influencing the mechanical properties along the plate interface and affecting its seismic style^{18–20}. For instance, the seismic behaviour at subduction setting can be influenced by the volume, distribution, and heterogeneity of subducted MTDs, triggering slow slip events instead of high magnitude earthquakes²¹ in the shallow parts of a subduction

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plate interface. Therefore, MTDs are pivotal in understanding how accretionary wedges work. In this regard, oceanic drilling provides direct access to trench environments²¹, and has significantly contributed, albeit locally, to our knowledge of these basins. By contrast, remnants preserved into collisional belts offer an opportunity to investigate the trench-related sedimentation dynamics^{19,22–24}. The study of MTDs outcrops allows to unveil the anatomy of these deposits aiming to highlighting their features and provide useful insights on how they affect tectonic processes.

In the Northern Apennines, several MTDs are preserved in the tectonic units derived from the Ligure-Piemontese Oceanic (LPO) basin and its transition to the Adria margin, respectively²⁵. The LPO was an oceanic area opened during Middle to Late Jurassic between the continental margins of European and Adria plates²⁶. In the Campanian (Late Cretaceous), the LPO basin was affected by convergence, leading first to development of an east-dipping subduction zone and subsequently, in the middle Eocene, to continental collision between Europe and Adria plate margins^{27,28}. As a result of the subduction, an accretionary wedge developed since Campanian, whose remnants are today represented by the Internal Ligurian Units²⁹ (IL). These, along with the External Ligurian (EL), the Subligurian (SUB) and the Tuscan (TC) Units (Fig. 1a), form the Northern Apennines (Fig. 1a). The reconstructed stratigraphic log of the IL Units includes a Middle to Upper Jurassic ophiolites sequence originated in an ultra-slow spreading ridge³⁰, topped by Middle to Late Jurassic to Upper Cretaceous pelagic to hemipelagic deposits (i.e., Monte Alpe Cherts, Calpionella Limestone and Palombini Shale Fms.), that grade upward into a thick succession consisting of carbonate to siliciclastic turbidite sequence³¹ ranging in age from Campanian to lower Paleocene (i.e., Mangesiferi Shale, Monte Verzi Marl, Zonati Shale and Gottero Sandstone Fms.). The top of this succession is represented by the Bocco Shale Fm., interpreted by Meneghini et al.²² as MTDs deposits resulting from the erosion of the accretionary wedge lower slope into a trench environment. The succession reflects the progressive transfer of a portion of the LPO basin to the accretionary prism³². This scenario is confirmed by the late Paleocene-late Eocene structural evolution of the IL Units, that first experienced a deformation typical of coherent underplating processes (D1 phase³³) at the base of the accretionary wedge under prehnite-pumpellyite to low blueschist facies metamorphic condition^{34–36}. After their accretion, IL Units have been exhumed within the accretionary wedge developed under decreasing pressure and temperature (D2 phase³³).

This contribution provides a complete anatomy of the Bocco Shale Fm. of the well-preserved succession exposed in the Vara Valley region (Eastern Liguria). In this area, trench-related deposits have not undergone intense deformation, allowing us to decipher their stratigraphic and sedimentary evolution. A complete dataset including stratigraphic, sedimentologic, paleontological, geochemical, and detrital zircon dating is provided to identify the features of the deposits of the Bocco Shale Fm. and estimate their extent, volumes, and sources. The resulting picture is discussed to provide novel insights on the tectonic and sedimentation interplay at convergent margins.

Results

The study area is located near the Teviggio Village (44°21'56"N – 9°37'18"E), where the IL Units are set into an E-verging stack (Fig. 1). At the top of the pile, the Gottero Unit includes coarse-grained deep-sea fan turbidites belonging to the upper part of the Gottero Sandstone Fm., and the uppermost deposits of the Bocco Shale Fm., regarded as reflecting the beginning of the trench sedimentation³⁷. The internal geometry of the Gottero Unit results from subduction and exhumation processes related to the building of the Alpine accretionary wedge²⁸.

Anatomy of the trench-related deposits

The sedimentary features of the Bocco Shale Fm. can be used to decipher the remobilization and recycling history recorded by MTDs and their interaction with underlying turbidite system (Gottero Sandstone Fm.—GOT), this fed by the European margin^{28,38}, that by-passed the underlying oceanic lithosphere and were deposited within the trench-fill successions. Such a frame offers valuable constraints on the complex depositional architectures that characterize trench basins formed during the subduction of oceanic lithosphere.

The boundary between the Bocco Shale Fm. and the underlying Gottero Sandstone Fm. is not exposed in the Teviggio section. It has been documented in other sectors of the Northern Apennines as an erosive, unconformable contact^{22,38} indicating the significant onset of trench infill by MTDs sourced from the accretionary wedge. However, the uppermost levels of the Gottero Sandstone Fm. outcropping in the study area (Fig. 2a) are characterized by an intercalation (Fig. 2b) of fine-grained deposits formed by the association of mudstones (Fig. 2c), pebbly-mudstones (Fig. 2d) and thin-bedded turbidites (SIL in Fig. 2b), respectively derived from mudflows, cohesive debris flows and low-density turbidites. These bodies, well known in literature as “argillitic intercalations”³⁹, hereafter are reported as Shaly Intercalation Lithofacies (SIL). In the study area, the SIL hosts calcareous beds (Fig. 2b) made up of bioturbated calci-mudstones to wackestones containing radiolaria and planktonic foraminifers, associated with sparse benthic textularid foraminifers, sponge spicules, echinoderm fragments, ostracods and lithoclasts of calci-mudstone and very rare angular silt- to fine-sand grade, detrital quartz grains. Planktonic foraminifers (samples BUT15–17, Supplementary material S1) are tentatively attributed to the genera *Hedbergella*, *Muricohedbergella*, *Microhedbergella*, *Laeviella*, *Ticinella* and *Praeglobotruncana* associated with rotaliporids. Radiolaria are made of silica and chalcedony or partially to completely replaced by calcite microsparite to sparite. The planktonic foraminifer association is indicative of an Albian age^{40,41}. The recognized age, as well as the origin of the carbonate fragments, indicate a reworking of the sedimentary covers of the oceanic lithosphere (cf. Palombini Shale Fm.) as a possible source area.

In the study area, the Bocco Shale Fm. can be divided, from bottom to the top, in three different lithofacies (Figs. 2e–j): the Block-in-Matrix Lithofacies (BML), the Varicoloured Shaly Lithofacies (VSL), and the Thin-Bedded Turbidite lithofacies (TBT).

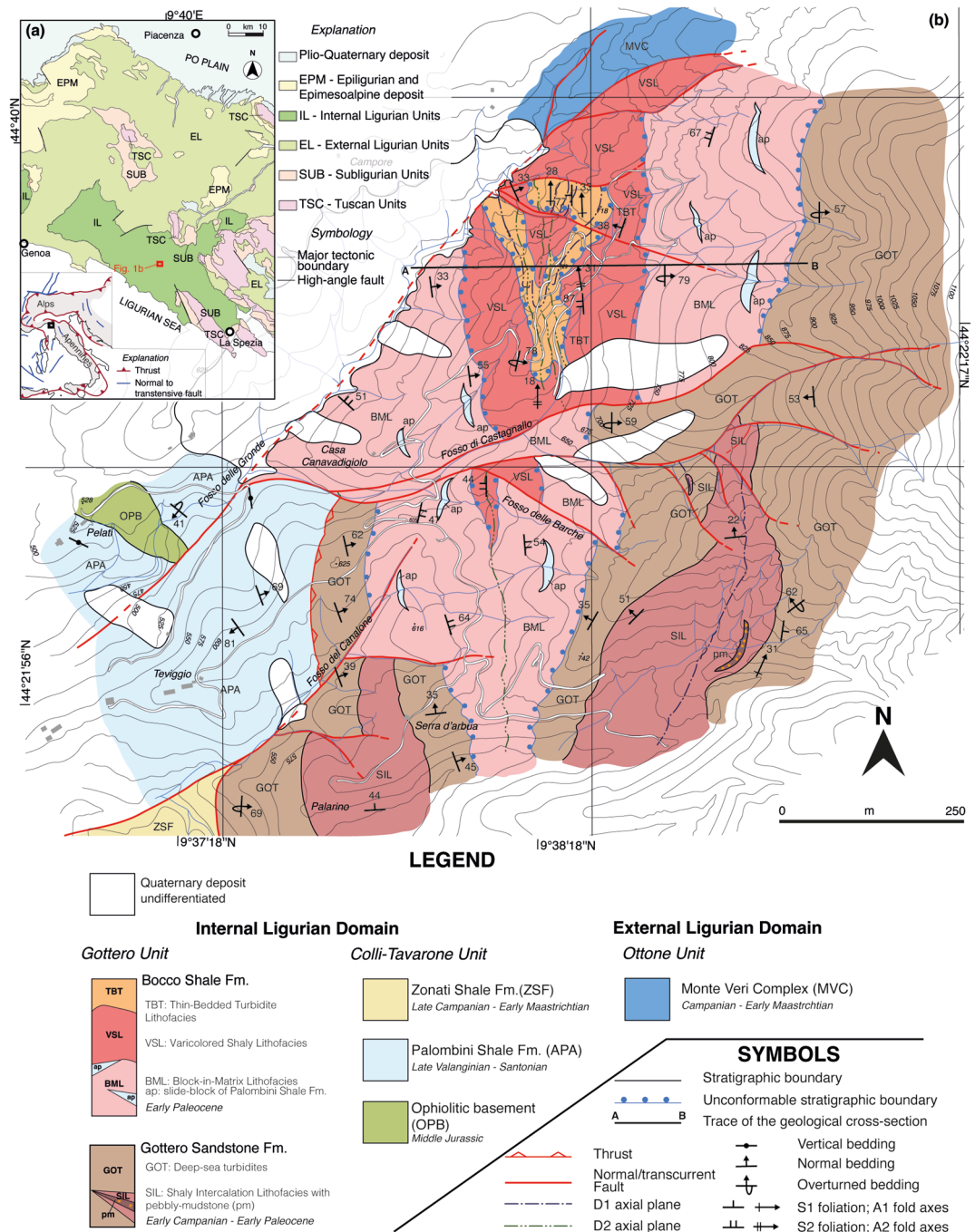


Fig. 1. Geographic and geological setting of the area of interest. (a) Geographic location and tectonic sketch of the Northern Apennine collisional belt. (b) Geological map of the investigated area (red box in a). The trace of the interpretative geological cross-section A-B is indicated (see Supplementary material S1).

The BML is represented by 80–100 m thick facies association which includes plurimetric, partly dismembered slide-blocks of Palombini Shale Fm. embedded in a shaly matrix (cf. “broken formation” of Abbate et al.⁴²—Fig. 2e). The slide-blocks are often wrapped by pebbly-mudstones. Where slide-blocks are missing, this facies association is replaced by the same pebbly-mudstones interfingering with shales and marly-shales. The pebbly-mudstones are represented by matrix-supported, monomict breccias and/or conglomerates (cf. “olistostrome” of Abbate et al.⁴² and F1 facies of Mutti⁴³), with clasts of limestones and marly-limestones derived from the Palombini Shale Fm. (Fig. 2f). These deposits have been interpreted as formed by cohesive debris flows (*sensu* Costa⁴⁴) and hyper-concentrated flows. The mudymatrix is made up of soft clasts that rework the hemipelagic pelites belonging to the Palombini Shale Fm. These sediments can be interpreted as the evolution of a cohesive debris flow into a hyper-concentrated flow (F1 to F2 facies of Mutti⁴³), both originated by submarine landslides that mainly rework the Palombini Shale Fm., which may already be weakly deformed during the frontal

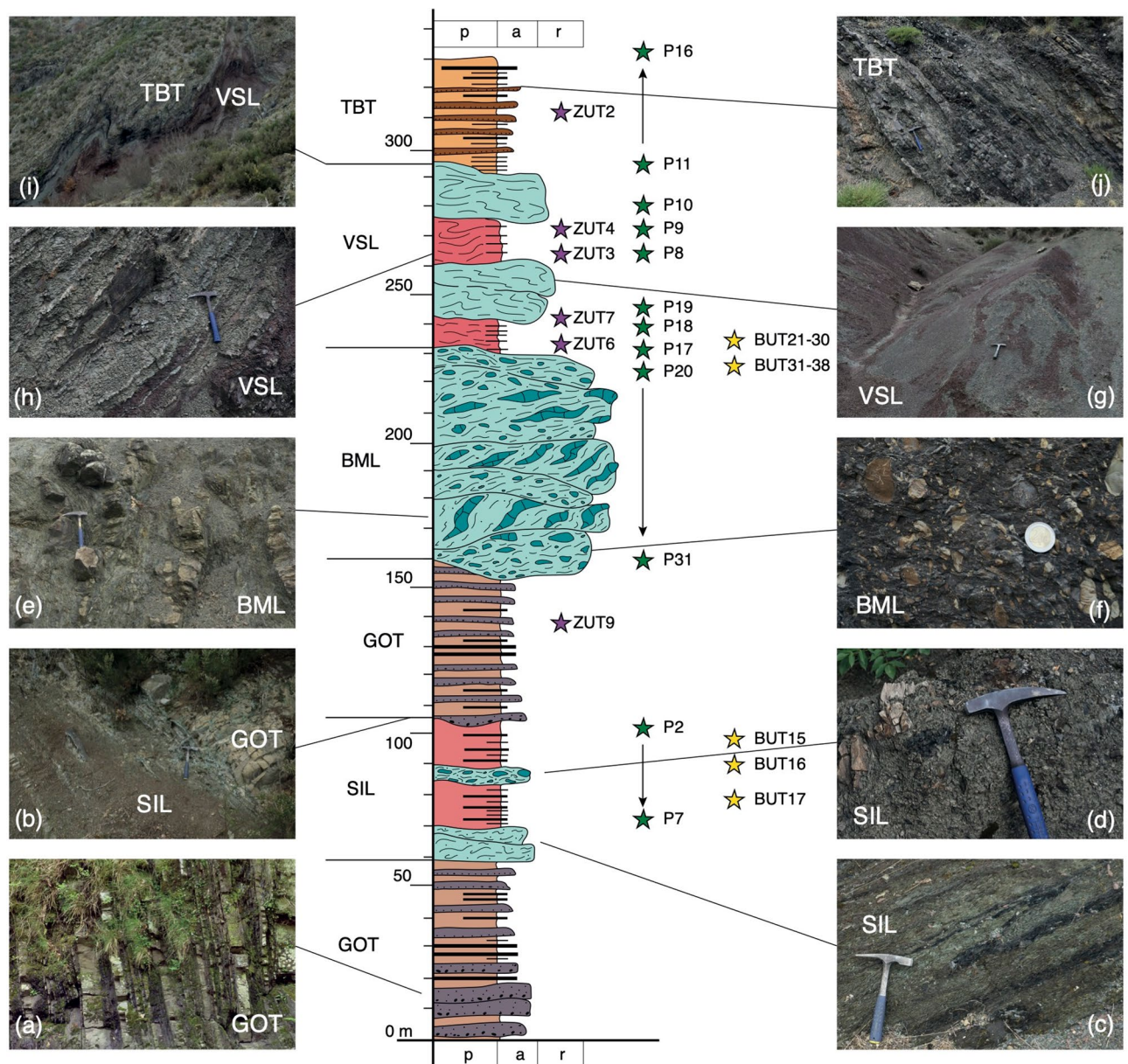


Fig. 2. Stratigraphic log of the Gottero Unit exposed in the area of interest. The collected samples are located in the stratigraphic log (ZUT for zircon samples, P for pelite geochemistry samples, BUT for fossil samples). Gottero Sandstone Fm. including Shaly Intercalation Lithofacies: (a) field occurrence of the Gottero Sandstone Fm. typical facies; (b) stratigraphic relationships between fine grained turbidites in the Shaly Intercalation Lithofacies (SIL) and Gottero Sandstone Fm. (GOT); (c) mudflow-derived mudstones facies in SIL; (d) cohesive debris flow-derived pebbly-mudstones facies in SIL. Different lithofacies recognized in the Bocca Shale Fm. block in matrix lithofacies (e) and matrix supported pebbly-mudstone (f) in the Block-in-Matrix Lithofacies (BML); (g) varicoloured pelites and silt to fine-grained quartz-rich turbidites (h) in the Varicoloured Shaly Lithofacies (VSL); (i) relationships between VLS and Thin-Bedded Turbidites lithofacies (TBT), the stratigraphic boundary is folded by the D1 deformation phase; (j) field occurrence of the TBT.

accretion process. Moreover, mud diapirs smaller than 3 m in diameter can be recognized in the fine-grained pelites (Supplementary material S1). The occurrence of this lithofacies from the top of the Gottero Sandstone Fm. onward indicates the entry of the subducting plate into the influence zone of the accretionary prism, characterized by a significant trench sedimentation. Additionally, the presence of lithofacies like those described for the BML, i.e., the SIL, recognized at the top of the Gottero Sandstone Fm., indicates that feeding from a source area located along the frontal part of the accretionary wedge begins early, even during the sedimentation transition from Gottero Sandstone Fm. to Bocca Shale Fm.

The BML is unconformably overlain by a 60–70 m thick VSL (Figs. 2g–i). This lithofacies is formed by varicoloured (red to green, Fig. 2g) siliciclastic pelites alternated with cm-thick laminated turbidite beds (silt

to fine-grained quartz-rich turbidites, Fig. 2h). Marlstones, and less commonly marly-limestones, also occur close to the contact with the underlying facies, while dark and organic-rich pelites can be observed mainly in the upper part of VSL (Fig. 2i). The most prominent sedimentary feature is represented by soft-deformation structures, such as folds (Fig. 2g) and/or slumps probably generated by water rich and unconsolidated fine-grained sediments. These soft-sediment processes involved both the muddy and the fine-grained turbidites facies, suggesting a gravity-unstable slope origin. Calcareous nannofossils content was analyzed by sampling the marly beds at the boundary between VSL and BML. Many samples resulted to be barren, while four were found (Supplementary material S1) to contain very rare and poorly preserved specimens referable to *Cyclagelosphaera* sp., *Eiffellithus* sp., *Nannoconus* sp., *Retecapsa* sp. and *Watznaueria* sp. Because of the absence of markers and rarity of forms, it is possible to deduce a Late Albian age on the occurrence of *Eiffellithus* sp.⁴⁵ and *Nannoconus* sp.⁴⁶.

These deposits are unconformable covered by the TBT lithofacies (Fig. 2j). This is characterized by a pluri-dam sequence (at least 40–50 m thick) of cm-thick, very fine-grained quartz-rich turbidites and siltstones alternated with siliciclastic shales. The arenites/pelites ratio is < 1. The arenite beds are characterized by moderate lateral continuity. Td-e and subordinately Tc-e base-missing Bouma sequences can be recognized, as well as traction plus fall-out structures, such as plane laminations, ripples and climbing ripple. Bioturbation affects arenites and shales. Although soft sediment deformation structures can also be recognized in this lithofacies, it is evident that they are extremely less common than in the two underlying lithofacies. Both the stratigraphic and sedimentological features of these deposits can be interpreted as originated by low-density turbidity currents sedimented onto a confined depositional environment (cf. F9b facies of Mutti⁴³).

Geochemistry of pelites

Overall, the positive correlation of Al_2O_3 with major (e.g., K_2O and TiO_2) and trace elements (e.g., Sc and Nb) suggests that Al-rich phases, such as clay minerals, are the main host of these elements in the investigated pelites (Figs 3a, b, c and Supplementary material S1 and S2). The TBT (samples P11–16, Fig. 3a) shows the highest values of SiO_2 , while the BML (samples P20–31) is characterized by higher Al_2O_3/SiO_2 (Fig. 3a). The lack of correlation of major and trace elements with Zr and P_2O_5 (Supplementary material S1) indicates that REE distribution is not controlled by accessory minerals such as zircon or apatite and monazite⁴⁷. All the investigated pelites show a first-order chemical homogeneity, as suggested by similar chondrite-normalized REE pattern for all the sampled lithofacies (Supplementary material S1). All the samples are characterized by an enrichment of light REE to heavy REE and a moderately negative Eu anomaly. Such pattern is thought as typical of well mixed shale, such as composite of Paleozoic European Shale, considered thus to reflect the composition of the upper continental crust (UCC) exposed to weathering and erosion⁴⁸. The trace element patterns (Supplementary material S1) are shown as concentrations of selected elements normalized to UCC (values from Rudnick and Gao⁴⁹, including LILE (large ion lithophile elements, e.g., Rb, K, Ba, Cs), HFSE (high field strength elements, e.g., Zr, Nb, Ta, Th, U, Y) and REE. Overall, the normalized values of each element tend to plot around the unity, with a more fractionated pattern shown by incompatible elements. The Eu anomaly against the $Th/(Cr + Ni + V)$ and the $(Cr + Ni + V)/TE$ ($TE = \text{total of trace elements}$), and the La/Yb ratios (Figs. 3d, e and f) are used to distinguish mafic vs. felsic contributions on pelites^{50,51}. The SIL (samples P2–7), BML and VSL (samples P8–10 and P17–19) deposits show higher values of $(Cr + Ni + V)/TE$ and a lower La/Yb ratio than those from TBT. On the other hand, TBT shows higher $Th/(Cr + Ni + V)$ and La/Yb ratios than the underlying lithofacies. Additionally, Th/Sc and La/Sc distribution for the same deposits outlined marked compositional trend with TBT enriched in Th and La over VSL, BML and SIL (Supplementary material S1 and S2).

U-Pb ages of detrital zircons

Zircons were separated and picked up from a homogeneous quantity of material (ca. 1 kg/sample) representative of the Bocco Shale Fm. and of the youngest part of the Gottero Sandstone Fm. Selected 112 zircon grains were analysed from six samples (ZUT2, ZUT3, ZUT4, ZUT6, ZUT7, ZUT9). Zircons range in size between 30 and 150 μm , and appear stubby, prismatic, or anhedral, and broken in most cases. They show different internal textures such as oscillatory zoning, inherited cores, patchy rims and microcracks (Fig. 4a). Twenty zircons were excluded due to the > 10% discordance.

In the Bocco Shale Fm., zircon crystals were found in the VSL and TBT lithofacies. In the VSL (samples ZUT3, ZUT4, ZUT6 and ZUT7), U-Pb ages vary from 230 to 2,730 Ma (Fig. 4b). The main cluster reproducible in all the four samples ranges 300–500 Ma, as well as a second zircon group which culminates at 600 Ma. Triassic to Jurassic ages are less common but observed in almost all the samples of this group, whereas peaks older than 800 Ma are inhomogeneous but documented in all the four samples (Fig. 4b). In the TBT (sample ZUT2), the U-Pb ages detected range between 170 and 450 Ma (Fig. 4b). Kernell density estimate shows that almost all the crystals of these samples are distributed in a Gaussian that culminates at 300–310 Ma, which is slightly younger than the density observed in the zircons from VSL (Fig. 4b).

In the Gottero Sandstone Fm., zircons were separated from a single sample (ZUT9) collected close to the contact with the Bocco Shale Fm. (Fig. 2). Like TBT, zircon age varies from 140 to 760 Ma, with a single exception, which yields an age of 1,700 Ma (Supplementary material S3). The U-Pb age distribution estimated for this lithofacies is characterized by Silurian-Devonian and Permian main populations. Minor clusters at ca. 200 and 600 Ma are also observed (Fig. 4b).

The Th/U ratio was used to discriminate the origin of the zircon between igneous (> 0.3) and metamorphic (< 0.3) rocks (Fig. 4c)^{52,53}. In all the samples studied, detrital zircons older than 1 Ga mainly have an igneous derivation, whereas the metamorphic provenance increases in the main populations between 300 and 500 Ma, reaching the 50% of the contributions in the samples ZUT2 and ZUT4 (i.e., VSL and TBT lithofacies,

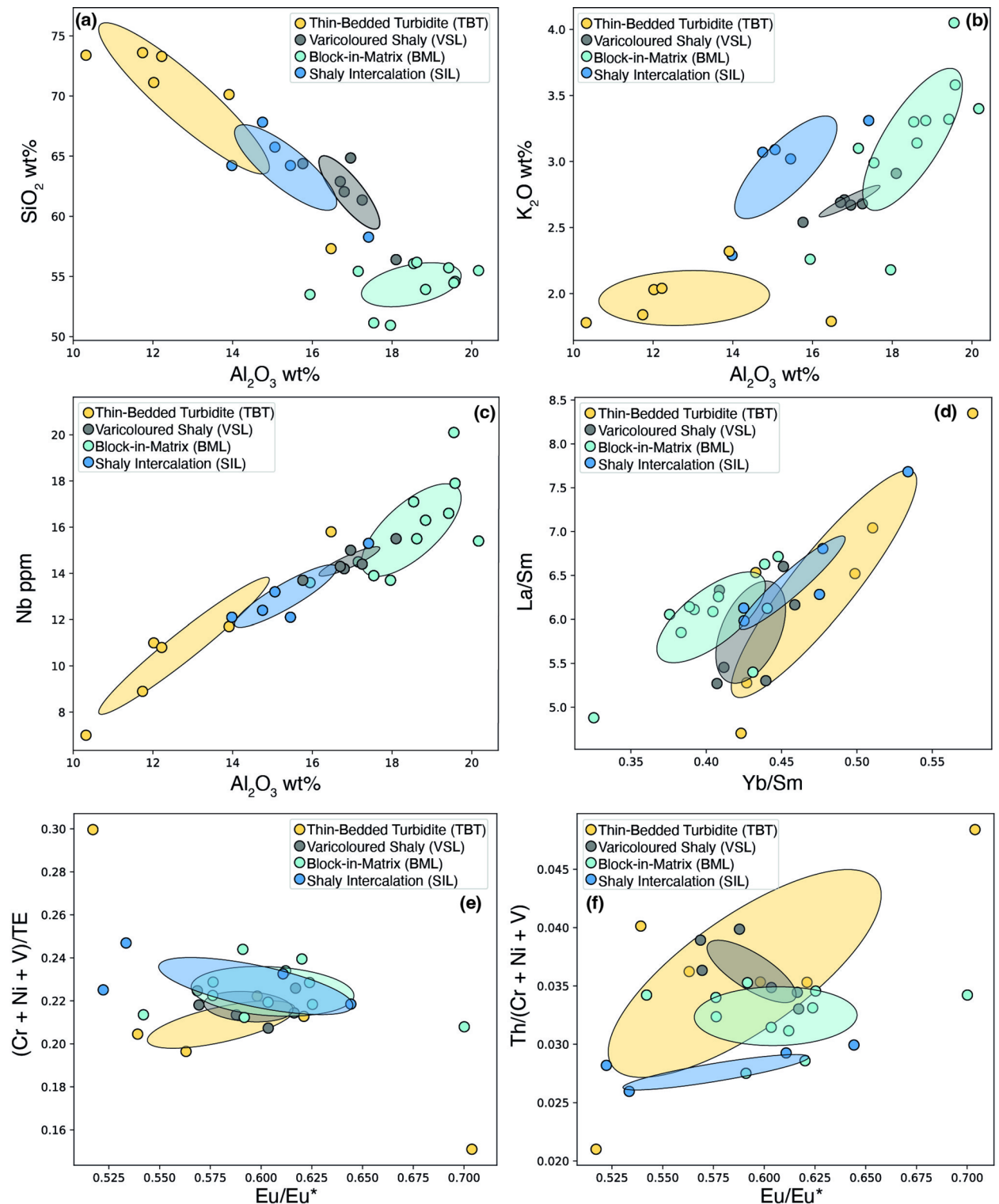


Fig. 3. First-order geochemical features of pelites. Major element distribution with (a) SiO_2 - Al_2O_3 and (b) K_2O - Al_2O_3 plots. Minor element distribution with (c) Nb- Al_2O_3 and (d) La/Sm-Yb/Sm plots. Plots of (e) $(\text{Cr} + \text{V} + \text{Ni})/\text{TE}$ over Eu/Eu^* and (f) $\text{Th}/(\text{Cr} + \text{V} + \text{Ni})$ over Eu/Eu^* are reported. Colour-coded ellipses represent the value distribution along X and Y axes. All plots are characterized by ellipses reflecting data distribution with a strong correlation and an overall low variance.

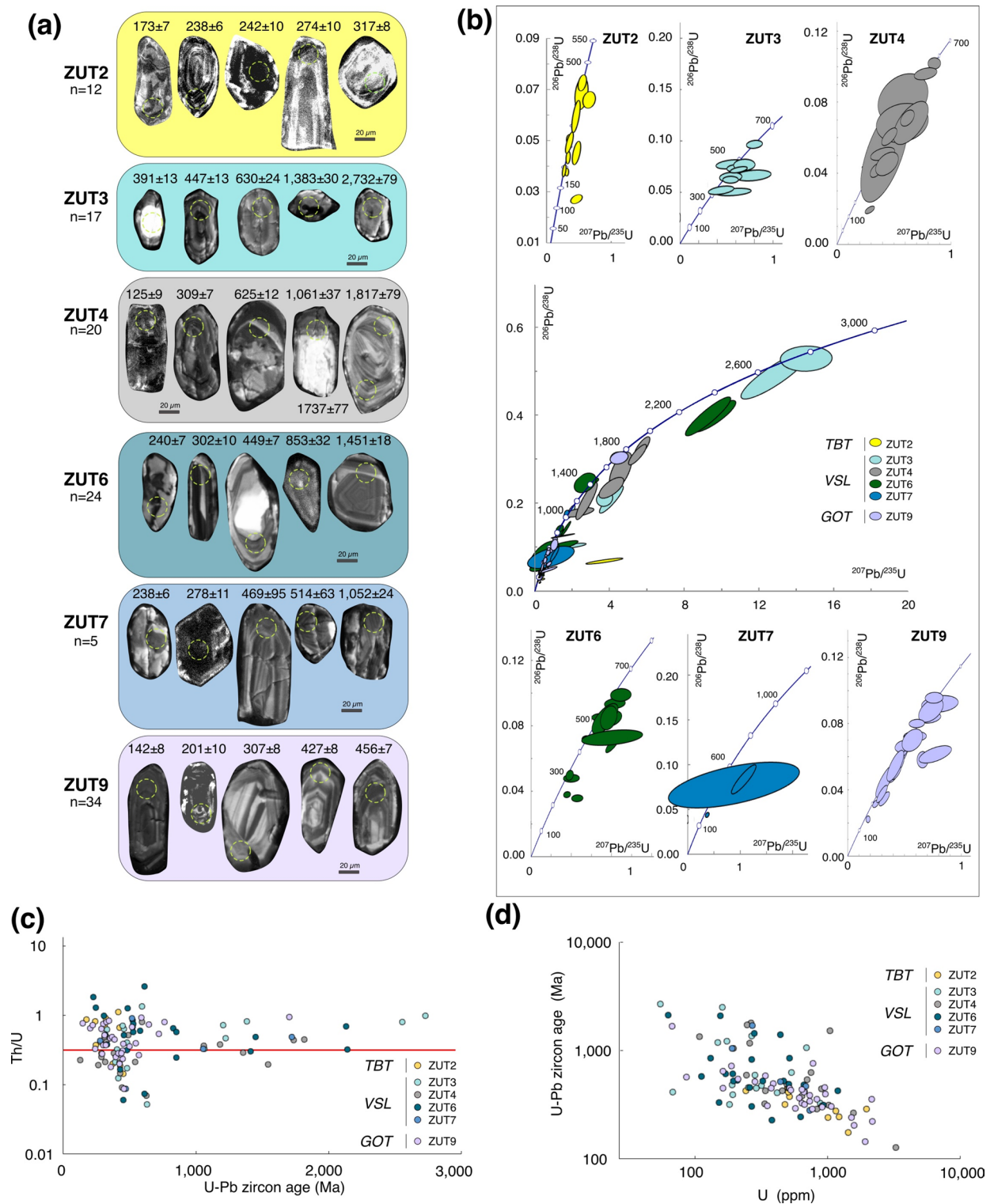


Fig. 4. U-Pb zircon dating of the lithofacies from the Bocca Shale Fm. **(a)** CL images of selected zircon grains and related $^{238}\text{U}/^{206}\text{Pb}$ ages. Circles indicate the location of the ablated area; **(b)** Concordia diagrams showing the complete distribution of the dated grains and close-up of the single distributions during Phanerozoic; **(c)** U-Pb ages vs. Th/U diagram. Red line indicates the limit between the metamorphic and the magmatic zircons, and **(d)** U concentration vs. U-Pb ages diagram.

respectively—Fig. 2). U-in-zircon concentrations vary from 100 ppm in the oldest grains up to 6,000 ppm in the youngest, following the general trend of decreasing U content with time (Fig. 4d)⁵⁴.

Discussion

The anatomy of the Bocca Shale Fm., including its relationships with the underlying substratum, clearly reflects sedimentation within a tectonically dynamic, narrow, sediment-dominated trench basin (according to Meneghini et al.²² and Marroni and Pandolfi³⁸—Fig. 5a). The latter, whose dimensions have been estimated to be no more than a few tens km in the Late Cretaceous⁵⁵, is characterised by sediments sourced from areas located on either side of the trench (i.e., the accretionary wedge and the European margin) and an inherited rough topography of the subduction plate resulting from ultra-slow spreading processes. During the underplating, entire sections of the lower plate were deformed by a polyphase deformation history, which culminates in the prehnite-pumpellyite to low blueschist facies metamorphic condition^{34–36} (i.e., D1 phase, Fig. 1, Supplementary material S1) and accreted to the wedge. The latter was mostly formed by pieces of accreted and subsequently exhumed mafic oceanic crust, including its sedimentary cover, while the European continental margin consisted of felsic rocks and carbonate platform^{37,38}.

In the Bocca Shale Fm. exposed in the study area, pelites, siliciclastic turbidites and slide-blocks are the most common deposits accumulated in the trench. The lowest BML lithofacies exhibits an internally disorganized architecture, reflecting submarine landslide reworking of materials already accreted within the wedge^{22,38} (Fig. 5b). In this context, slide-blocks of Palombini Shale Fm. wrapped by a pebbly-mudstone matrix reworked marls and shales. The Albian age of nannofossils content from the marl layers at the boundary between BML and VSL supports the reworked origin, i.e., MTDs, of these deposits. The latter likely shaped the topography of the basin by enhancing the asperity of the depositional interface. Additionally, the presence of lithofacies with biostratigraphic, stratigraphic and sedimentary features similar to those described for the BML, i.e., the SIL,

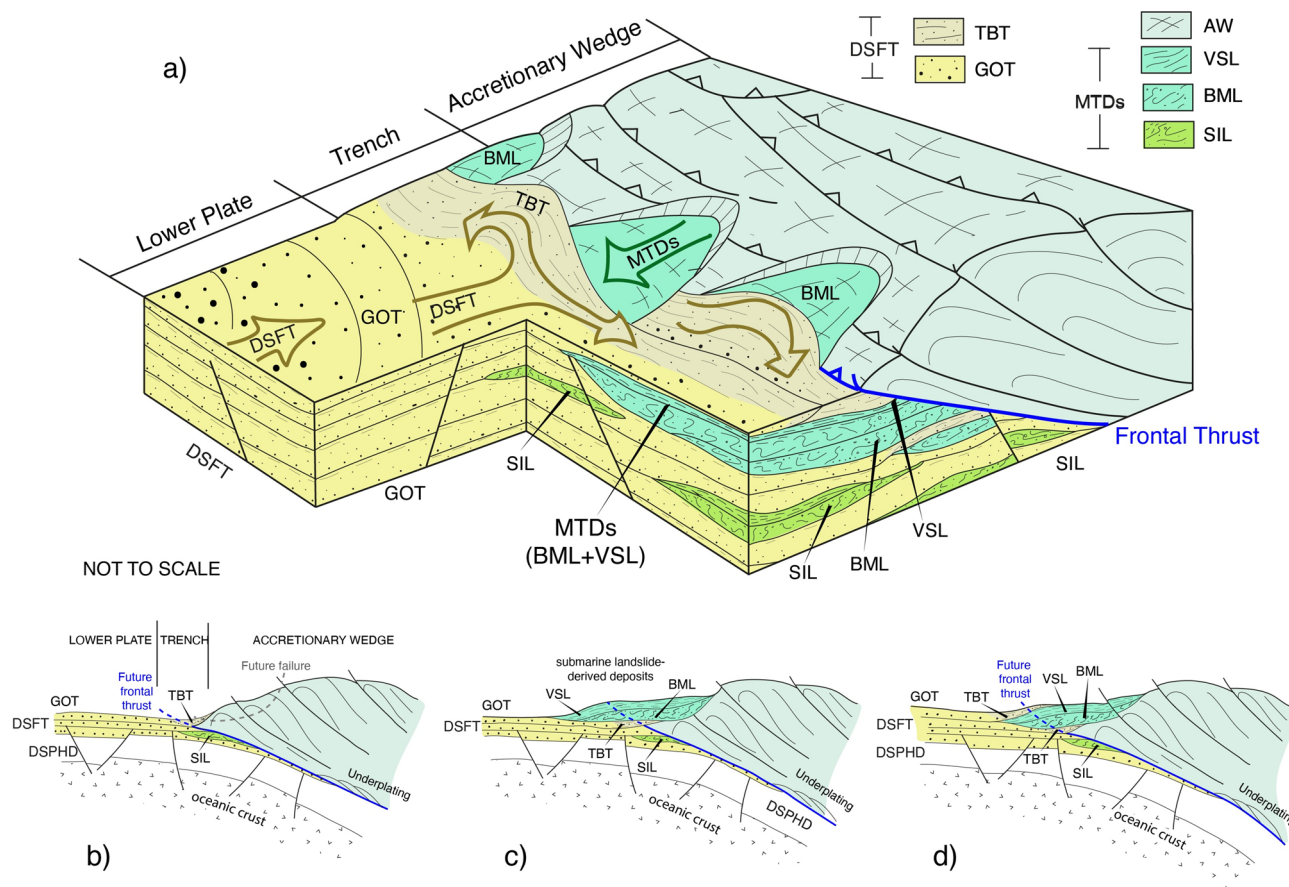


Fig. 5. Schematic geological setting reflecting the heterogeneous sedimentation inside a trench-basin according to what was recognized during the field work. **(a)** 3D scheme of a subduction zone with the trench basin fed by Mass Transport Deposits (MTDs) and Deep-Sea Fan Turbidites (DSFT) stemming from the accretionary wedge, from one side, and by the continental margin, on the other side. **(bd)** simplified perpendicular-to-depocenter 2D sketches of the trench basin investigated in this work. GOT: Gottoro Sandstone Fm.; TBT: Thin Bedded Turbidites; AW: Accretionary Wedge; VSL: Varicoloured Shaly Lithofacies; BML: Block-in-Matrix Lithofacies; SIL: Shaly Intercalation Lithofacies. DSPHD: Deep Sea Pelagic and Hemipelagic Deposits, sedimentary cover of the oceanic lithosphere. The sketches are not to scale and the thickness of some sedimentary bodies is deliberately exaggerated to make the diagram readable.

recognized at the top of the Gottero Sandstone Fm., indicates that feeding from a source area located along the frontal part of the accretionary wedge begins early, i.e., when sedimentation in the trench is largely dominated by coarse-grained deep-sea fan turbidites (here represented by the Gottero Sandstone Fm.).

The intermediate VSL lithofacies is mainly characterized by mud deposits and shows evidence for syn-sedimentary deformation (Fig. 5c). This highlights gravitational instability at the depositional interface, which is coherent with meso-scale angular unconformities found within different packages of beds. Additionally, VSL shows silt to fine-grained quartz-rich turbidites with scarce lateral continuity, typical of a sedimentation draping the edges of a confined basin (Fig. 5c). There, turbidites may move along-strike and perpendicular to the trench, shaping its complex topography and favouring instability. This in turn caused submarine landslides from the opposite sides of the trench, including that bounded by the accretionary wedge. This process has affected all the VSL package which has acquired the sedimentary and stratigraphic features of MTDs deposits. Quartz-rich turbidites of this lithofacies shows the same sedimentary features of the uppermost TBT lithofacies, which unconformably onlap onto the underlying deposits (Fig. 5d). The quartz-rich, fine-grained turbidites found in the VSL and TBT can be referred to low-density turbiditic currents with low erosive ability and deposited in a small, narrow trench environment (Fig. 5c, d), both reflecting a new sedimentation event whose deposits were fed by a source area located along the continental margin (i.e., the European margin).

The geochemical signature of the pelites associated with the three lithofacies of the Bocco Shale Fm., including those found at the top of the Gottero Sandstone Fm., sheds light on the differences in their source areas. The high values of Th and La, typically hosted in minerals forming evolved rocks^{50,51}, over Cr, V, and Yb, as well as the Th/Sc and La/Sc, indicate a marked felsic contribution for pelites associated to the uppermost TBT lithofacies of the Bocco Shale Fm. (Fig. 6a and Supplementary material S1). A strong mafic contribution, indicated by high values of V and Cr, these typically hosted in mafic rock-forming minerals like olivine, pyroxene and spine^{50,51}, over Th and a lower value of La/Yb, Th/Sc and La/Sc ratios, is documented in pelites associated with the SIL, the BML and the VSL, suggesting a common source area for the MTDs (Fig. 6a). The distinct mafic geochemical signature of these pelites reflects feeding from the accretionary wedge, formed by accreted slices of oceanic lithosphere³⁸, and support the reworking of the VSL packages, which can be considered as MTDs. The more felsic imprint for pelites of the TBT lithofacies invokes a source area located on a continental margin, which also fed the deposits of the Gottero Sandstone Fm. (i.e., the European margin).

Comparing the cumulative age distributions calculated on the total zircons analysed from both the Gottero Sandstone and the Bocco Shale Fms., further observations can be addressed. In both the Gottero Sandstone Fm. and the TBT lithofacies of the Bocco Shale Fm., the median of the distribution is 410 and 300 Ma, respectively, while in the VSL lithofacies it varies within 460–550 Ma (Fig. 6b). We lack information about the BML lithofacies, as no zircons were separated despite the same rock volume was processed. Notwithstanding, age distribution further supports the common source area located along the continental margin (i.e., the European margin) for the Gottero Sandstone Fm. and the quartz-rich turbidites found in TBT and VSL of the Bocco Shale Fm. The age distributions for each lithofacies thus reflect variability of the rocks forming the continental margin.

The U-Pb age model obtained from detrital zircons and the geochemical imprints of pelites reinforce field and stratigraphic constraints, elucidating the origin of the investigated deposits. Additionally, this integrated approach is demonstrated to be successful to unambiguously detect MTDs bodies from sediments with an organized internal structure. This allowed us to interpret the role played by MTDs during underthrusting, subduction and accretion processes.

Our results clearly highlight the interplay between different tectonically driven depositional events, such as deep-sea fan sedimentation vs. MTDs emplacement, within a sediment-dominated trench environment. The thickness of trench-fill sediments in shallow subduction zones can influence seismic coupling and the recurrence of megathrust earthquakes⁵⁶, while rheologically contrasting materials may affect the mechanical properties of the plate interface, thereby controlling the nucleation of slow-slip events at depth²¹.

Within this framework, the size, and distribution of MTDs, i.e., small- to medium clustered or single giant MTDs up hundreds of metres thick and till 1000 km² wide vs. a configuration of scattered small- to medium bodies (10–1000 km² over the host sediment package affect the nature of deformation and the seismic behavior at the plate interface (Festa et al.¹⁶ and references therein).

In the present case, the distribution of MTDs can be described as being characterized by small- to medium-clustered deposits and, at the scale of the IL Unit stack, it assumes a patchy configuration (Fig. 5). Data collected in the IL Units³³ suggest an accretionary mechanism for the MTDs by coherent underplating into the depth of the subduction interface²². No evidence for structures that, to date^{57–59}, are thought to probably represent the signature of slow-slip events (e.g., hydro-shear veins) was observed in the study area. A possible explanation lies in the relative size of the MTDs (here represented by the BML, VSL and SIL lithofacies) to the thick host sediments (here represented by the Gottero Sandstone Fm. and TBT lithofacies), which are supposed to be responsible of anomalies along the plate boundary. According to Festa et al.¹⁶, the patchiness configuration consisting of small- to medium-clustered MTDs has probably caused fluids migration and shearing away from the MTDs, leading to the development of mechanically weak horizons, where deformation has been partitioned. Such a configuration, together with ‘pre-packed’ discontinuities such as debris flow levels in the older deposits (i.e., in the Zonati Shale Fm.²⁸), is thought to have contributed to the dynamics of the accretion process by favouring coherent underplating mechanisms. To date, clear examples of active convergent margins where the subduction of MTDs with a patchy configuration or characterized by large volumes has been associated with destructive ruptures induced by megathrust events (e.g., Chilean margin⁶⁰). In this setting, the occurrence of earthquakes associated with megathrust development may, in turn, trigger large landslides on the lower slope of the accretionary wedge, producing volumes of MTDs that are sedimented on the subducting plate and subsequently underthrust at depth.

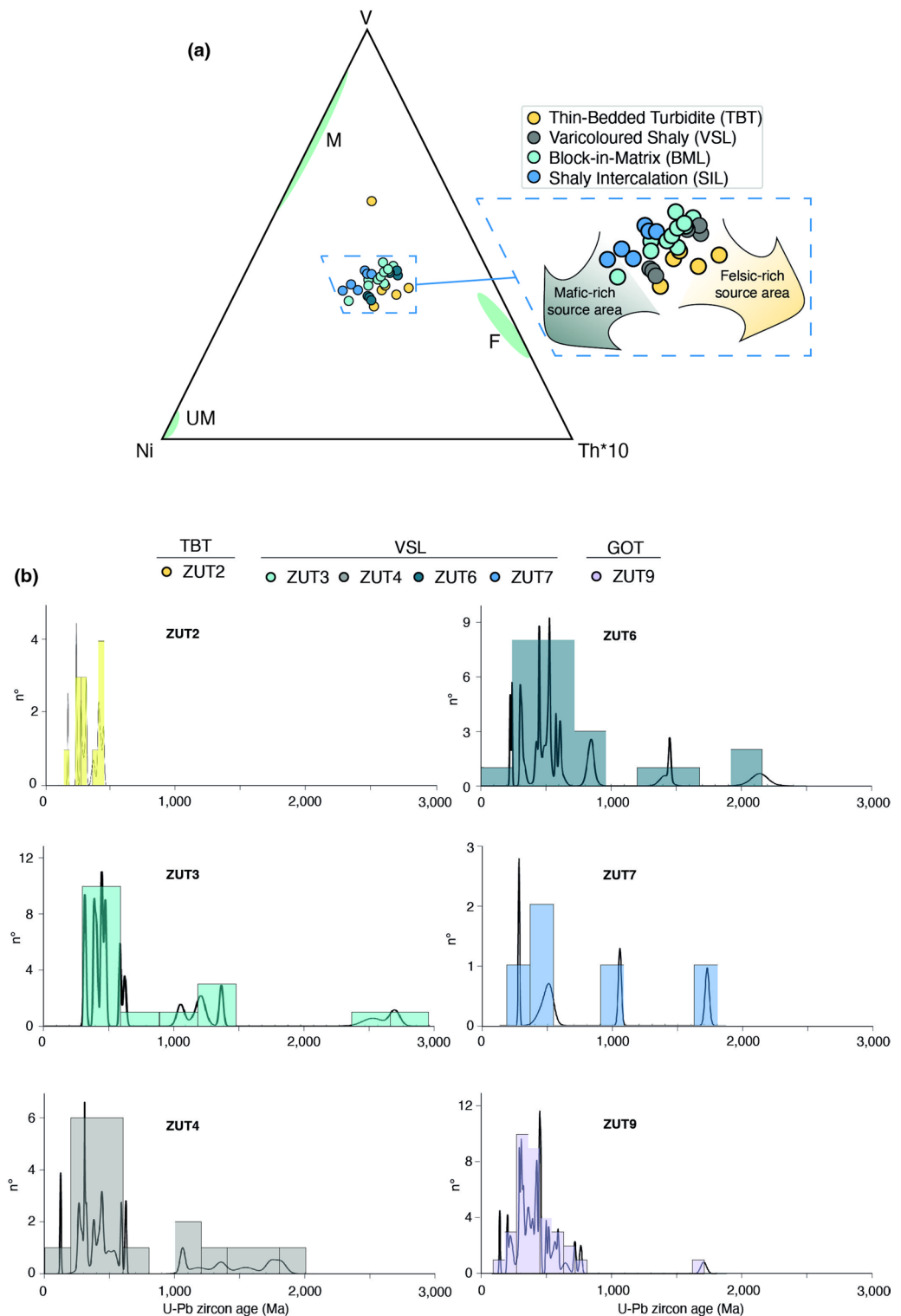


Fig. 6. Summary of geochemical and geochronological constraints for genetically different trench-related deposits. **(a)** V-Ni-Th*10 plot of pelites. Concentration of elements are in ppm. Green areas represent compositions of felsic (F), mafic (M) and ultramafic (UM) rocks (range from Bracciali et al.⁵⁰). The shifting of samples from MDTs toward Ni-V side indicates the ultramafic to mafic imprint of these pelites. By contrast, the deep-sea fan turbidites (TBT) show a more felsic component, and **(b)** Cumulative distributions of the $^{238}\text{U}/^{206}\text{Pb}$ zircon ages of the six samples studied.

In conclusion, we propose that the study area represents an exceptionally preserved fossil record of the interplay between deep-sea fan turbidites and MTDs supplied by two, opposite source areas in a trench-like environment. Stratigraphic, biostratigraphic, sedimentary, geochemical, and geochronological characteristics of the described deposits demonstrate the complexity and heterogeneity of the sedimentation processes active in a trench basin, which is a first-order feature in this tectonically driven depositional environment. The inherited framework of the subducting plate or discontinuities associated with the distribution and size of the MTDs deposits, i.e. the configuration of the MTDs above the host sediments in a trench environment, provide weak horizons where deformation can focus, thereby favouring coherent underplating processes.

Method

Field mapping High-resolution geological mapping, stratigraphic and structural analysis has been carried out in the Teviggio area (Eastern Liguria) by exploiting the classic field techniques. Structural data have been systematically collected in the whole investigated area.

Thin section Samples for microstructural and microtextural observation have been collected from the coarse-grained beds in the Bocco Shale Fm. lithofacies and from the shaly intercalation within the Gottero Sandstone Fm.

Microfacies petrography and nannofossils assemblage Marls have been sampled and they were prepared as smear slide and analyzed through an optical microscope at 1250X in order to detect the calcareous nannofossils assemblages. The analysis of the microfacies and microfossils assemblages has been performed through petrographic analysis by using the optical microscope on the two thin sections representative of the calcareous beds within the shaly intercalations close to the boundary between the Gottero Sandstone Fm. and the overlying Bocco Shale Fm.

Geochemistry of pelites Whole-rock analysis for major, minor and trace elements distribution of 31 powdered samples of pelites (Supplementary material S1 for the location of the sample) have been performed at Actlabs in Ancaster (Ontario, Canada). The fusion technique employs a lithium metaborate/tetraborate fusion. Analysis is performed by Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS). For data accuracy, calibrations were done using international reference materials together with measurement of four duplicates. Chemical analyses for each powdered sample are reported in the Supplementary material S2.

U-Pb dating A total of 150 zircons were hand-picked from seven samples of fine-grained sandstone collected in the thin-bedded turbidites and varicoloured lithofacies of the Bocco Shale Fm. and one from the Gottero Sandstone Fm. close to the boundary with the overlying Bocco Shale Fm. The grains were pictured at the cathodoluminescence (CL) and then dated by using the laser ablation ICP-MS U-Pb dating procedure (details in the Supplementary material S1 and S3).

Data availability

All data generated or analysed during this study are available within this published article (and its Supplementary material S1, S2 and S3). Data are also available on request from the corresponding author.

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References

- Platt, J. P. Dynamics of orogenic wedges and the uplift of high-pressure metamorphic rocks. *Geol. Soc. Am. Bull.* **97**, 1037–1053 [https://doi.org/10.1130/0016-7606\(1986\)972.0.CO;2](https://doi.org/10.1130/0016-7606(1986)972.0.CO;2) (1986).
- Moore, J. C. Tectonics and hydrogeology of accretionary prisms: role of the décollement zone. *J. Struct. Geol.* **11**, 95–106 [https://doi.org/10.1016/0191-8141\(89\)90037-0](https://doi.org/10.1016/0191-8141(89)90037-0) (1989).
- Cawood, P. A. et al. Accretionary orogens through Earth history. *Geol. Soc. Lond. Special Publication*. **318**, 1–36 <https://doi.org/10.1144/SP318.1> (2009).
- Haberland, C. et al. Anatomy of a crustal-scale accretionary complex: insights from deep seismic sounding of the onshore Western Makran subduction zone, Iran. *Geology* **49**, 3–7 <https://doi.org/10.1130/G47700.1> (2021).
- Angiboust, S., Menant, A., Gerya, T. & Oncken, O. The rise and demise of deep accretionary wedges: A long-term field and numerical modeling perspective. *Geosphere* **18**, 69–103 <https://doi.org/10.1130/GES02392.1> (2022).
- Sample, J. C. & Moore, J. C. Structural style and kinematics of an underplated slate belt, Kodiak and adjacent islands, Alaska. *Geol. Soc. Am. Bull.* **99**, 7–20 [https://doi.org/10.1130/0016-7606\(1987\)992.0.CO;2](https://doi.org/10.1130/0016-7606(1987)992.0.CO;2) (1987).
- Kukowski, N., Lallemand, S. E., Malavieille, J., Gutscher, M. A. & Reston, T. J. Mechanical decoupling and basal duplex formation observed in sandbox experiments with application to the Western Mediterranean ridge accretionary complex. *Mar. Geology*. **186**, 29–42 [https://doi.org/10.1016/S0025-3227\(02\)00171-8](https://doi.org/10.1016/S0025-3227(02)00171-8) (2002).
- Sick, C. et al. Seismic images of accretive and erosive subduction zones from the Chilean margin. In *The Andes* (ed Oncken, O. et al.) 147–169 (Springer, 2006). https://doi.org/10.1007/978-3-540-48684-8_7.
- Menant, A., Angiboust, S. & Gerya, T. Stress-driven fluid flow controls long-term megathrust strength and deep accretionary dynamics. *Sci. Rep.* **9**, 9714 <https://doi.org/10.1038/s41598-019-46191-y> (2019).
- Beaumont, C., Ellis, S. & Pfiffner, A. Dynamics of sediment subduction-accretion at convergent margins: Short-term modes, long-term deformation, and tectonic implications. *J. Geophys. Res. : Solid Earth*. **104**, 17573–17601 <https://doi.org/10.1029/1999JB900136> (1999).
- Gutscher, M. A., Kukowski, N., Malavieille, J. & Lallemand, S. Episodic imbricate thrusting and underthrusting: analog experiments and mechanical analysis applied to the Alaskan accretionary wedge. *J. Geophys. Res. : Solid Earth*. **103**, 10161–10176 (1998). <https://doi.org/10.1029/97JB03541>
- Stern, R. J. & Gerya, T. Subduction initiation in nature and models: A review. *Tectonophysics* **746**, 173–198 (2018). <https://doi.org/10.1016/j.tecto.2017.10.014>
- Collot, J. Y., Lewis, K., Lamarche, G. & Lallemand, S. The giant ruatoria debris avalanche on the Northern Hikurangi margin, New Zealand: result of oblique seamount subduction. *J. Geophys. Res. : Solid Earth*. **106**, 19271–19297 <https://doi.org/10.1029/2001JB900004> (2001).

14. Lamarche, G., Joanne, C., Collot, J. Y. & Successive Large mass-transport deposits in the South Kermadec fore-arc basin, New Zealand: the Matakaoa submarine instability complex. *Geochem. Geophys. Geosyst.* **9**, 1–30 <https://doi.org/10.1029/2007GC001843> (2008).
15. Strasser, M. et al. A slump in the trench: tracking the impact of the 2011 Tohoku-Oki earthquake. *Geology* **41**, 935–938 <https://doi.org/10.1130/G34477.1> (2013).
16. Festa, A. et al. Does subduction of mass transport deposits (MTDs) control seismic behavior of shallow-level megathrusts at convergent margins? *Gondwana Res.* **60**, 186–193 <https://doi.org/10.1016/j.gr.2018.05.002> (2018).
17. Fagereng, Å. & Sibson, R. H. Mélange rheology and seismic style. *Geology* **38**, 751–754 <https://doi.org/10.1130/G30868.1> (2010).
18. Cloos, M. Flow melanges: numerical modeling and geologic constraints on their origin in the Franciscan subduction complex, California. *Geol. Soc. Am. Bull.* **93**, 330–345 [https://doi.org/10.1130/0016-7606\(1982\)93<2.0.CO;2](https://doi.org/10.1130/0016-7606(1982)93<2.0.CO;2) (1982).
19. Festa, A., Pini, G. A., Dilek, Y. & Codegone, G. Mélanges and mélange-forming processes: a historical overview and new concepts. *Int. Geol. Rev.* **52**, 1040–1105 <https://doi.org/10.1080/00206810903557704> (2010).
20. Dilek, Y., Festa, A., Ogawa, Y. & Pini, G. A. Chaos and geodynamics: mélanges, mélange-forming processes and their significance in the geological record. *Tectonophysics* **568**, 1–6 <https://doi.org/10.1016/j.tecto.2012.08.002> (2012).
21. Barnes, P. M. et al. Slow slip source characterized by lithological and geometric heterogeneity. *Sci. Adv.* **6**, 3314–3324 <https://doi.org/10.1126/sciadv.aay3314> (2020).
22. Meneghini, F., Pandolfi, L. & Marroni, M. Recycling of heterogeneous material in the subduction factory: evidence from the sedimentary mélange of the Internal Ligurian Units, Italy. *J. Geol. Soc.* **177**, 587–599 <https://doi.org/10.1144/jgs2019-081> (2020).
23. Sanità, E., Di Rosa, M., Lardeaux, J. M., Marroni, M. & Pandolfi, L. The Moglio-Testico unit as subducted metamorphic oceanic fragments: stratigraphic, structural and metamorphic constraints. *Minerals* **12**, 1343 <https://doi.org/10.3390/min12111343> (2022).
24. Zanzucchi, P., Sanità, E., Catanzariti, R., Pandolfi, L. & Marroni, M. Revisiting the Internal Ligurian Units of the Antessio area (Ligurian Apennines, Italy): insights into the oceanic lithosphere of the Ligurian-Piedmont basin. *Ophioliti*, **50**(2), 47–62 <https://doi.org/10.4454/phioliti.v50i2.578> (2025).
25. Festa, A. et al. Comparative analysis of the sedimentary cover units of the Jurassic Western Tethys ophiolites in the Northern Apennines and Western Alps (Italy): processes of the formation of mass-transport and chaotic deposits during seafloor spreading and subduction zone tectonics. *J. Geol.* **129**, 533–561 <https://doi.org/10.1086/716498> (2021).
26. Bortolotti, V., Principi, G. & Treves, B. Mesozoic evolution of Western Tethys and the Europe/Iberia/Adria plate junction. *Mem. Soc. Geol. It.* **45**, 393–407 (1990).
27. Molli, G. Northern Apennines-Corsica orogenic system: an updated overview. *Geol. Soc. Lond. Spec. Publ.* **298**, 413–442 (2008).
28. Marroni, M., Meneghini, F. & Pandolfi, L. A revised subduction inception model to explain the Late Cretaceous, double-vergent orogen in the precollisional Western Tethys: evidence from the Northern Apennines. *Tectonics* **36**, 2227–2249 <https://doi.org/10.1002/2017TC004627> (2017).
29. Principi, G. & Treves, B. Il sistema Corso-Appenninico come prisma di accrezione. Riflessi sul problema generale del limite Alpi-Appennini. *Mem. Soc. Geol. It.* **28**, 549–576 (1984).
30. Sanfilippo, A. & Tribuzio, R. Melt transport and deformation history in a nonvolcanic ophiolitic section, Northern Apennines, Italy: Implications for crustal accretion at slow spreading settings. *Geochem. Geophys. Geosyst.* **12**, 1–34 <https://doi.org/10.1029/2010GC003429> (2011).
31. Fonesu, M. & Felletti, F. Facies and architecture of a sand-rich turbidite system in an evolving collisional-trench basin: A case history from the upper Cretaceous-Palaeocene Gottero system (NW Apennines). *Riv. Ital. Paleol. Strat.* **125**, 449487 (2019) <https://dx.doi.org/10.13130/2039-4942/11789>.
32. Marroni, M., Molli, G., Montanini, A. & Tribuzio, R. The association of continental crust rocks with ophiolites in the Northern Apennines (Italy): implications for the continent-ocean transition in the Western Tethys. *Tectonophysics* **292**, 43–66 [https://doi.org/10.1016/S0040-1951\(98\)00060-2](https://doi.org/10.1016/S0040-1951(98)00060-2) (1998).
33. Marroni, M., Meneghini, F. & Pandolfi, L. From accretion to exhumation in a fossil accretionary wedge: a case history from Gottero unit (Northern Apennines, Italy). *Geodin. Acta* **17**, 41–53 <https://doi.org/10.3166/ga.17.41-53> (2004).
34. Meneghini, F., Di Rosa, M., Marroni, M., Raimbourg, H. & Pandolfi, L. Subduction signature in the Internal Ligurian Units (Northern Apennine, Italy): Evidence from P–T metamorphic peak estimate. *Terra Nova*, **36**, 182–190 <https://doi.org/10.1111/ter.12694> (2023).
35. Sanità, E., Di Rosa, M., Marroni, M., Meneghini, F. & Pandolfi, L. Insights into the subduction of the Ligure-Piemontese oceanic basin: new constraints from the metamorphism in the Internal Ligurian Units (Northern Apennines, Italy). *Minerals* **14**, 64 <https://doi.org/10.3390/min14010064> (2024).
36. Sanità, E., Di Rosa, M. & Mugnaioli, E. Non-conventional pressure estimates by using transmission electron microscopy coupled with energy-dispersive spectroscopy (TEM-EDS): testing on submicrometer white mica from low-grade metapelites. *Eur. J. Mineral.* **37**, 343–352 <https://doi.org/10.5194/ejm-37-343-2025> (2025).
37. Pandolfi, L. Stratigrafia ed evoluzione strutturale delle successioni torbiditiche cretacee della Liguria orientale (Appennino Settentrionale) 1–175 (PhD dissertation, University of Pisa, 1997). (1997).
38. Marroni, M. & Pandolfi, L. Debris flow and slide deposits at the top of the internal Liguride ophiolitic sequence, Northern Apennines, Italy: a record of frontal tectonic erosion in a fossil accretionary wedge. *Isl. Arc.* **10**, 9–21 <https://doi.org/10.1046/j.1440-1738.2001.00289.x> (2001).
39. Puccinelli, A., D'Amato Avanzi, A. & Perilli, N. Note illustrative del Foglio 233 Pontremoli della Carta Geologica d'Italia alla scala 1: 50.000. ISPRA Istituto Superiore per la Protezione e la Ricerca Ambientale - Serv. Geol. d'It. A.T.I. - S.E.L.C.A. srl - L.A.C. srl - System Cart srl, Firenze, Italy: 127 (2015).
40. Huber, B. T. & Leckie, R. M. Planktic foraminiferal species turnover across deep-sea Aptian/Albian boundary sections. *J. Foramin. Res.* **41**, 53–95 <https://doi.org/10.2113/gsjfr.41.1.53> (2011).
41. Huber, B. T., Petrizzo, M. R. & Falzoni, F. Taxonomy and phylogeny of Albian–Maastrichtian planispiral planktonic foraminifera traditionally assigned to globigerinelloides. *Micropaleontology* **68**, 117–183 (2022).
42. Abbate, E., Bortolotti, V. & Passerini, P. Olistostromes and olistoliths. *Sedim. Geol.* **4**, 521–557 (1970).
43. Mutti, E. Turbidite sandstones. AGIP, Istituto di geologia, Università di Parma, 275 (1992).
44. Costa, J. E. Rheologic, geomorphic and sedimentologic differentiation of water floods, hyperconcentrated flows and debris flows. In: V.R. Baker, R.C. Kochel and P.C. Patton (Eds.), Flood geomorphology, Wiley-Intersciences Publications. 113–122 (1988).
45. Shamrock, J. L. & Watkins, D. K. Evolution of the Cretaceous calcareous nannofossil genus Eifellithus and its biostratigraphic significance. *Cretac. Res.* **30**, 1083–1102 <https://doi.org/10.1016/j.cretres.2009.03.009> (2009).
46. Bown, P. R., Young, J. R. Techniques in *Calcareous Nannofossil Biostratigraphy*. British Micropaleontological Society Publications Series 16–28 (eds Bown, P. R.) (Chapman and Kluwer Academic, 1998). doi: 10.1007/978-94-011-4902-0
47. Condie, K. C. Another look at rare Earth elements in shales. *Geochim. Cosmochim. Acta* **55**, 2527–2531 (1991). [https://doi.org/10.1016/0016-7037\(91\)90370-K](https://doi.org/10.1016/0016-7037(91)90370-K)
48. Taylor, S. R. & McLennan, S. M. The Continental Crust: Its Composition and Evolution, 1–312 (Oxford, Blackwell, 1985). (1985).
49. Rudnick, R. L. & Gao, S. Composition of the continental crust. *Treatise Geochem.* **3**, 1–64 (2003).
50. Bracciali, L., Marroni, M., Pandolfi, L. & Rocchi, S. Geochemistry and petrography of Western Tethys Cretaceous sedimentary covers (Corsica and Northern Apennines): From source areas to configuration of margins. *Geol. Soc. Am. Sp. Pub.* **420**, 73–93 [https://doi.org/10.1130/2006.2420\(06\)](https://doi.org/10.1130/2006.2420(06)) (2007).

51. Bracciali, L., Pandolfi, L. & Rocchi, S. A snapshot of the late jurassic Western Tethys seafloor composition and morphology provided by the geochemistry of pelitic sediments (Corsica, Central Alps and Northern Apennines). *Basin Res.* **26**, 461–485 <https://doi.org/10.1111/bre.12036> (2014).
52. Rubatto, D. Zircon trace element geochemistry: partitioning with Garnet and the link between U–Pb ages and metamorphism. *Chem. Geol.* **184**, 123–138 (2002).
53. Fornelli, A., Gallicchio, S., Micheletti, F. & Langone, A. U–Pb detrital zircon ages from Gorgoglione flysch sandstones in Southern Apennines (Italy) as provenance indicators. *Geol. Mag.* **158**, 859–874 <https://doi.org/10.1017/S0016756820000886> (2021).
54. Marsellos, A. E. & Garver, J. I. Radiation damage and uranium concentration in Zircon as assessed by Raman spectroscopy and neutron irradiation. *Am. Mineral.* **95**, 1192–1201 <https://doi.org/10.2138/am.2010.3264> (2010).
55. Le Breton, E. et al. Kinematics and extent of the Piemonte–Liguria Basin—implications for subduction processes in the Alps. *Solid Earth.* **12**, 885–913 <https://doi.org/10.5194/se-12-885-2021> (2021).
56. Heuret, A., Conrad, C. P., Funicello, F., Lallemand, S. & Sandri, L. Relation between subduction megathrust earthquakes, trench sediment thickness and upper plate strain. *Geophys. Res. Lett.* **39**, 1–6 <https://doi.org/10.1029/2011GL050712> (2012).
57. Platt, J. P., Grujic, D., Phillips, N. J., Piazzolo, S. & Schmidt, D. A. Geological fingerprints of deep slow earthquakes: A review of field constraints and directions for future research. *Geosphere* **20**, 981–1004 <https://doi.org/10.1130/GES02722.1> (2024).
58. Fagereng, Å., Remitti, F. & Sibson, R. H. Incrementally developed slickenfibers—Geological record of repeating low stress-drop seismic events? *Tectonophysics* **510**, 381–386 <https://doi.org/10.1016/j.tecto.2011.08.015> (2011).
59. Fagereng, Å., Diener, J. F., Ellis, S. & Remitti, F. Fluid-related deformation processes at the up- and down-dip limits of the subduction thrust seismogenic zone: what do the rocks tell us? *Geol. Soc. Am. Spec. Paper.* **534**, 187–215 [https://doi.org/10.1130/2018.2534\(12\)](https://doi.org/10.1130/2018.2534(12)) (2018).
60. Olsen, K. M. et al. Thick, strong sediment subduction along south-central Chile and its role in great earthquakes. *Earth Plan. Sci. Lett.* **538**, 116195 <https://doi.org/10.1016/j.epsl.2020.116195> (2020).

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Author contributions

MM and LP were responsible for conceptualizing the research. ES performed the geological mapping and sample collection for fossil content and geochemical analysis and, for the latter, he also performed data reduction and interpretation. MDR performed sampling for detrital zircons analysis and U–Pb dating. RC performed the analysis of calcareous nannofossils content and GDP carried out the petrographic analysis of microfossils. All the authors contributed to the original writing, reviewing, editing and discussion, and the final approval of the manuscript.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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