Cenozoic Stratigraphy

Schlieren Flysch, Paleocene-Eocene, Sorenburg, Switzerland

Pre-Alpine Orogeny or (a in map) not involved in orogens

34, 35 — Limestones and marly limestones with chert, radiolarites, calcareous marls, marls and pelites, locally interbedded turbiditic calcarenites **(34)**; idem, frequently interbedded with calcarenitic and arenaceous turbidites, locally condensed limestones and marls **(35)**
Cretaceous-Tortonian, locally up to Pliocene

36, 37 — Shales and radiolarites, with alternating marls and turbiditic calcarenites **(36)**; idem, with low- to very low-grade metamorphism **(37)**
Cretaceous-Lower Miocene, locally since Middle Jurassic

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Jurassic, since Pliensbachian

42 — Limestones and dolostones, sometimes cherty, marly limestones and pelites, locally bituminous, with calcarenitic intercalations
Middle Triassic-Lower Jurassic

43 — Limestones, dolostones, pelites and sandstones, with frequent intercalations of turbiditic calcarenites and basalts
Permian

Symbols

Dashed where inferred or buried

- Edge of caldera
- Undifferentiated tectonic contact
- Normal fault
- Strike-slip fault
- Thrust and reverse fault

Epi-oceanic and epi-continental Platform and proximal Ramp carbonate deposits

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Miocene-Lower Pleistocene, locally since Oligocene

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Upper Cretaceous, locally since Lower Cretaceous or up to Paleogene

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Jurassic-Lower Cretaceous

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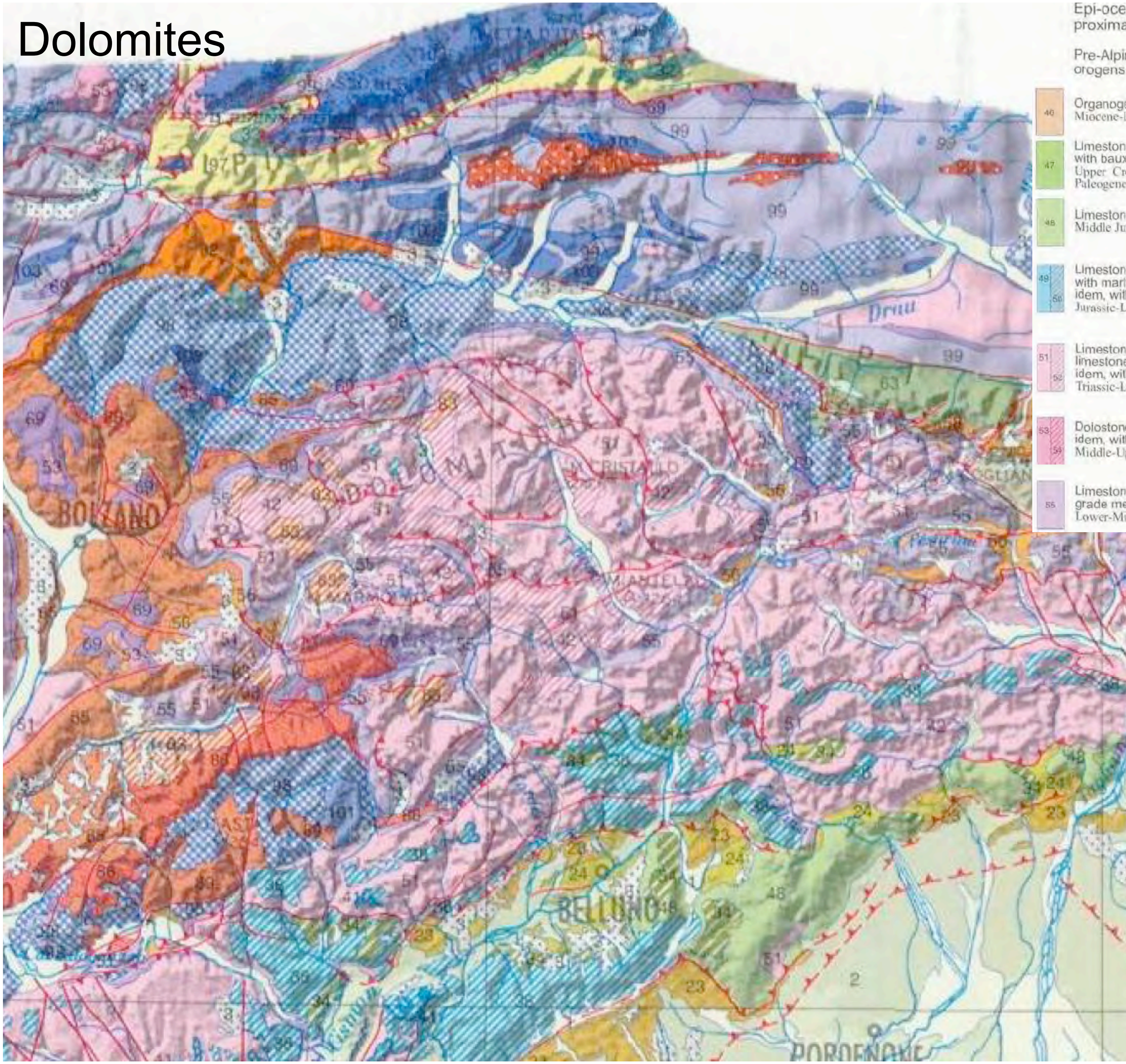
Triassic-Lower Jurassic

53, 54 — Dolostones, marls and evaporites **(53)**; idem, with low- to very low-grade metamorphism **(54)**
Middle-Upper Triassic, locally up to Lower Jurassic

55 — Limestones, sandstones and pelites, locally with low-grade metamorphism
Lower-Middle Triassic

Dolomites



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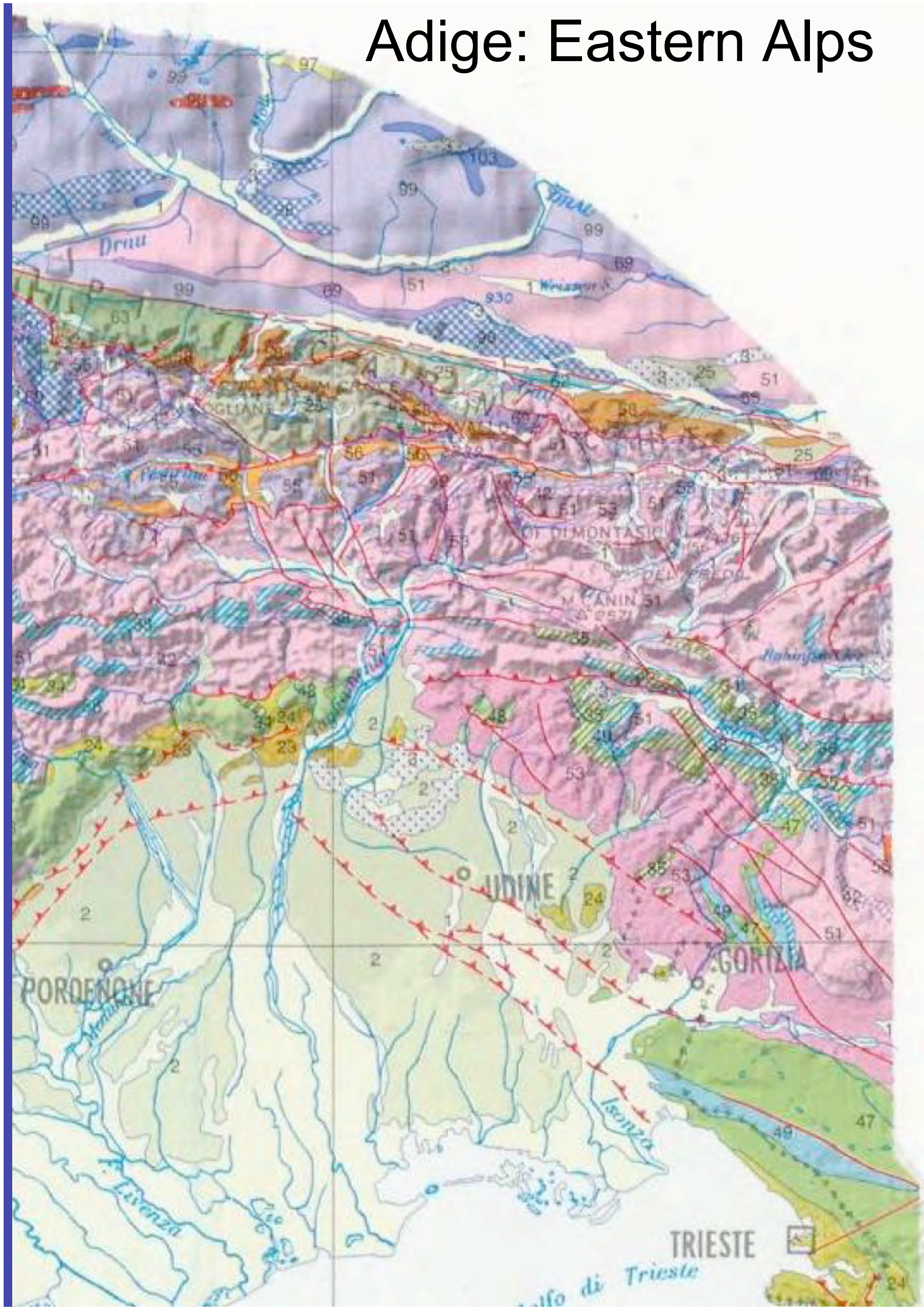
Adige: Eastern Alps



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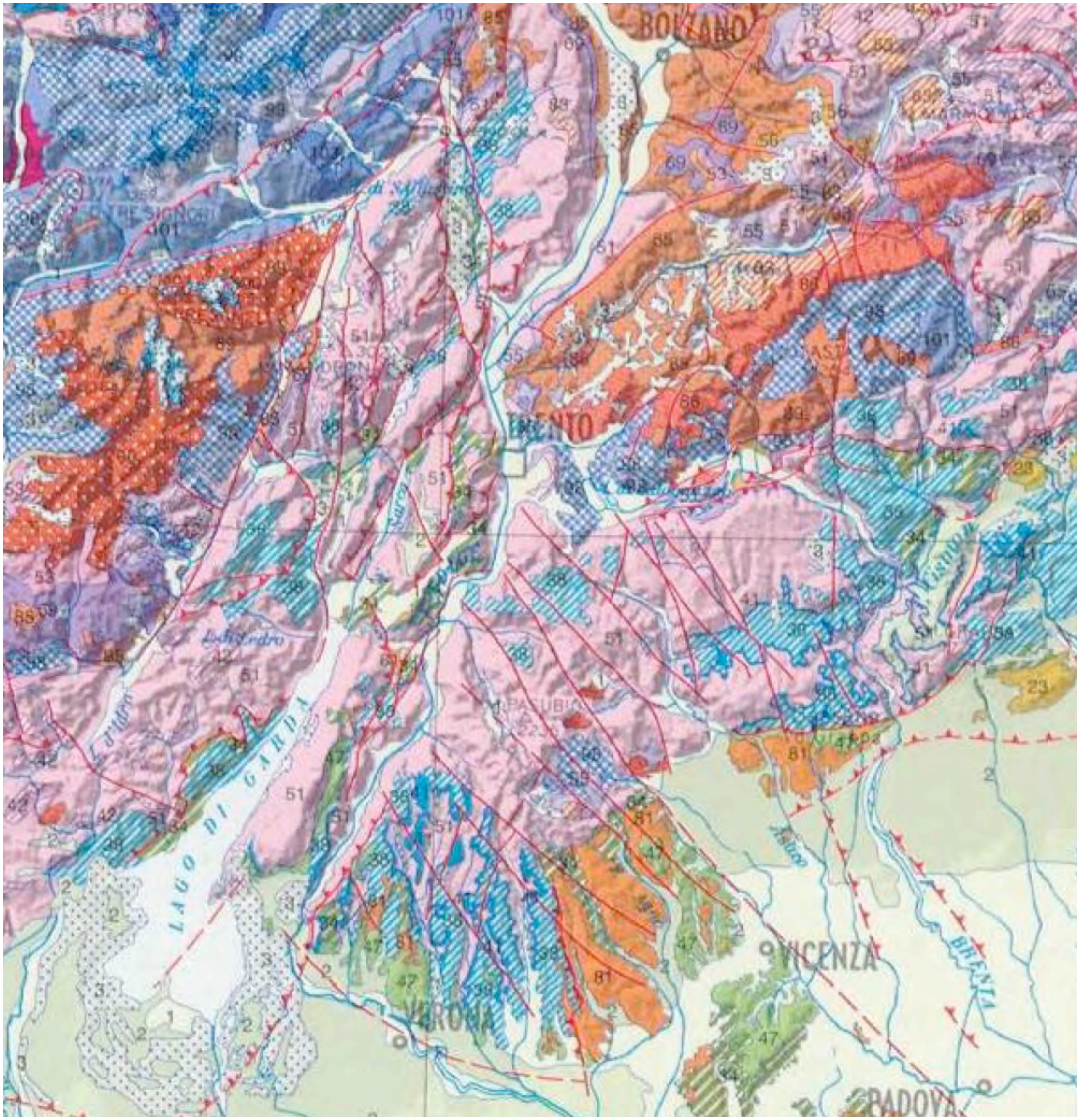

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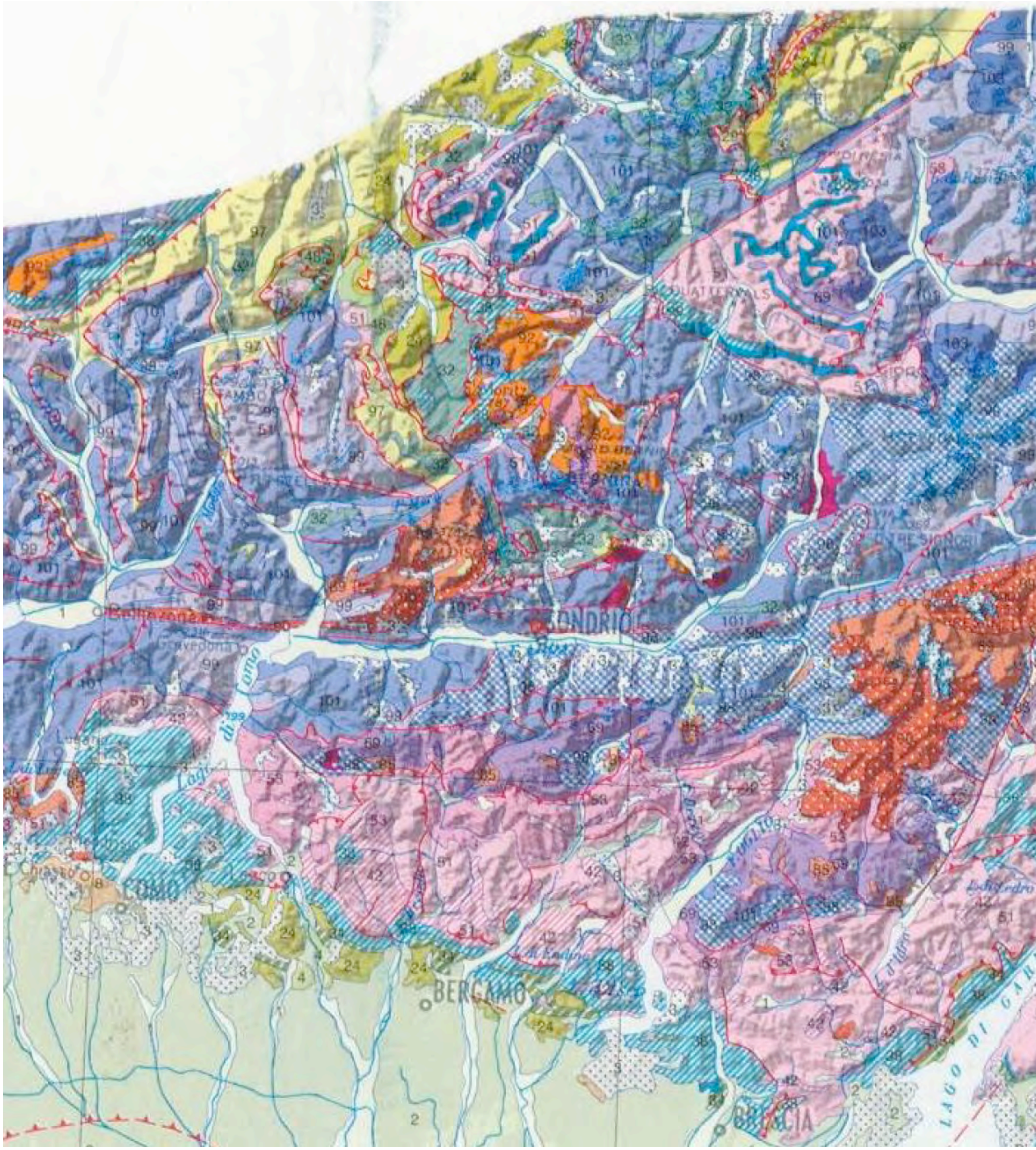

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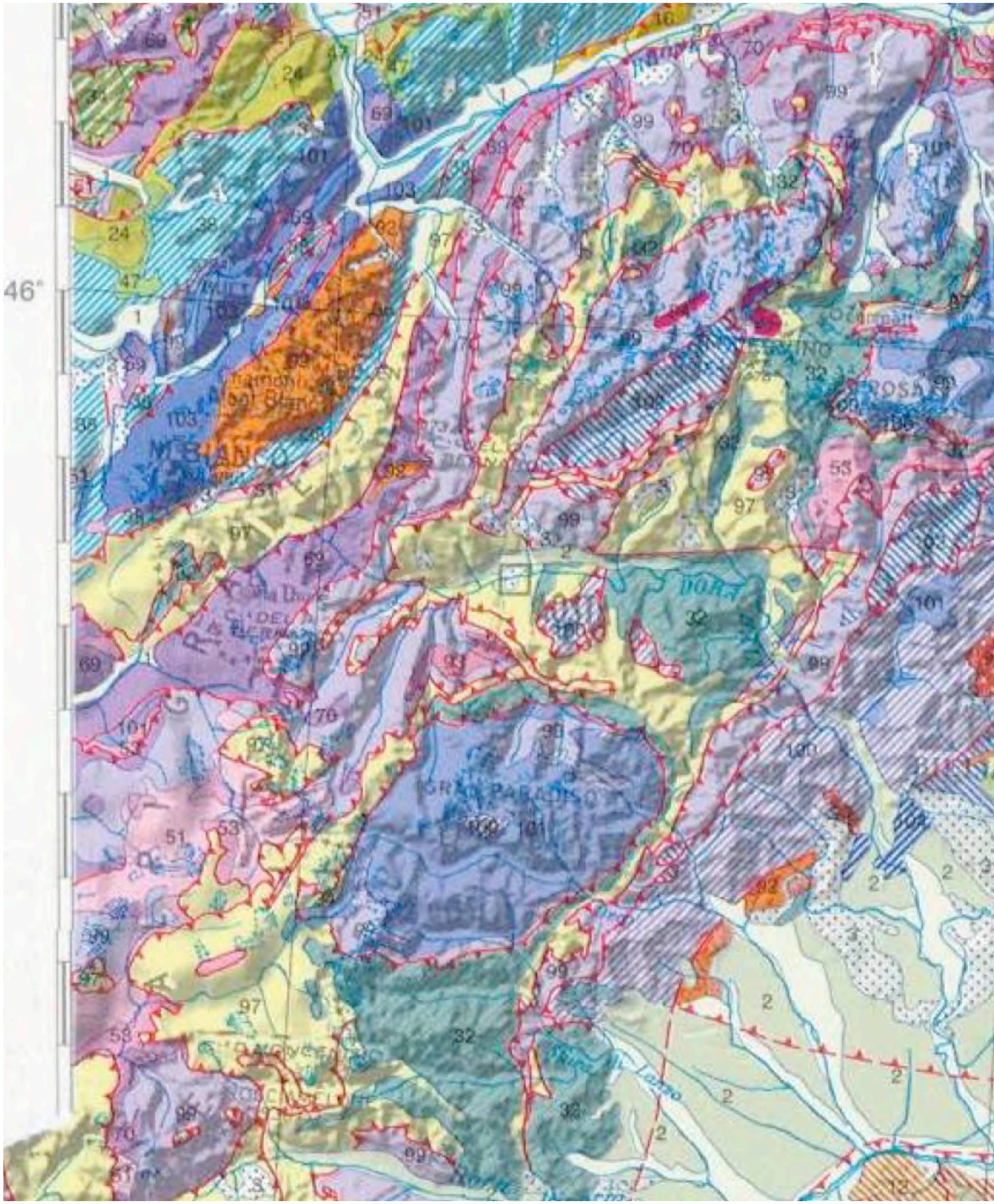

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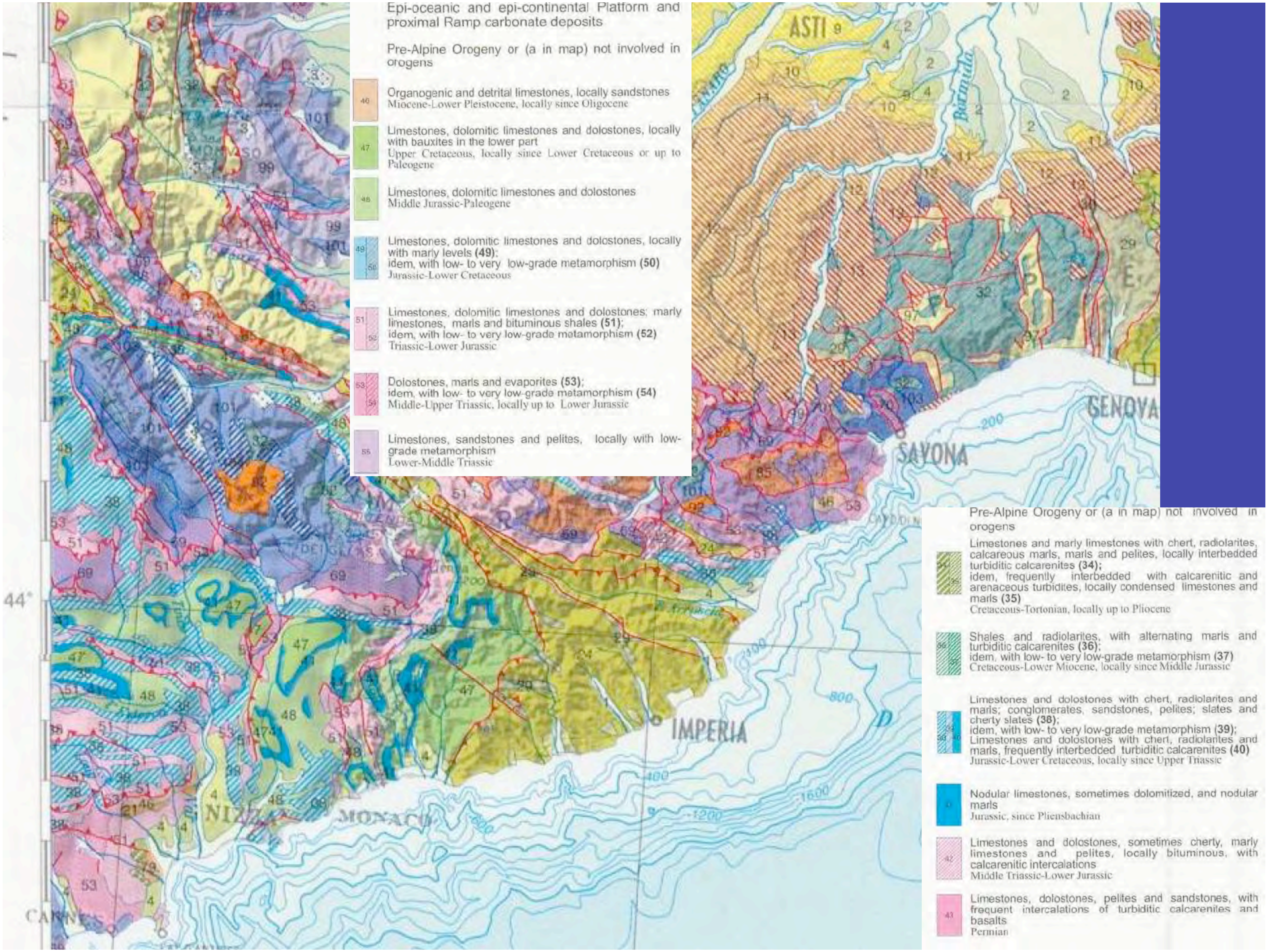

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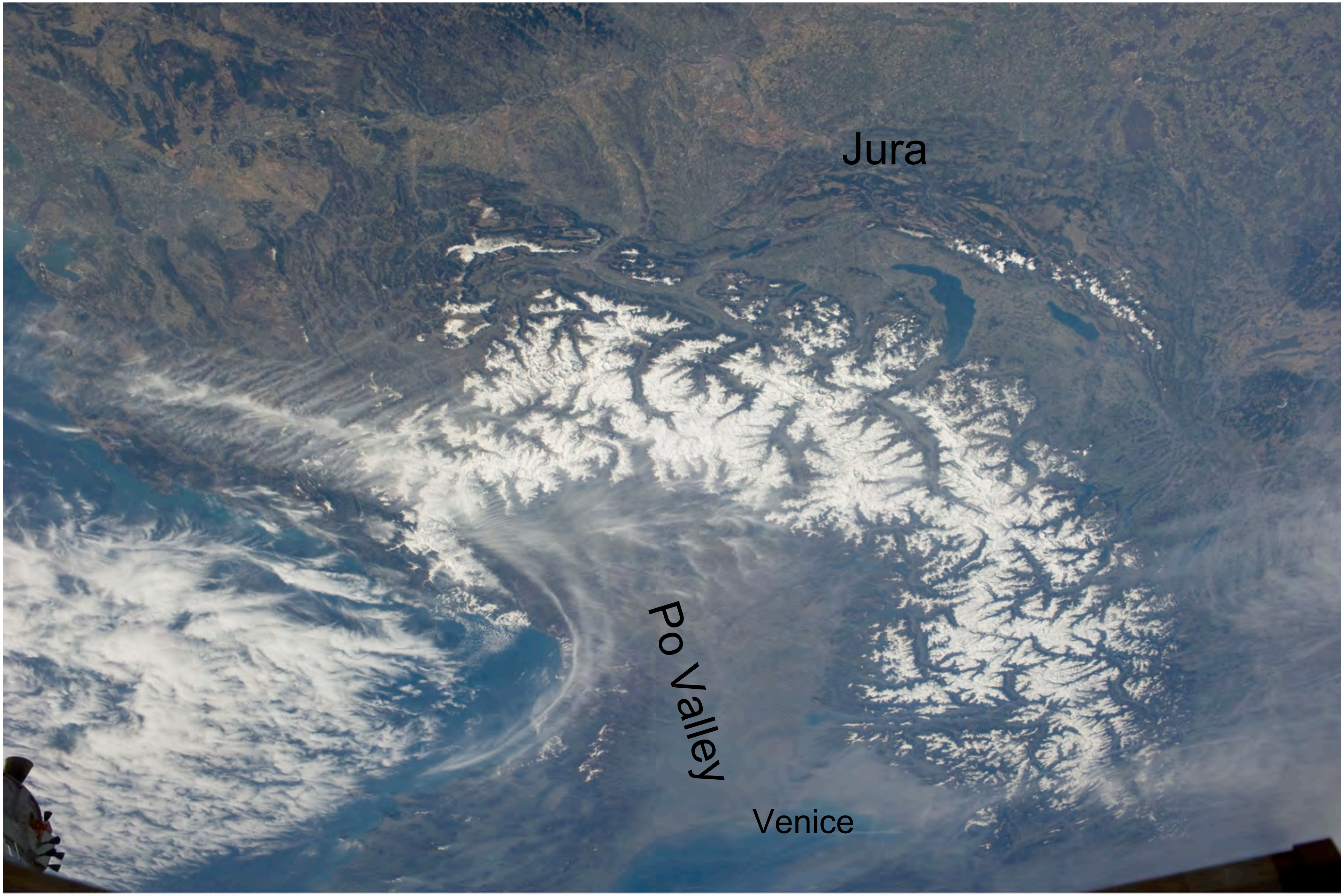

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Alps, Lake Geneva, Adriatic

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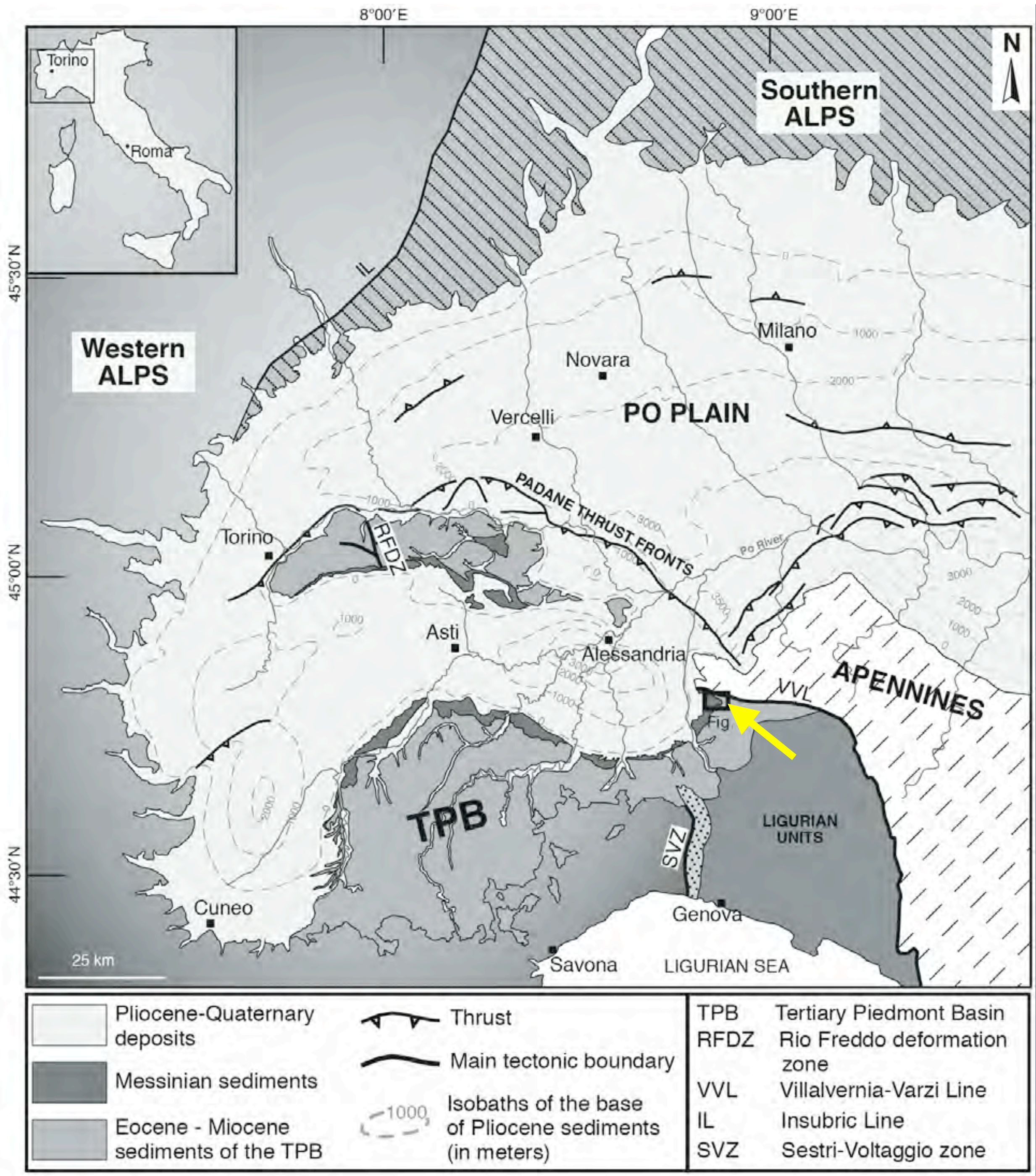

Figure 1. Structural sketch map of northwestern Italy (modified from Bigi et al., 1990) and location of the studied area.

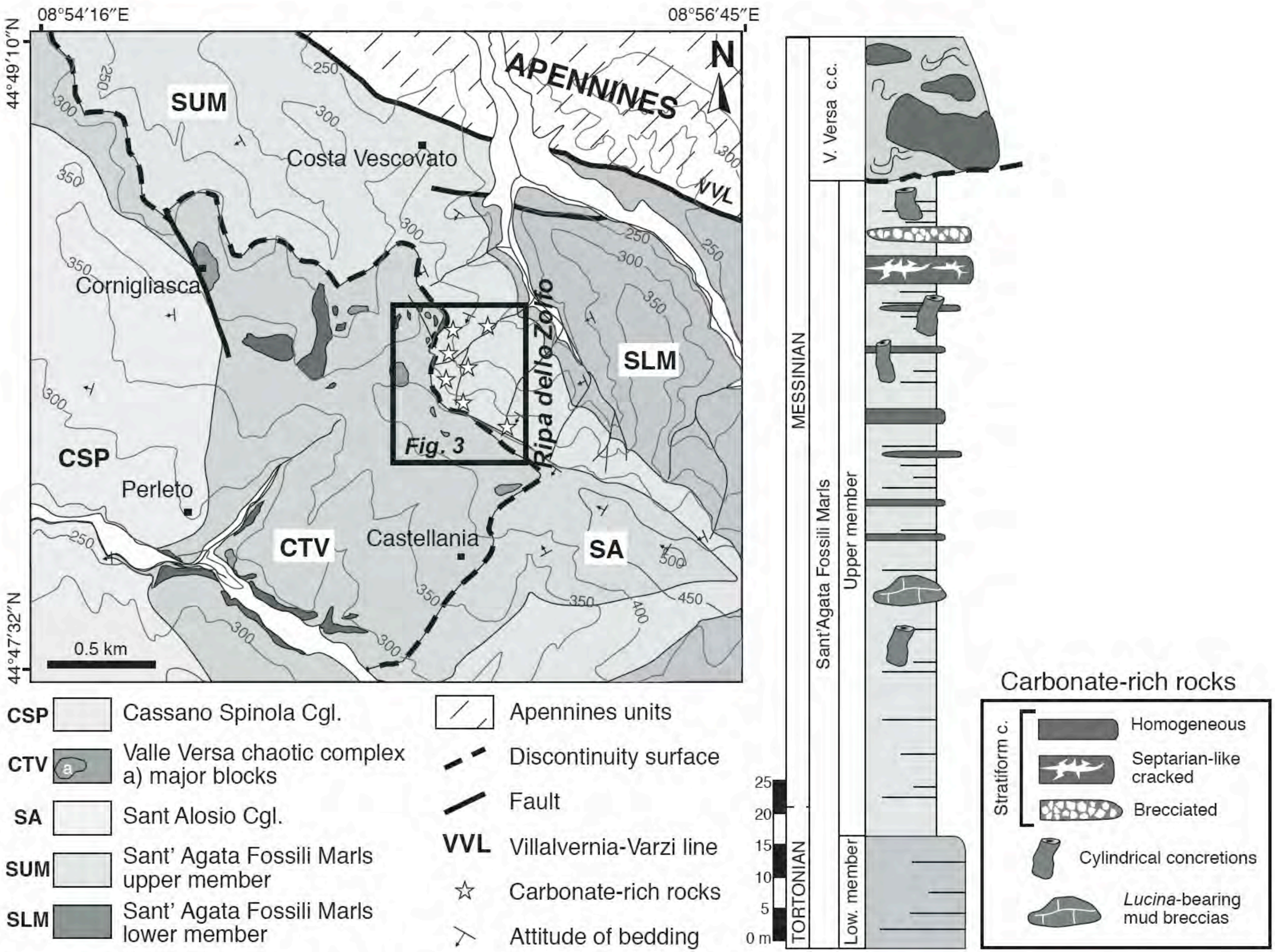

Figure 2. Geological map (modified from Ghibaudo et al., 1985) (left) and stratigraphic section (right) of the Upper Miocene sediments of the Ripa dello Zolfo area. Location of the map is shown in Figure 1.

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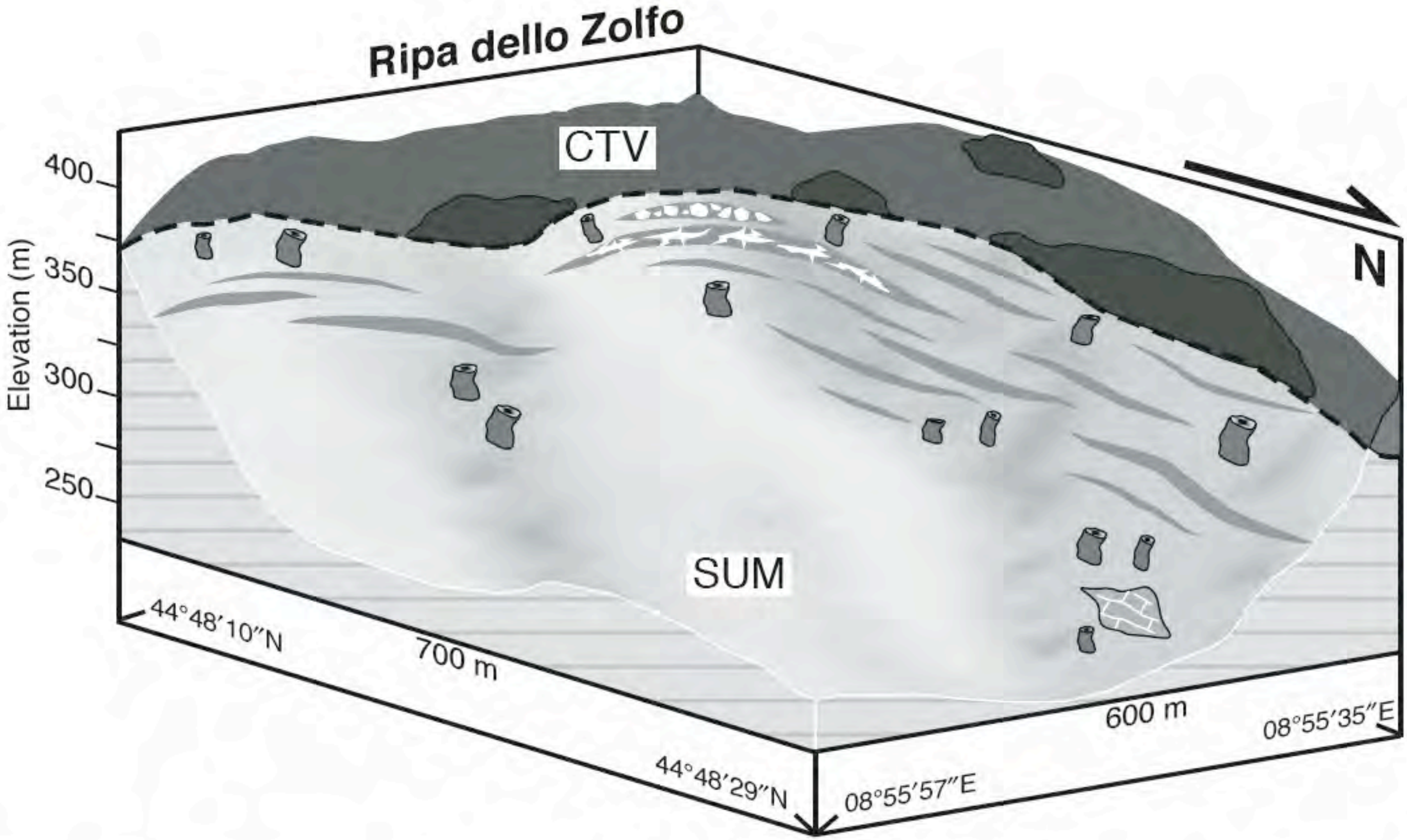

Figure 3. Block diagram showing the distribution of the carbonate-rich rocks discussed in the text. Symbols are as in Figure 2. SUM—Sant'Agata Fossili Marls, upper Member; CTV—Complesso Caotico della Valle Versa.

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Figure 4. *Lucina*-bearing mud breccias: (A) Outcrop view of the cemented rock body. The white dotted line shows the boundary with the hosting sediments. (B) Polished slab of the cemented mud breccias. Clasts of different size, floating in a darker fine-grained matrix, are recognizable. Small articulated and disarticulated bivalve shells (arrows) are also visible. (C) External mold of a *Lucina* bivalve. (D) Photomicrograph of a fracture cutting the matrix of the mud breccias. A fibrous aragonite rim, growing on micritic internal sediments, is recognizable.

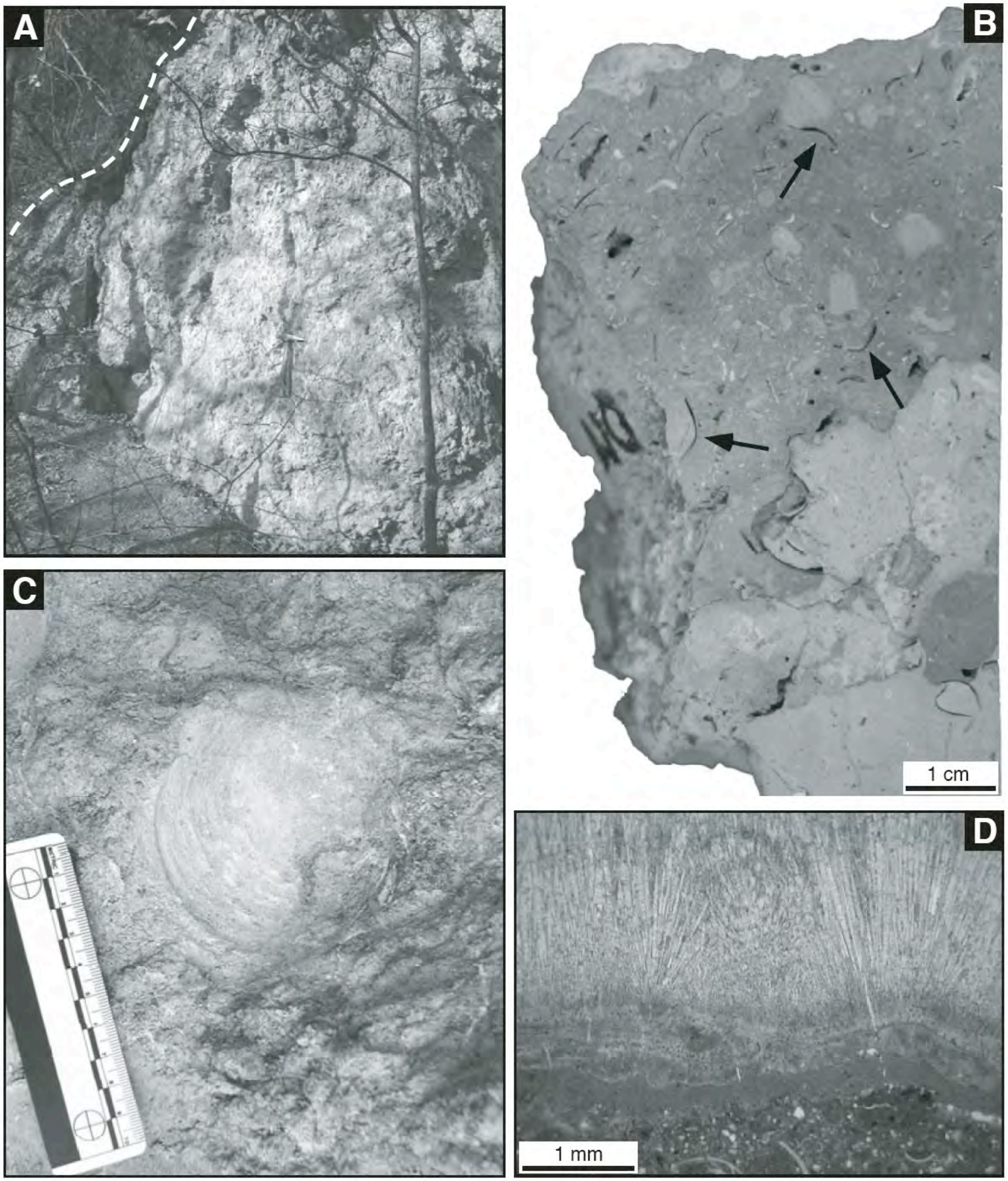

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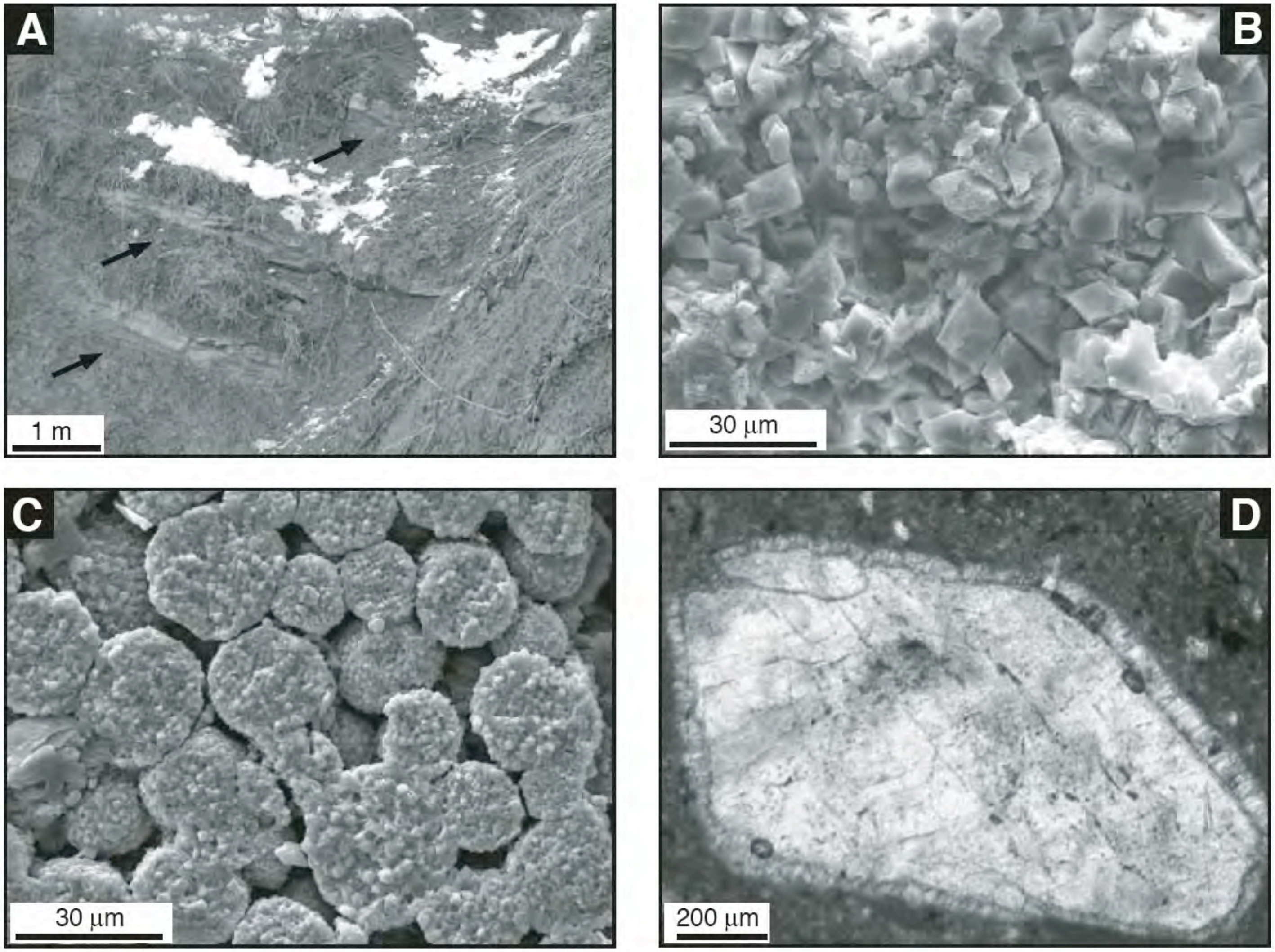
Figure 5. Stratiform concretions: (A) Outcrop view of stratiform concretions. Three superposed decimeter-thick cemented beds with a lateral continuity of several meters (arrows) are recognizable under the snow. Location is shown in Figure 3. (B) Scanning electron microscope (SEM) image of a broken chip of a homogeneous concretion body, showing the euhedral dolomite crystals cementing the sediments (slightly etched surface). (C) SEM image of pyrite framboids in an homogeneous concretion body (slightly etched polished surface). (D) Photomicrograph of a sand-sized quartz grain surrounded by a circumgranular rim filled with dolomite cement.



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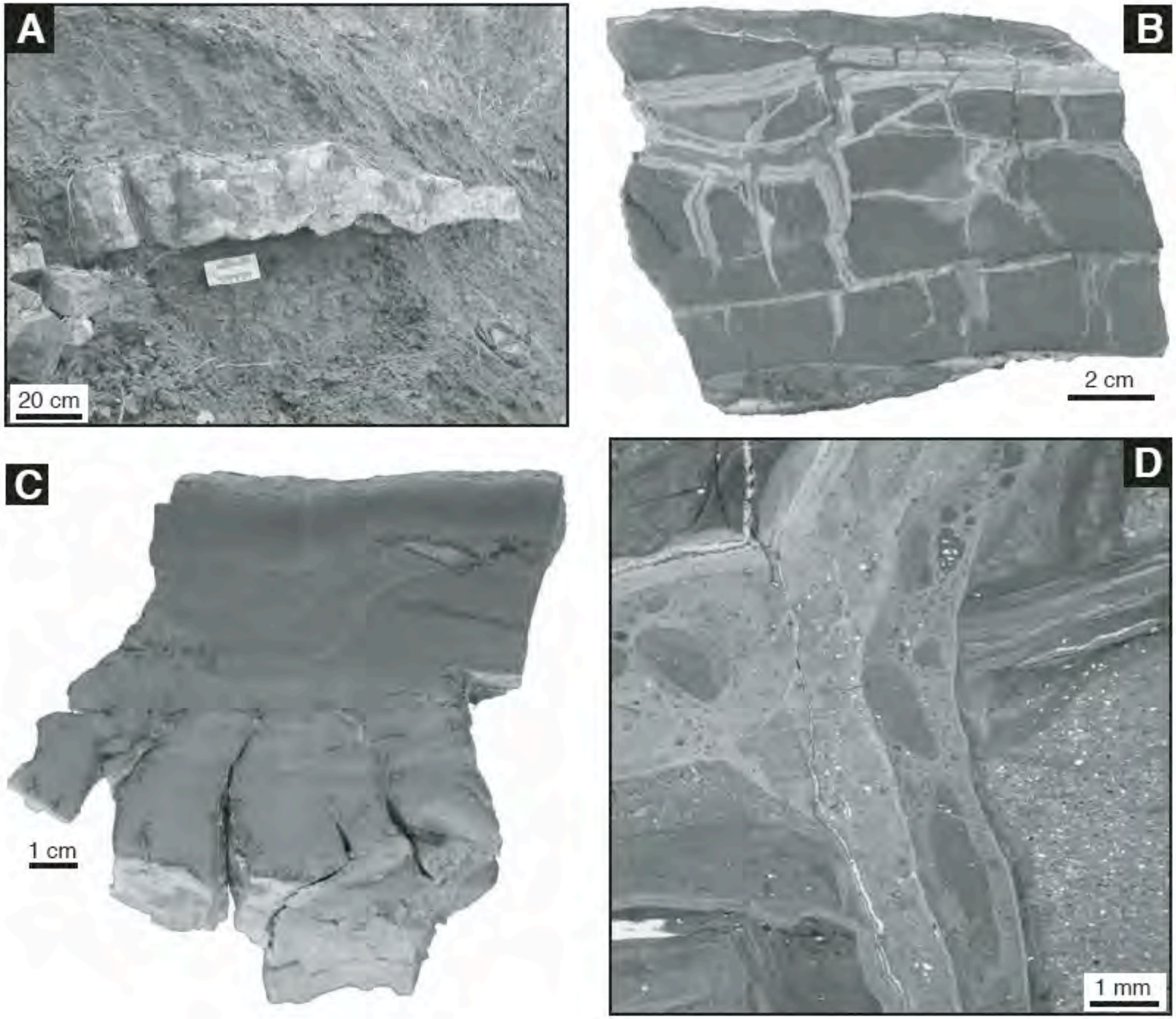

Figure 6. Septarian-like cracked concretions: (A) Outcrop view of the septarian-like cracked concretion described in the text. Note the sharp boundaries with hosting sediments and the wavy geometry. (B) Polished slab, cut perpendicular to bedding, of the septarian-like cracked concretion. Note the dense network of millimeter- to centimeter-wide sediment-filled fractures developed both parallel and perpendicular to bedding. Most fractures taper out downward and do not reach the external surface of the concretion. (C) Polished slab, cut perpendicular to bedding, of the upper part of the concretion. Note the wedge-shaped empty fissures that taper out toward the upper surface and open toward the central part of the concretions (lower part of the image). (D) Photomicrograph of crosscutting sediment-filled cracks. Different generations of sediment infilling are recognizable on the basis of color, content, and size of terrigenous grains. Note alignment of elongated muddy clasts to the crack walls.

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Figure 8. (A) Outcrop view of brecciated concretions. Note the partial overlap of the two layers and their lateral tapering off. (B) Polished slab, cut perpendicular to bedding, of the upper layer of A. Note that the edges of the clasts commonly fit together. The cement filling the interclast space is also visible. (C) Photomicrograph of the breccia. The dotted line indicates the outer boundary of a clast. It partly consists of microbreccia with elongated clasts that represent a sediment-filled crack (compare with Fig. 6D). The sparry Mg-calcite cement (cc) filling the interclast space is also visible. The arrows indicate the early isopachous rim of dolomite developed along the periphery of two clasts. (D) Scanning electron microscope (SEM) image of a broken chip cut at the boundary between a clast and the surrounding calcite cement (see C for location). The dolomite rim developed around the clast is recognizable (arrows). Due to the gentle etch of the sample by HCl, dolomite is in relief with respect to calcite (cc). (E) Cylindrical concretion: note the regular cylindrical shape and the sharp boundaries with the hosting sediments. (F) Axial polished slab of a cylindrical concretion, showing the darker fill of the axial portion (dotted line). The white arrow indicates a clast wrenched from the walls.

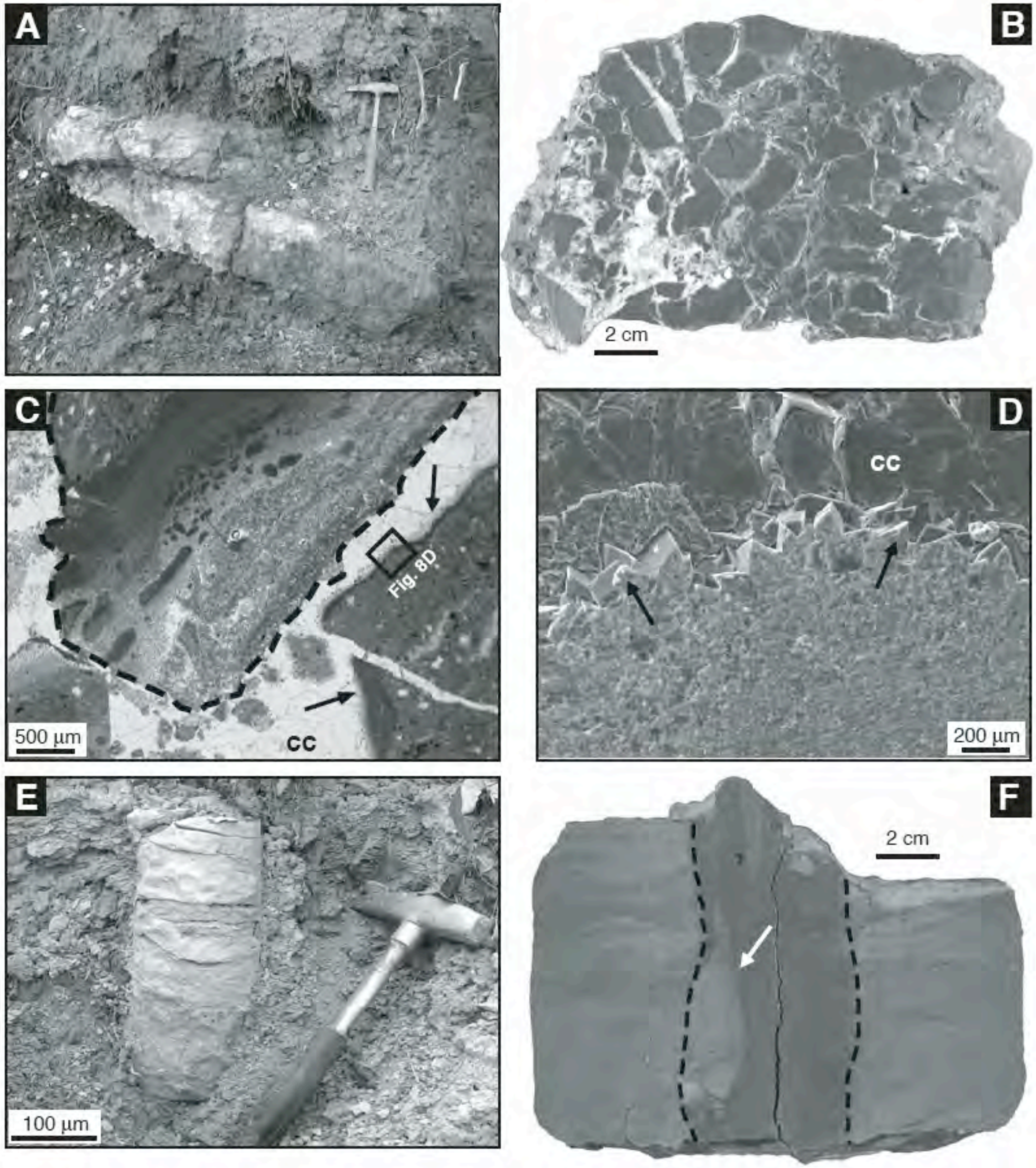

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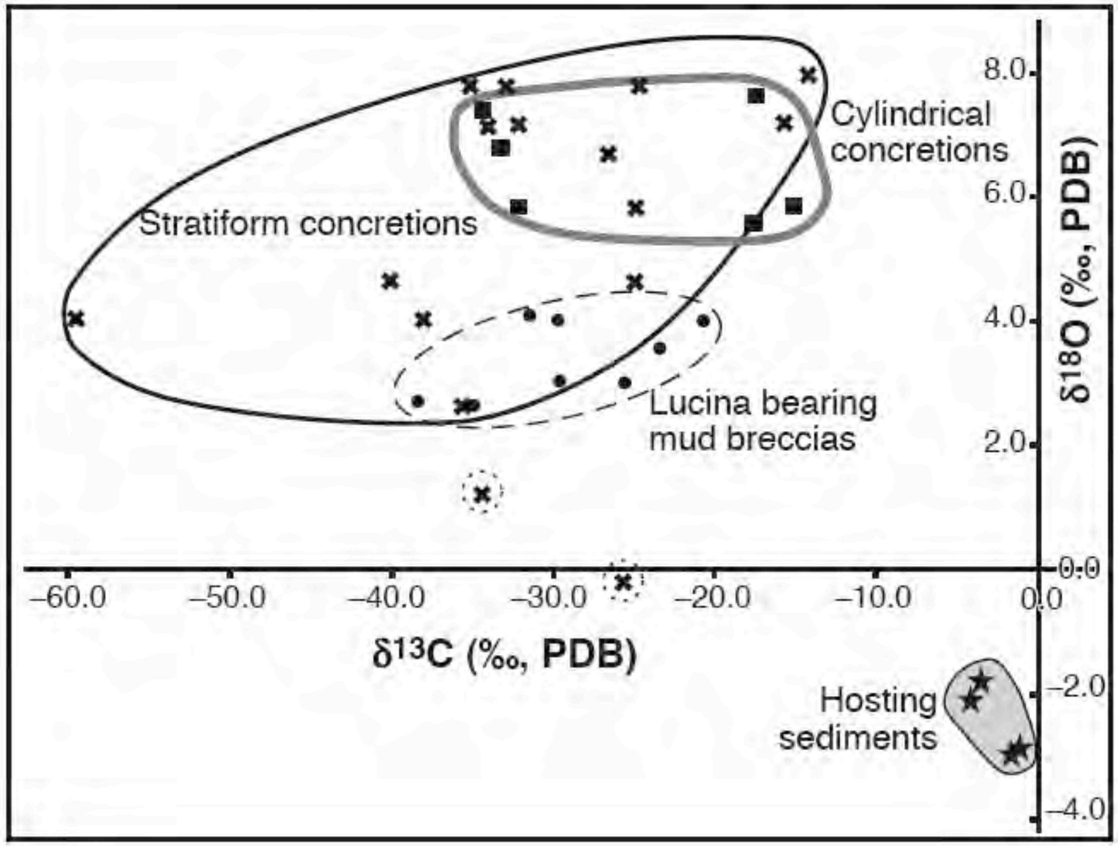
Figure 9. Cross-plot of isotope data of Ripa dello Zolfo carbonate-rich rocks. PDB—Peedee belemnite.



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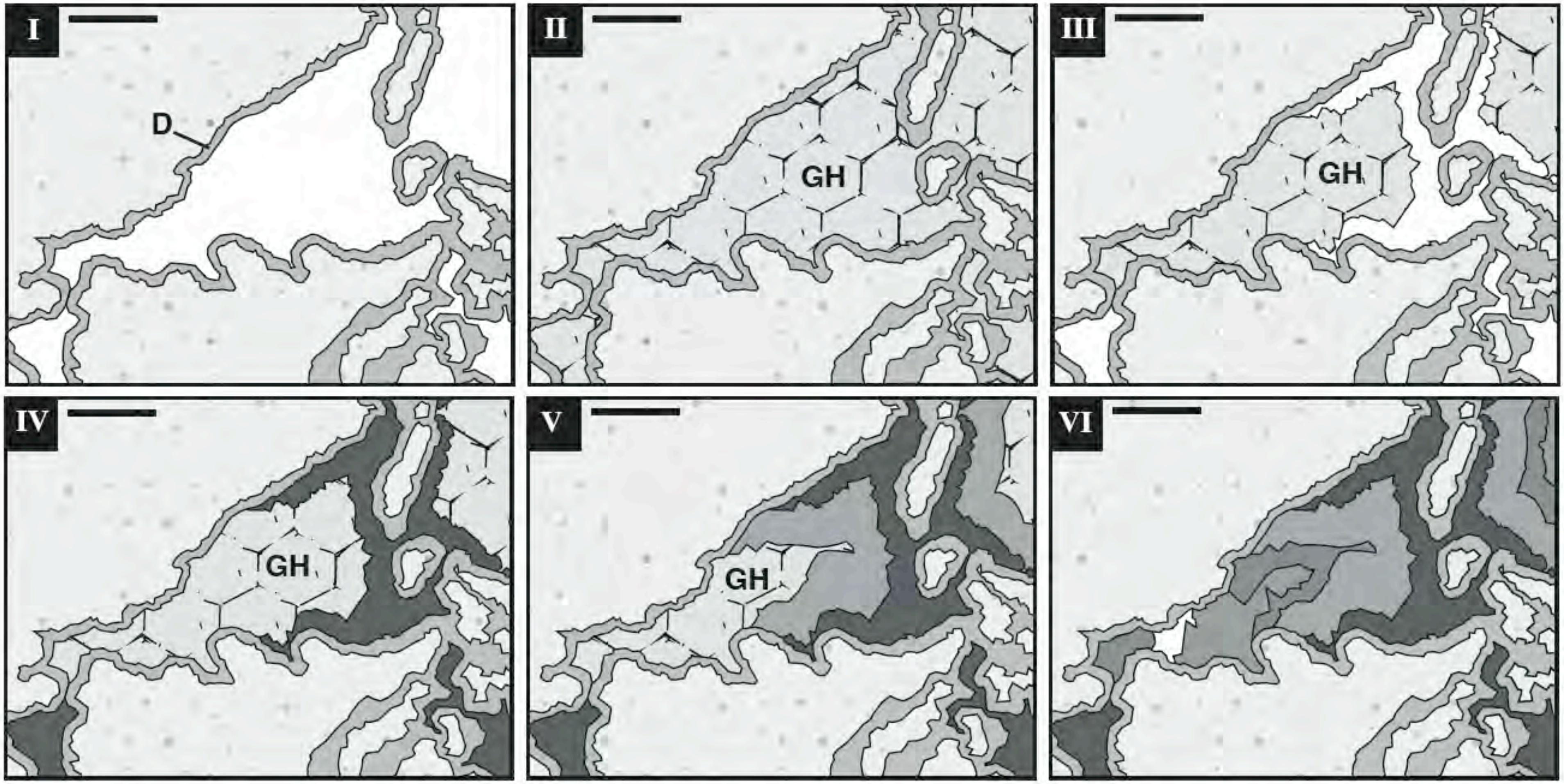

Figure 10. Sketches showing the filling mechanism of the fissure reported in Figures 7B and 7C. (I) An open fissure is occupied by gas hydrates (II). The progressive destabilization of gas hydrates (III) leaves open voids that are filled with lighter to darker zoned cements with diagnostic lateral pinch-out terminations (IV, V, and VI). For sake of simplicity, generation of voids after stage IV is omitted. White areas—open voids; GH—gas hydrate. For further details, see text.

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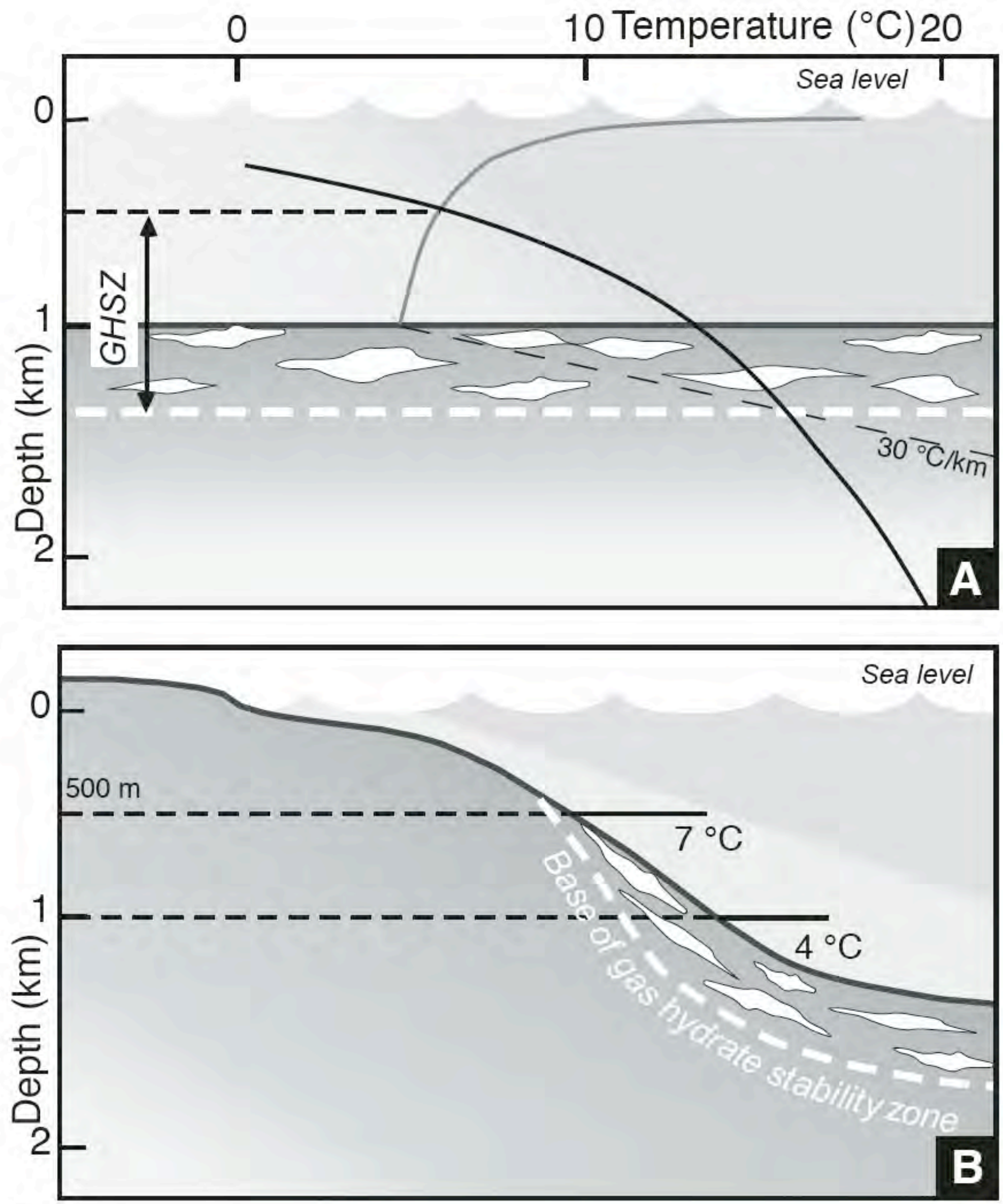
Figure 11. Evaluation of gas hydrate stability in the Tertiary Piedmont Basin (modified from Bohrmann and Torres, 2006). (A) Stability field of methane hydrates as defined by temperature and pressure (expressed as water depth) described in the text. (B) Thickness of the gas hydrate stability zone (GHSZ) at 500 and 1000 m water depth. For further details, see text.



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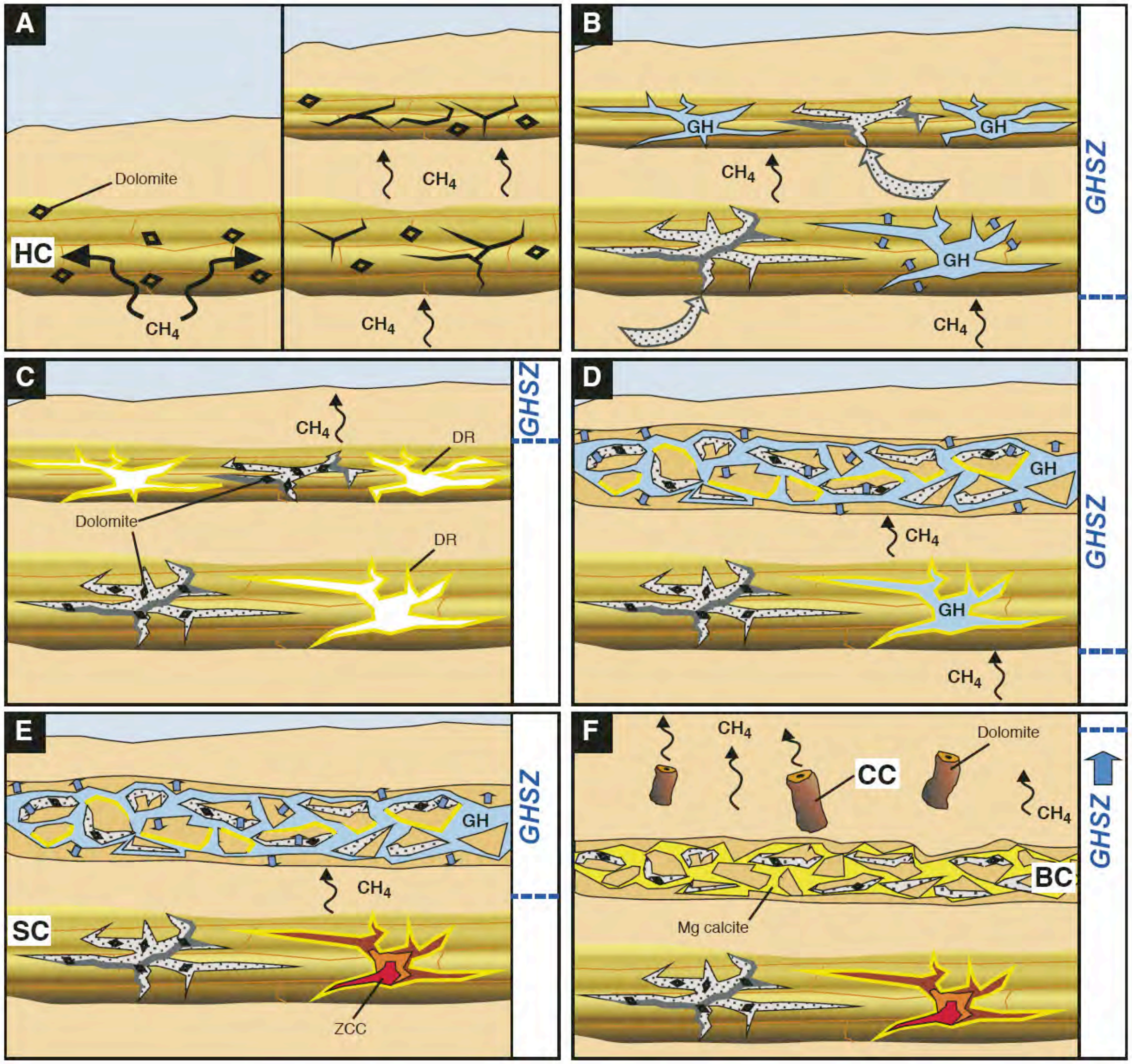

Figure 13. Schematic evolutionary model of concretion formation. For further details see the text. (A) Left: upward flow of CH_4-rich fluids (arrows) and formation of a homogeneous concretion (HC); right: contraction of sediments, resulting in a network of secondary fissures. (B) Enlargement of fissures by forceful mud injections (stippled gray) and gas hydrate (GH) crystallization; GHSZ—gas hydrate stability zone. (C) Upward shift of the base of the hydrate stability zone, and precipitation of dolomite both in the sediment-filled fissures and on the walls of the empty ones (DR—dolomite rim). (D) Downward shift of the base of hydrate stability zone and new phase of formation of gas hydrates. (E) Progressive destabilization of gas hydrates and precipitation of zoned calcite cements (ZCC) in the septarian-like cracked concretion (SC). For sake of simplicity, empty fissures within SC are not represented. (F) Destabilization of gas hydrates at shallow burial depth and production of brecciated concretion (BC); CC—cylindrical concretions.

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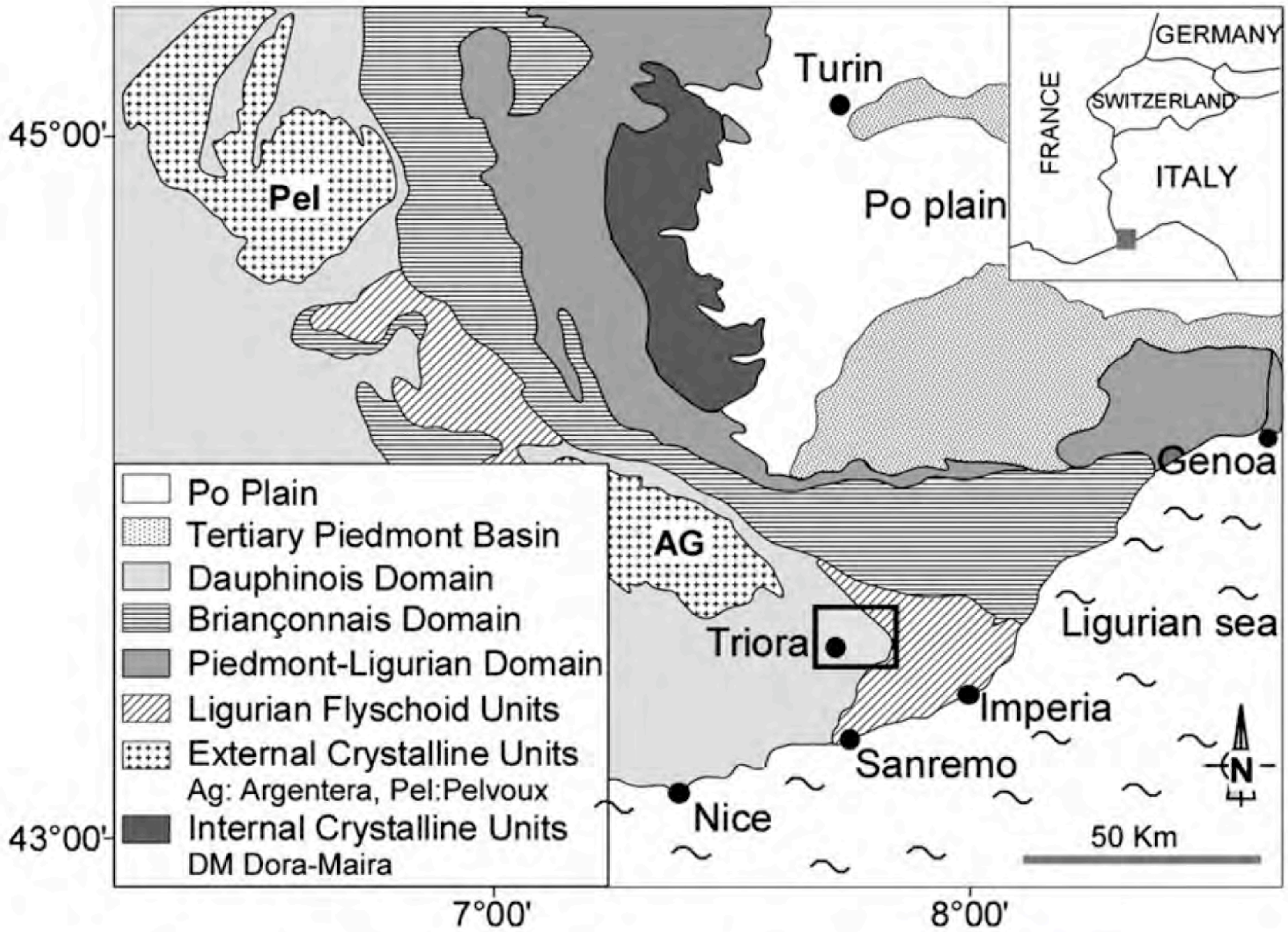

Fig. 1. Location of the study area (black square). Modified after Lanteaume (1968).

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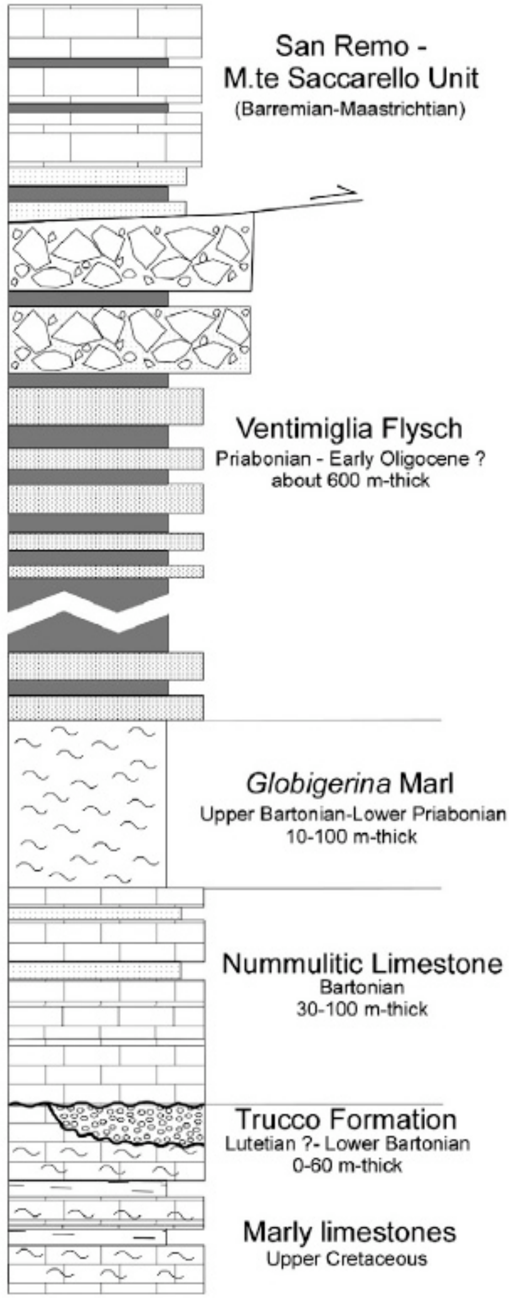

Fig. 2. Schematic log of the succession cropping out in the study area (not to scale).

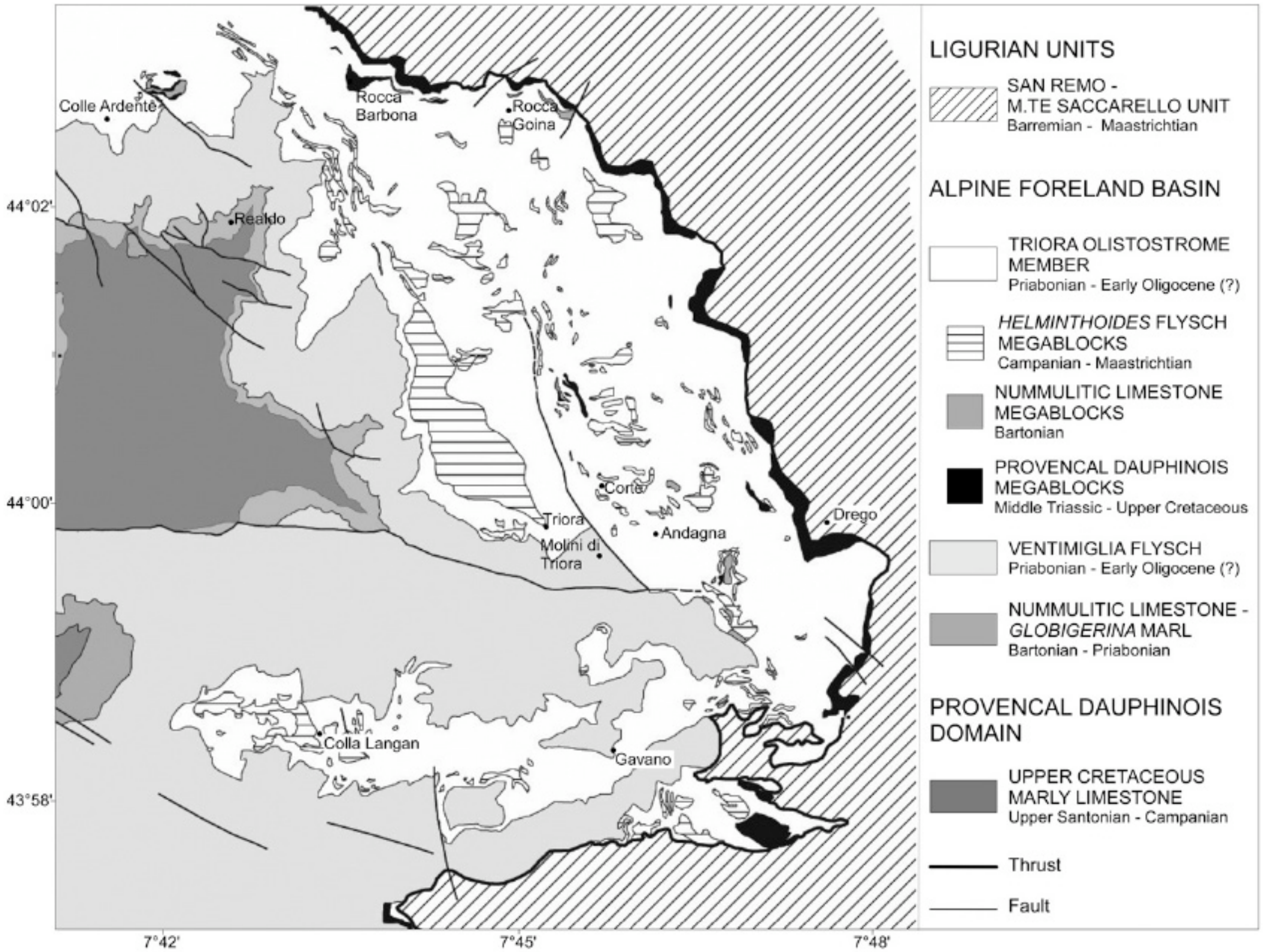

Fig. 3. Geological map of the Triora area, high Argentina valley.

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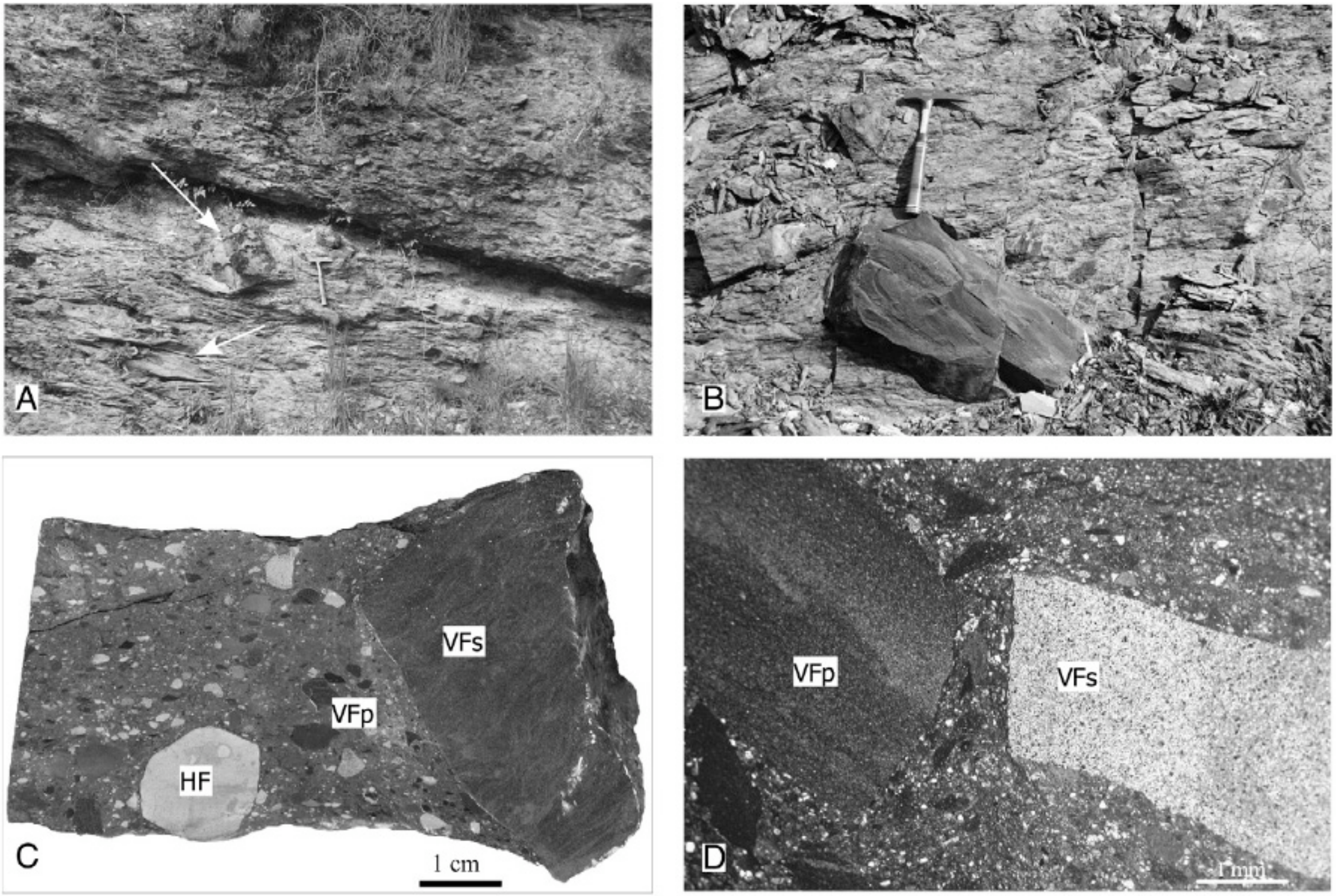

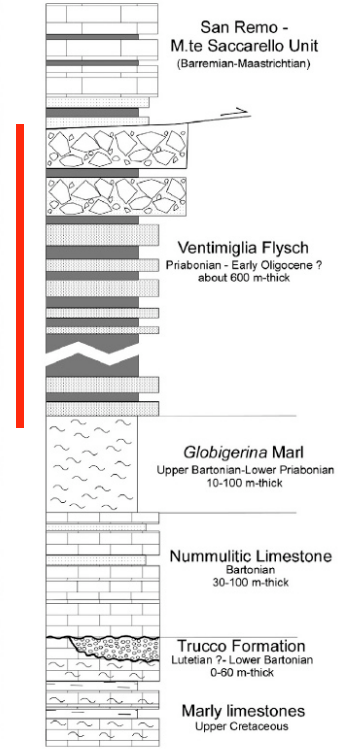

Fig. 2. Schematic log of the succession cropping out in the study area (not to scale).

Fig. 4. Main features of paraconglomerates clasts and matrix. A) Paraconglomerates organized in m-thick beds without any internal structure. The lower part show few dm-sized blocks (white arrows) floating in a muddy matrix; the upper part is characterized by more abundant and smaller clasts (Colla Langan sector). Hammer for scale is 35 cm long. B) Subangular dm-sized clast of Ventimiglia Flysch sandstones embedded in a muddy matrix in turn containing submm- to mm-sized lithic grains (see also Fig. 4h) (Gavano sector). Hammer for scale is 35 cm long. C) Polished slab showing rounded to subangular clasts of different composition and size (HF: *Helminthoides* Flysch; VFs: Ventimiglia Flysch sandstone; VFp: Ventimiglia Flysch pelite) (Gavano sector). D) Photomicrograph showing mm-sized intraformational clasts of different Ventimiglia Flysch beds. VFs: Ventimiglia Flysch sandstone clast; VFp: Ventimiglia Flysch pelite (Colla Langan sector). E) Photomicrograph showing a sub-cm-sized extraformational clast of the Upper Cretaceous marly limestone.

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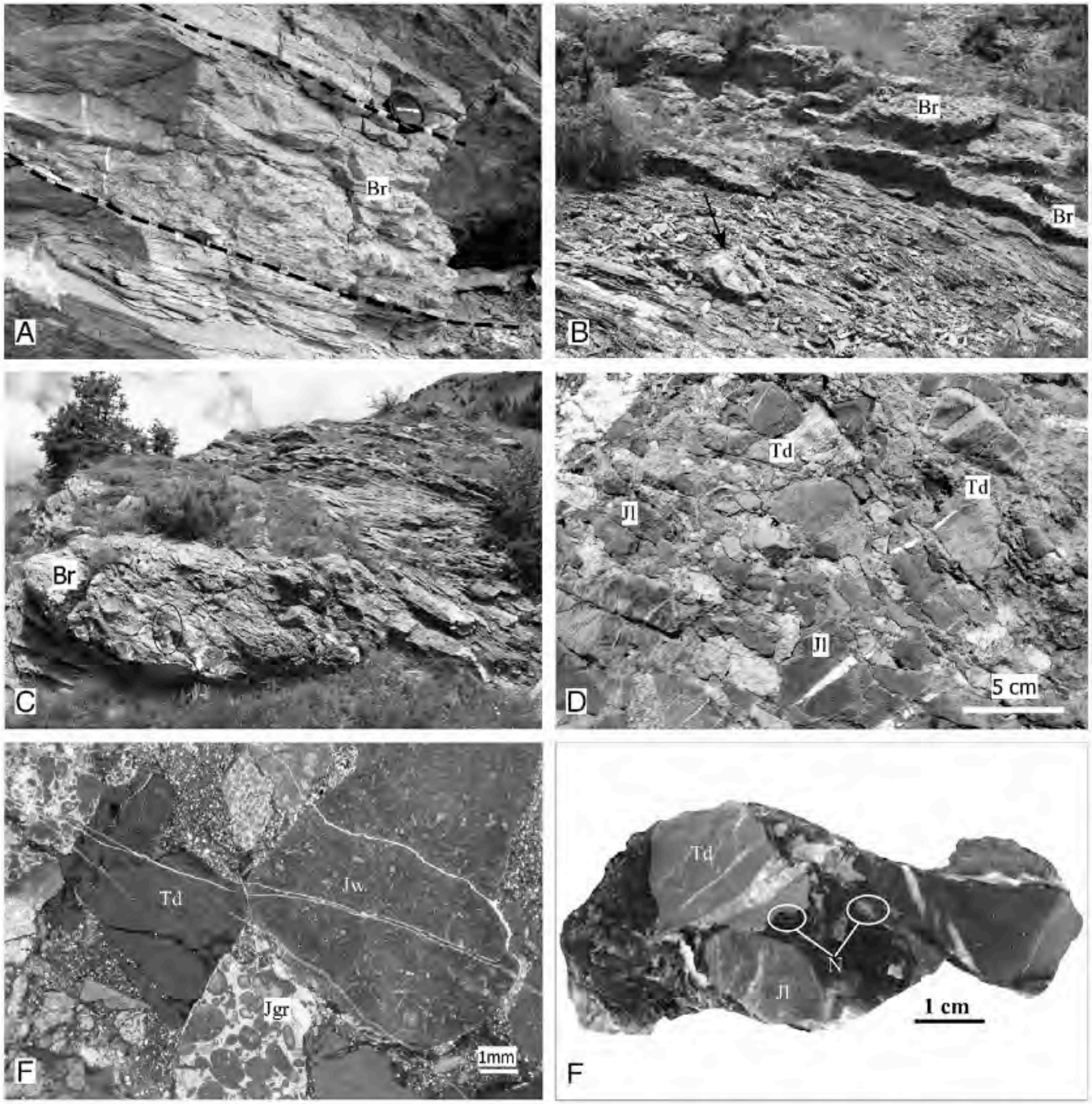

Fig. 8. Main features of breccia deposits in the Rocca Barbona area. A) dm-thick layer of breccia (Br) interbedded with sandstone-shales turbidite couplets. Hatched black lines point to the lower and upper breccia boundaries. Lens cap for scale is 6.5 cm in diameter. B) Alternation of dm- to m- thick breccia beds (Br) and m-thick turbidite beds. Note the occurrence of a 70 cm-large clast (black arrow) scattered within shales. C) Thick bed of clast-supported breccias interbedded within shale beds. Hammer for scale is 35 cm long (black circle). D) Detail of clast-supported breccias characterized by angular to sub-angular cm-sized clasts made up of lithologies referable to different formations of the Provençal Dauphinois succession (Td: Triassic dolostone clast; Jl: Jurassic limestone clasts). Note that the clasts are compenetrated along stylolitic contacts. E) Photomicrograph showing the different composition of breccia clasts: Td: Triassic dolostone clast, Jw: Jurassic bioclastic wackestone clast; Jgr: Jurassic grainstone. F) Polished slab showing Triassic dolostone clasts (Td) and Jurassic limestone clasts (Jl) scattered in a calcareous matrix with sparse nummulitid fragments (N, encircled in white).

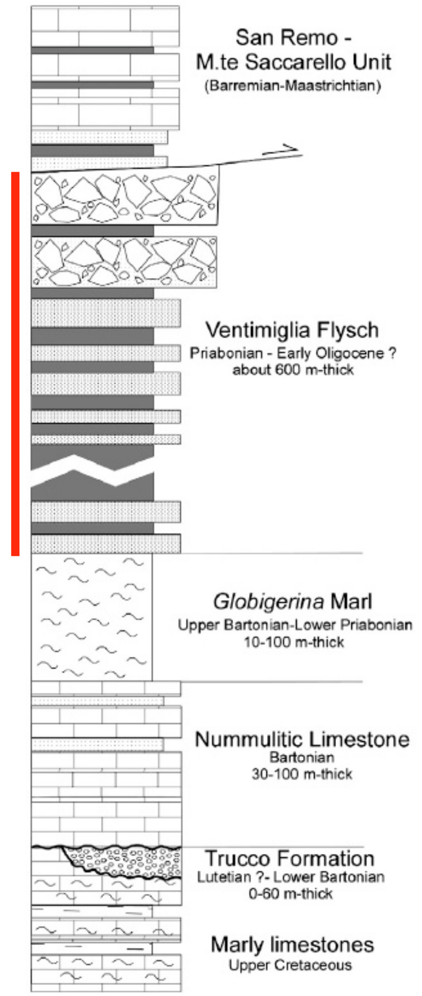

Fig. 2. Schematic log of the succession cropping out in the study area (not to scale).

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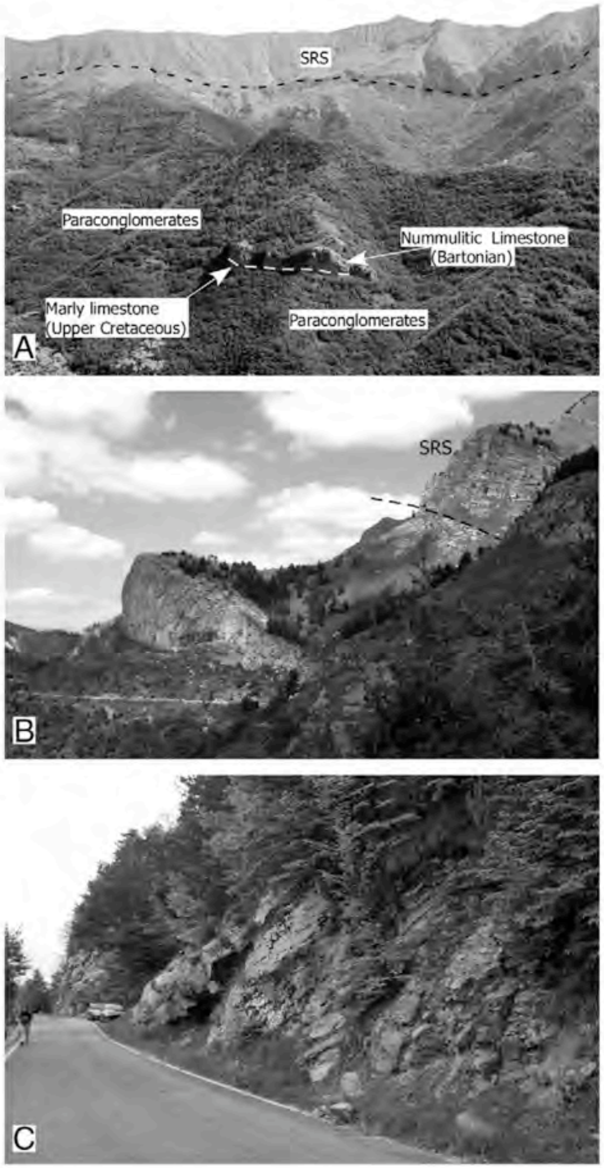

Fig. 9. Some examples of hm- to km- sized megablocks scattered in the Triora Olistostrome Member. A) Panoramic view of Corte area, showing an extraformational megablock consisting of Upper Cretaceous marly limestones overlain, with an erosional surface (hatched white line), by m-thick beds of bioclastic rudstones of Nummulitic Limestone. The megablock is embedded within paraconglomerate deposits. The hatched black line indicates the thrust at the base of the San Remo–Monte Saccarello unit (SRS). B) Panoramic view of an extraformational megablock characterized by a condensed succession ranging from Triassic dolostones to Eocene turbidites. The megablock is overlain by the thrust of the SRS unit (hatched black line), (Rocca Barbona sector). C) Km-sized, exotic megablock at Colla Langan. In the foreground, the lowermost part of the block shows a chaotic structure, characterized by disharmonic folds and bed

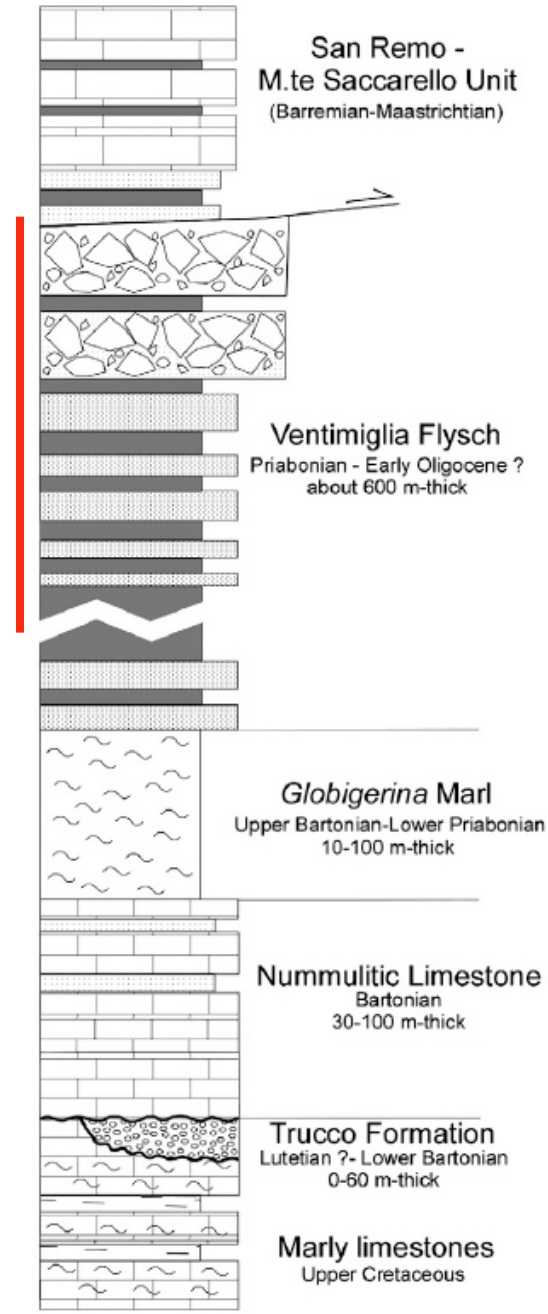

Fig. 2. Schematic log of the succession cropping out in the study area (not to scale).

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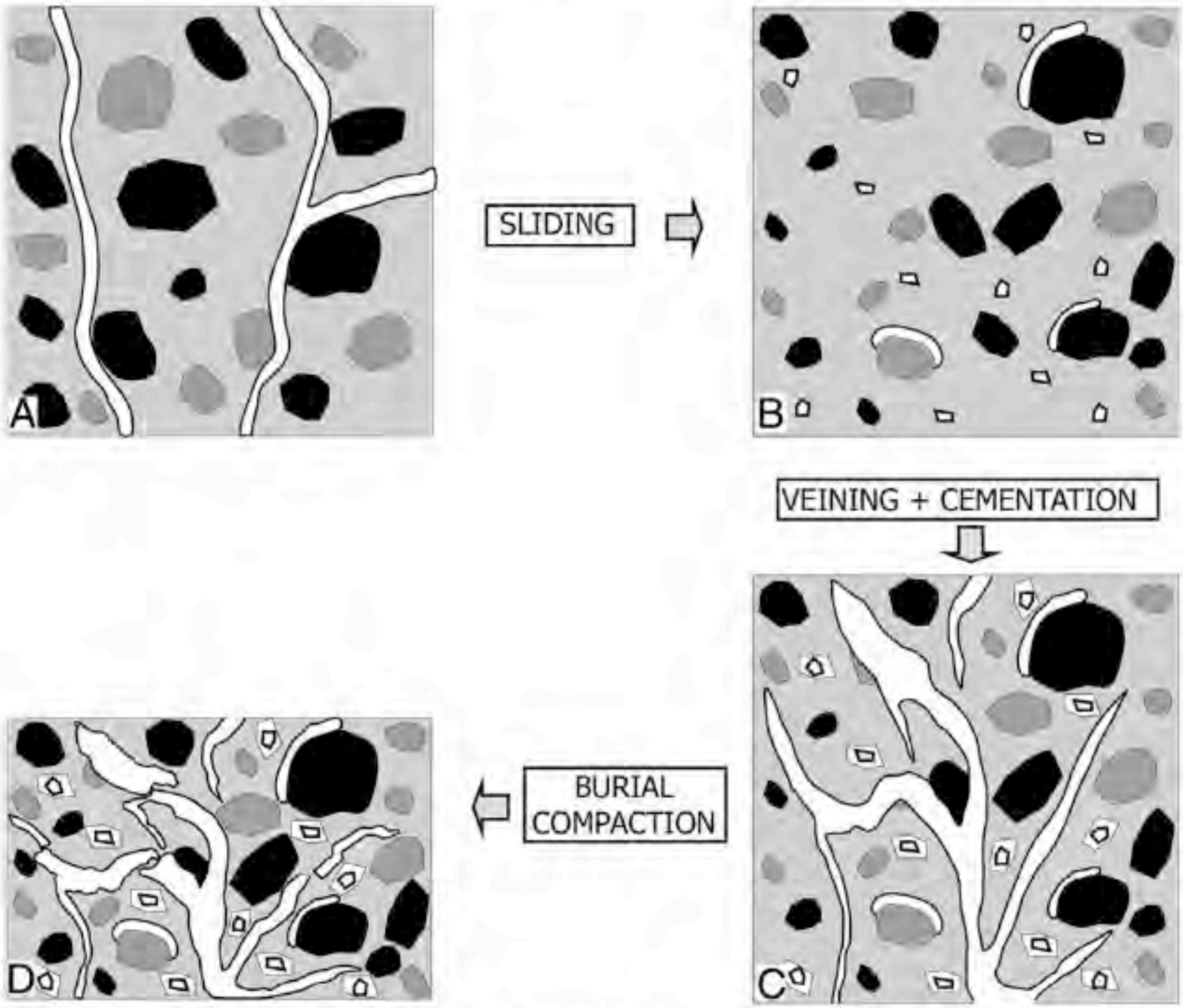

Fig. 11. Sketch synthesizing the main steps in the diagenetic evolution of paraconglomerates. A first phase of veining (A) is followed by sliding that causes production of small fragments of veins (white angular grains) and paraconglomerate clasts partly bordered by veins (B). A second phase of veining takes place and is associated with calcite overgrowth around vein fragments (C). Finally, burial compaction produces breakage and crumpling of the second vein generation (D).

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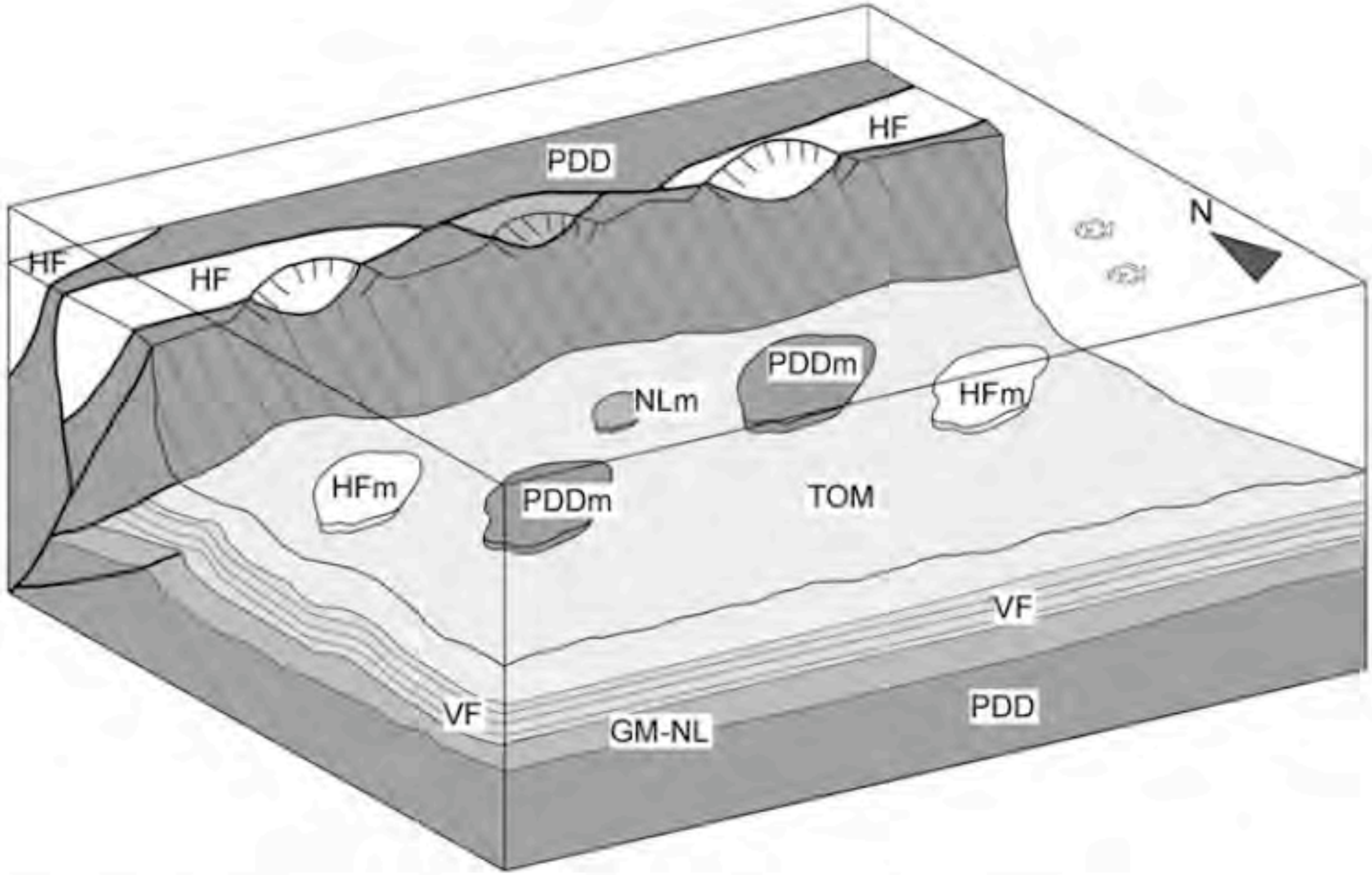

Fig. 12. Block diagram depicting the geotectonic setting in which TOM was formed. For further details see text. HF: *Helminthoides* Flysch; HFm: *Helminthoides* Flysch megablock; GM–NL: *Globigerina* Marls–Nummulitic Limestone; NLm: Nummulitic Limestone megablock; PDD: Provençal Dauphinois Domain; PDDm: Provençal Dauphinois Domain megablock; TOM: Triora Olistostrome member; VF: Ventimiglia Flysch. Orientation of the diagram is purely indicative and refers to present-day coordinates.

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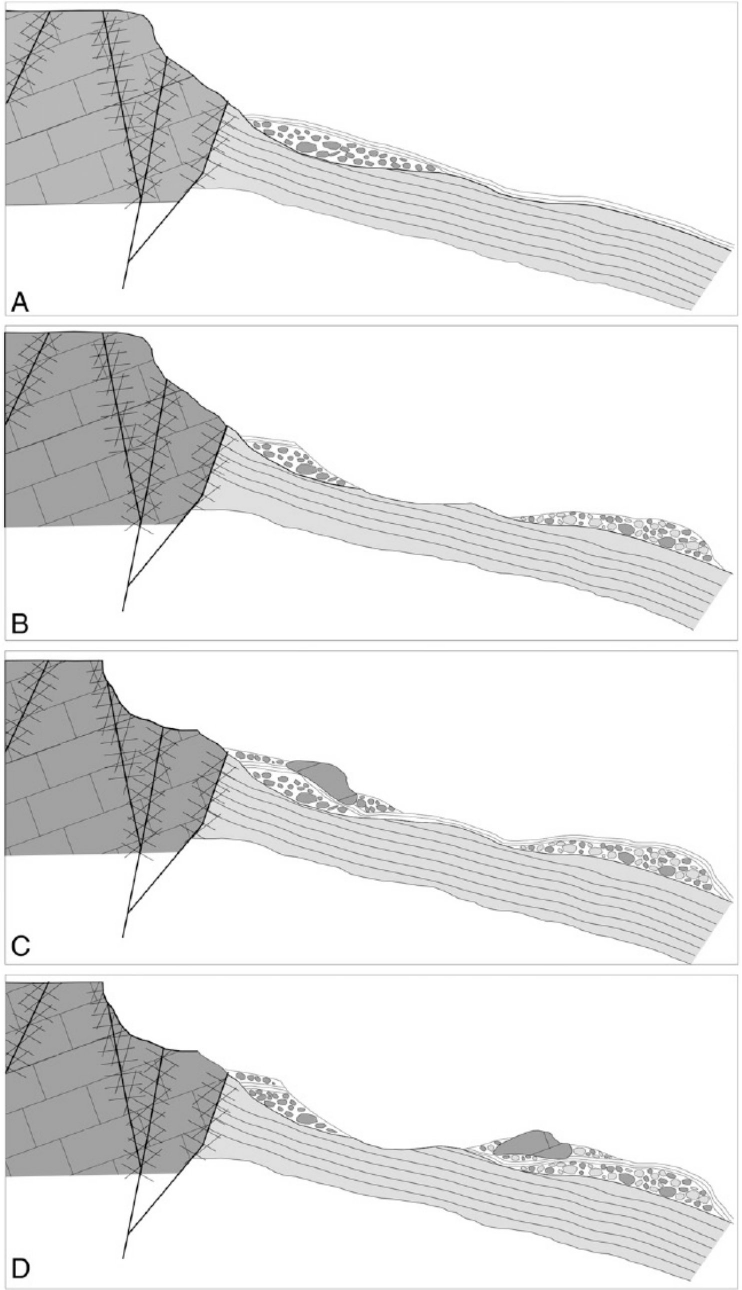

Fig. 13. Schematic sketch summarizing the main steps in the genesis of the TOM. Clasts of lithified carbonate units, exposed in fault-bounded, internally fractured, ridges, accumulate as breccias at the foot of the scarp and are covered by fine grained turbidites (A). Slope failures involve breccias and turbidite deposits including concretions and disrupted cemented beds giving rise to polygenic paraconglomerates (B). Catastrophic rock falls generate emplacement of megablocks (C) that may be further involved in gravitational movements together with breccias and paraconglomerates (D).

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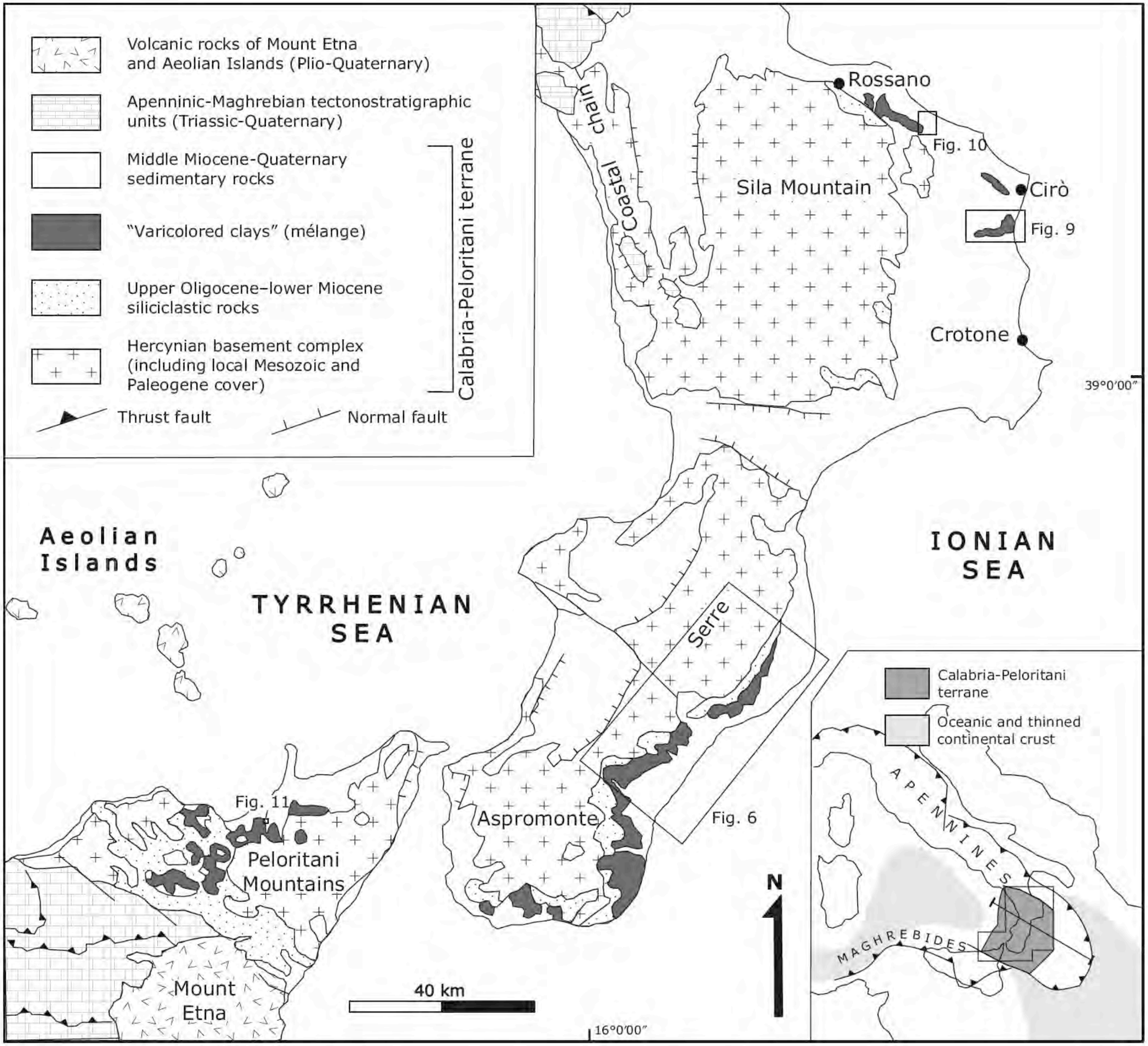
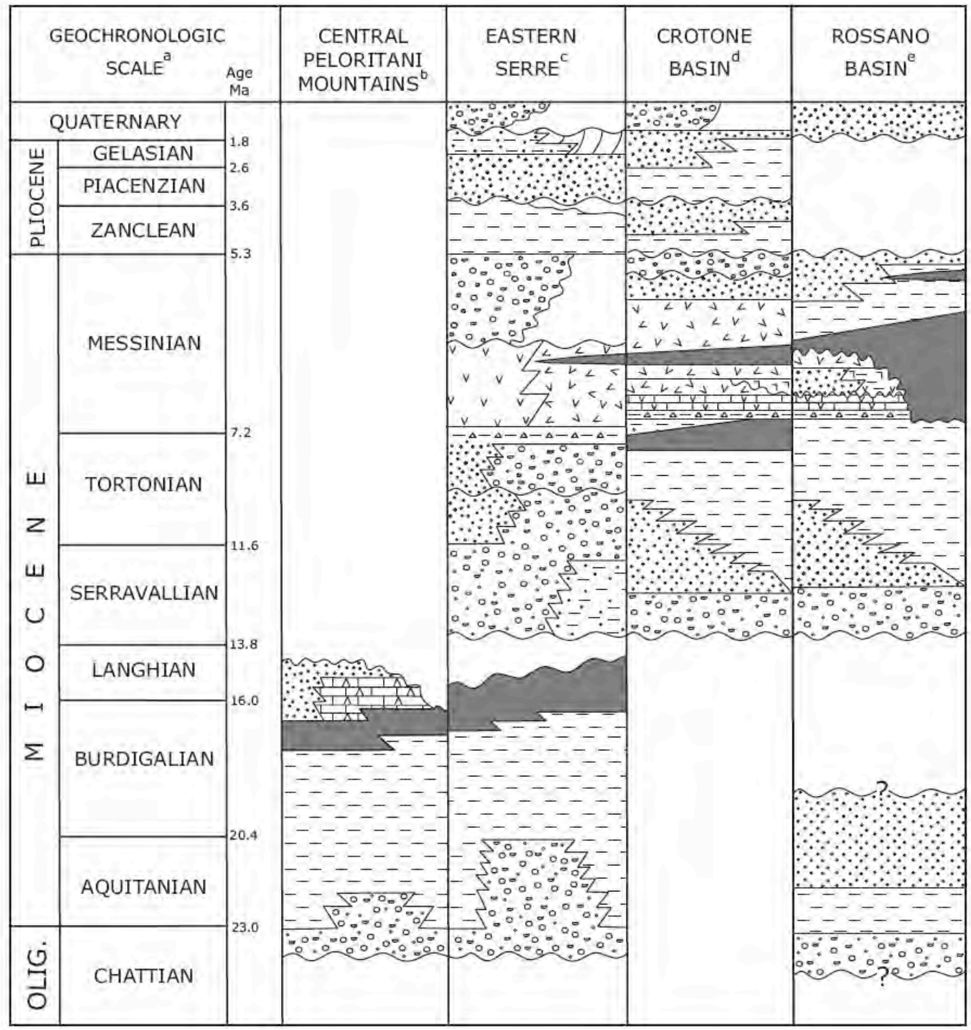


Figure 2. Geological sketch map of the Calabria-Peloritani terrane (CPT) of southern Italy. The inset shows the geodynamic context of the CPT and the trace of the cross section of Figure 3.

Cavazza & Barone 2010



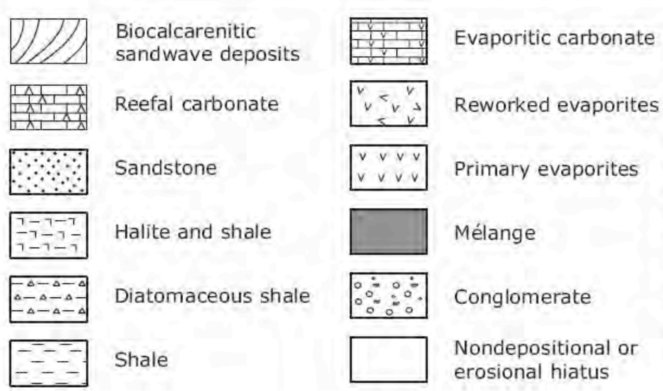


Figure 4. Chronolithostratigraphic chart of the Ionian sedimentary succession of the Calabria-Peloritani terrane. Only surface data are considered. A post-Langhian sedimentary section along the northern margin of the Peloritani Mountains related to extension in the Tyrrhenian Sea is not included in this chart. Superscripted footnotes: a—Geochronologic boundaries according to Gradstein et al. (2004). Sources: b—Carbone et al. (1993), Patterson et al. (1995); c—DeCelles and Cavazza (1992, 1995), Cavazza and DeCelles (1993, 1998), Patterson et al. (1995), Cavazza et al. (1997); d—Van Dijk (1992), Smale (1991), Zecchin et al. (2004), Barone et al. (2008); e—Roda (1967), Van Dijk (1992), Bonardi et al. (2005), Barone et al. (2008).

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Figure 5. Stratigraphic contact between Stilo–Capo d'Orlando (SCO) Formation and overlying *varicolored clays* (38°24′32.64″N, 16°25′38.33″E). For location, see Figure 2. The outcrop shows the lowermost section of the *varicolored clays* with coherent blocks of *varicolored clays* enclosed within reworked mélange with a clastic fabric and intraclasts from the underlying Stilo–Capo d'Orlando turbidites.

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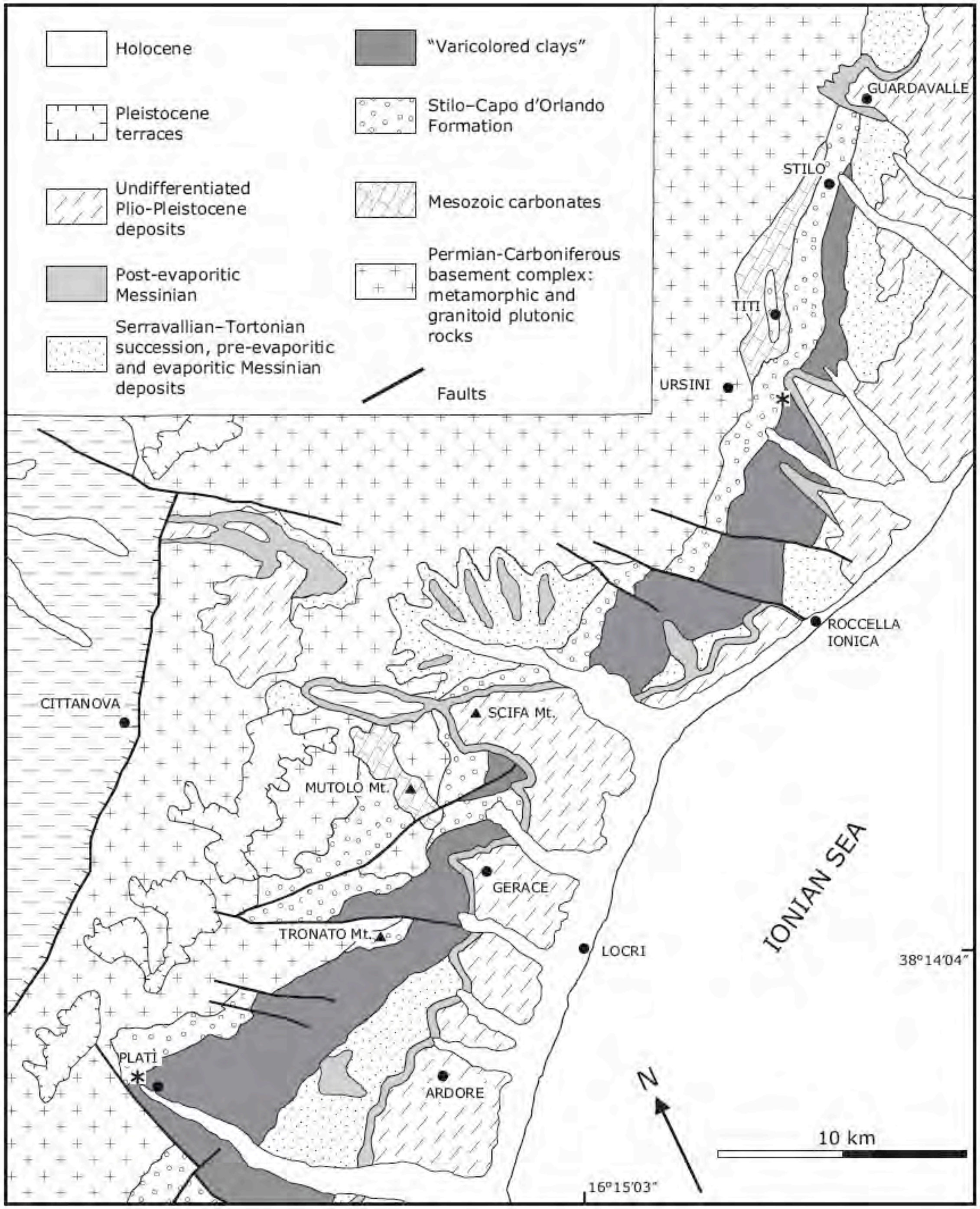

Figure 6. Simplified geologic map of southeastern Calabria. See Figure 2 for location. Mt.—Mountain.

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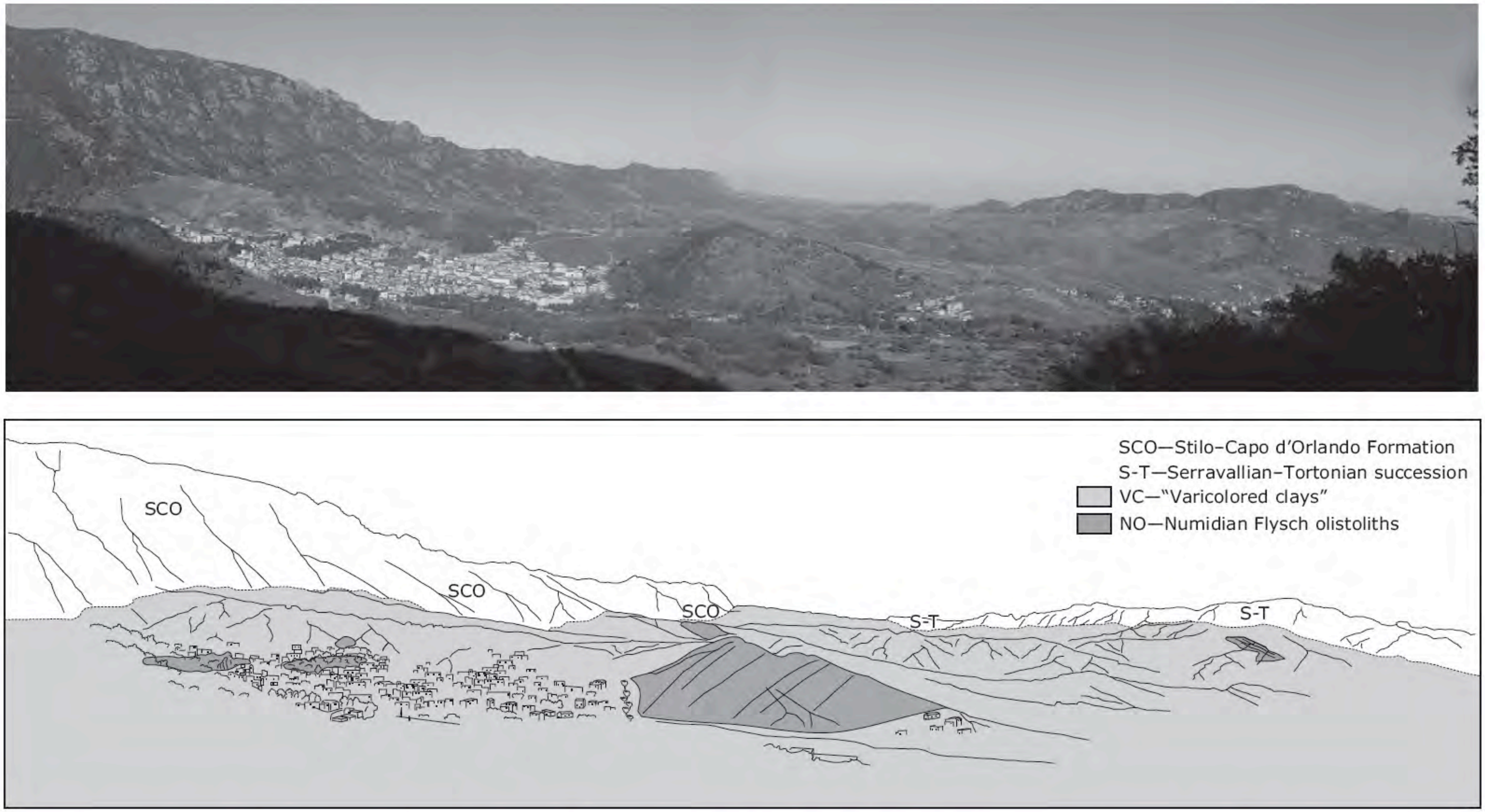

Figure 7. Large blocks *(knockers)* of Numidian Flysch quartzarenites enclosed within the mélange of the *varicolored clays* near the village of Platì (see Fig. 2 for location). View looking northeastward.

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Barone 2010

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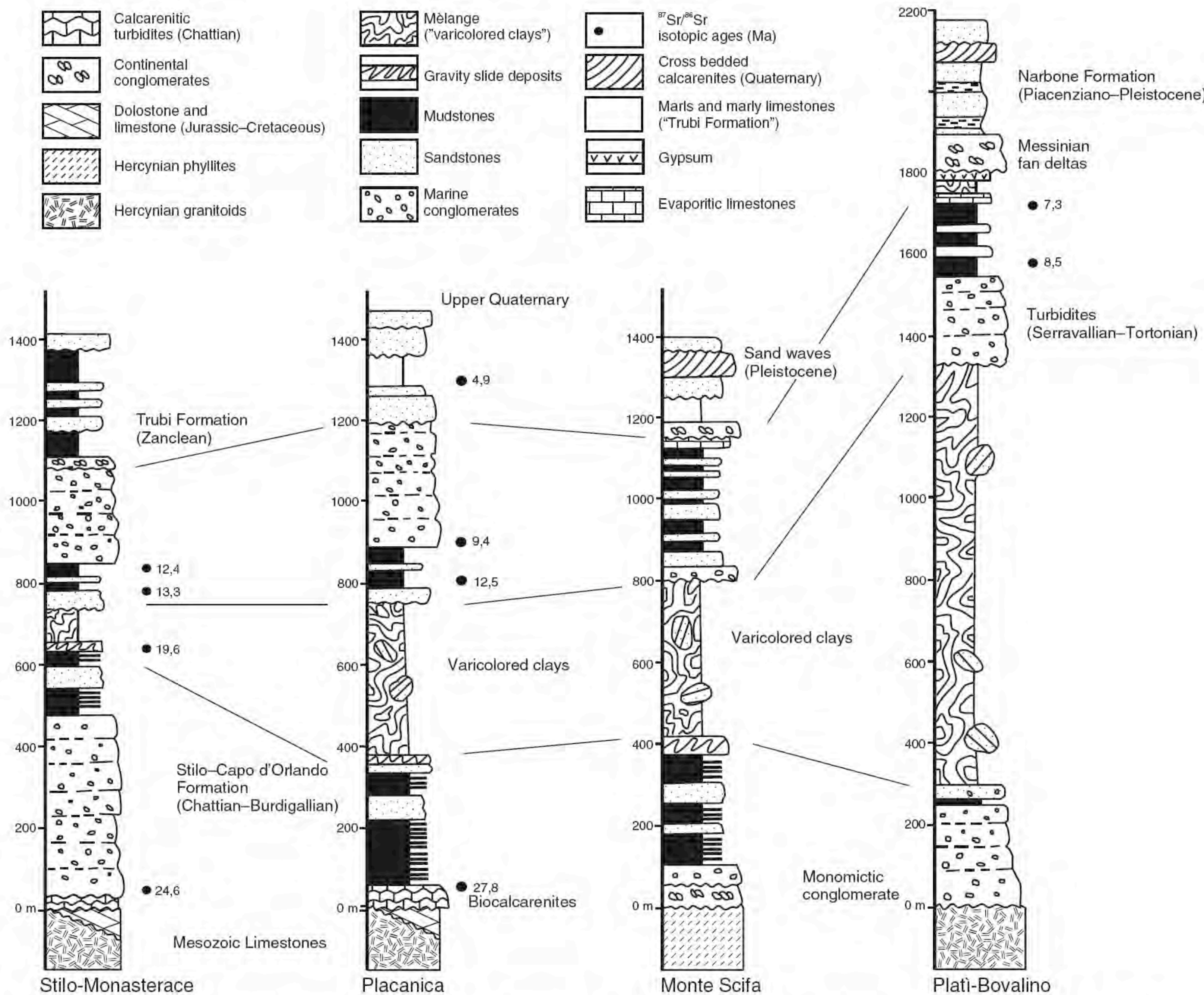

Figure 8. Simplified stratigraphic sections of the proximal part of the Ionian forearc basin fill (after Cavazza et al., 1997). Note progressive pinchout of the mélange of the *argille varicolori (varicolored clays)* from SW to NE along the Ionian coast (see Fig. 6 for location).

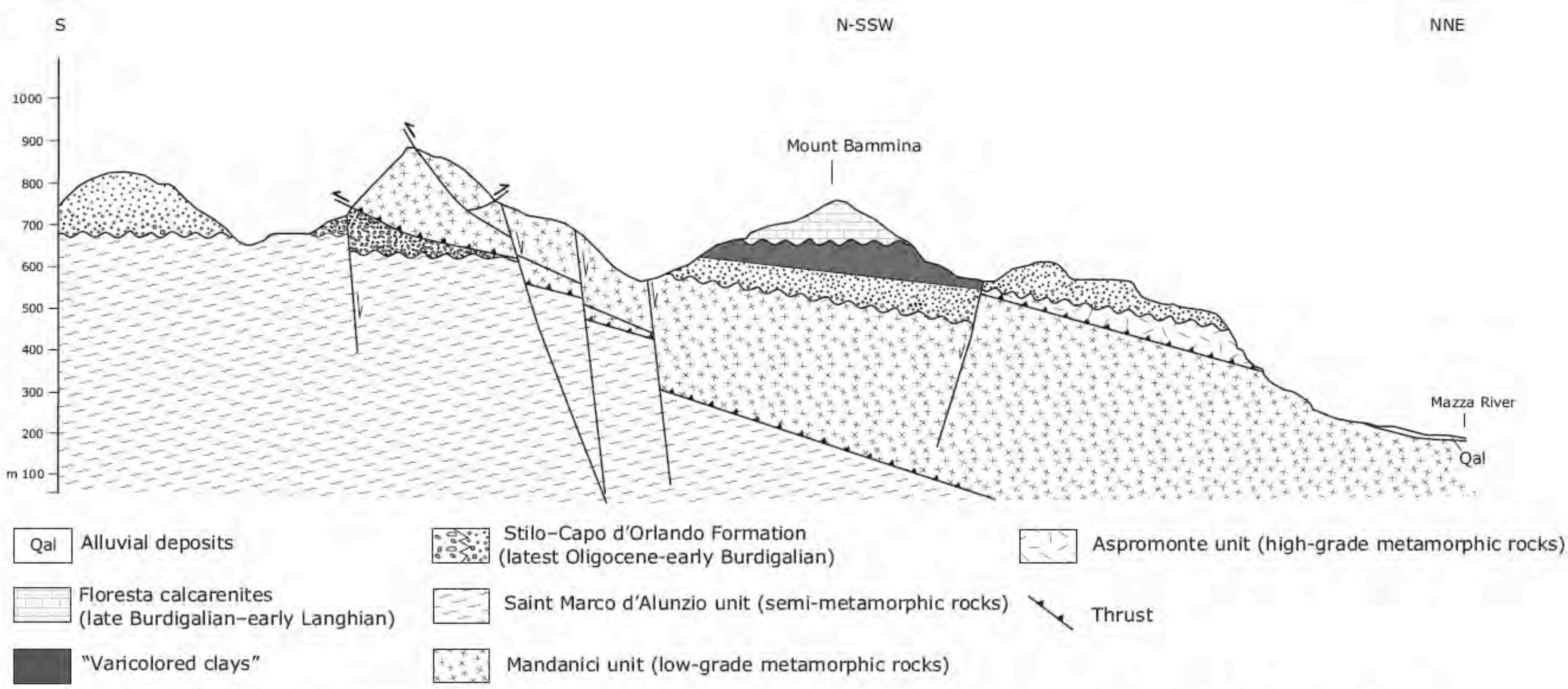

Figure 11. Geologic section across Mount Bammina in the Peloritani Mountains (based on Lentini et al., 2000) (see Fig. 1 for location). In this area, as well as in the surroundings, the shallow-marine Floresta calcarenites (late Burdigalian–early Langhian) sit on top of a complex series of south-verging thrust sheets and cover the *varicolored clays*. See text for further discussion.

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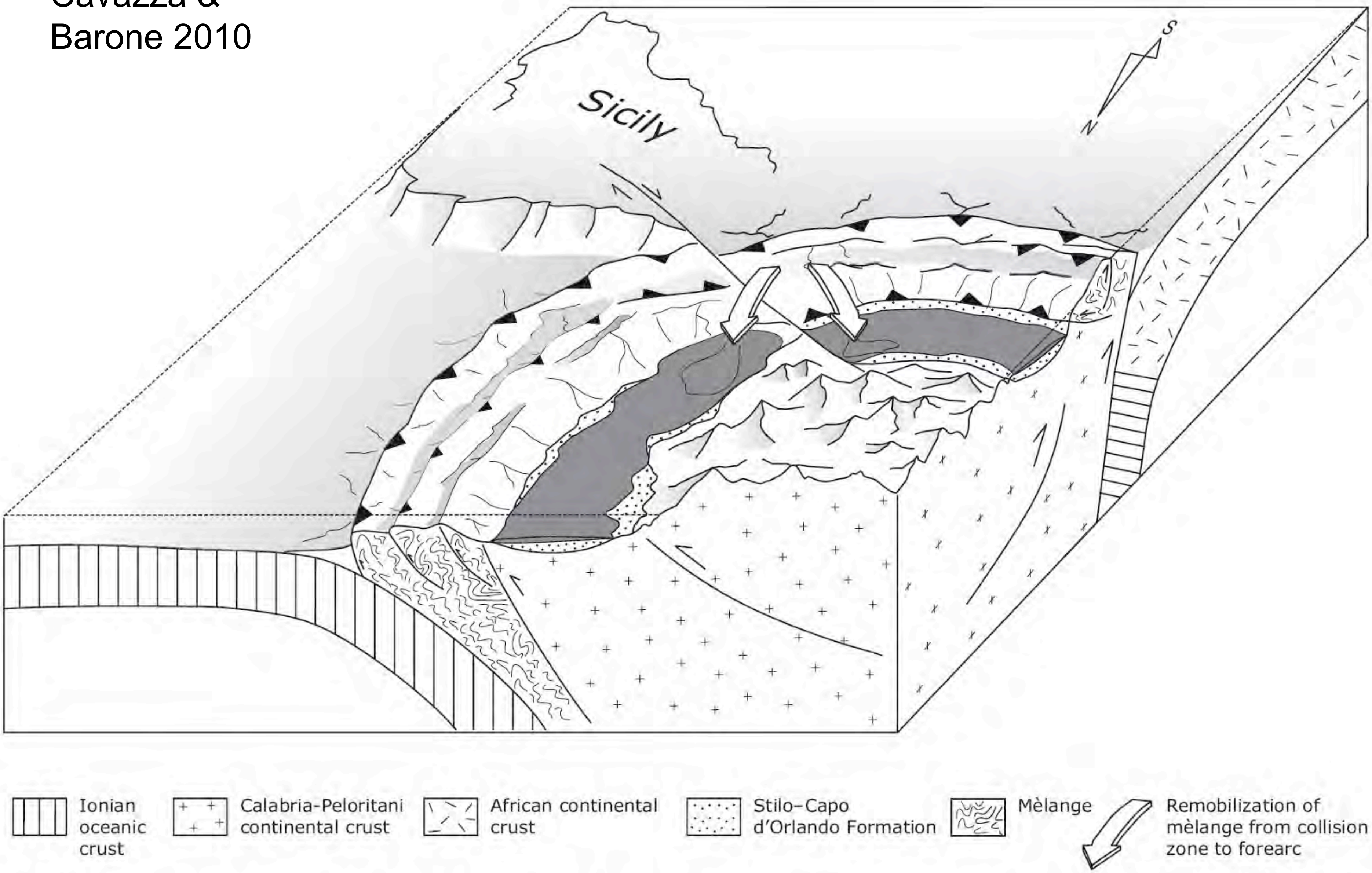

Figure 13. Cartoon depicting the emplacement mechanism for the main interval of *varicolored clays* present within the Ionian forearc succession. Incipient collision of the Calabria-Peloritani terrane with the northern African margin induced remobilization of mélange from the subduction complex into the forearc basin. No scale implied.

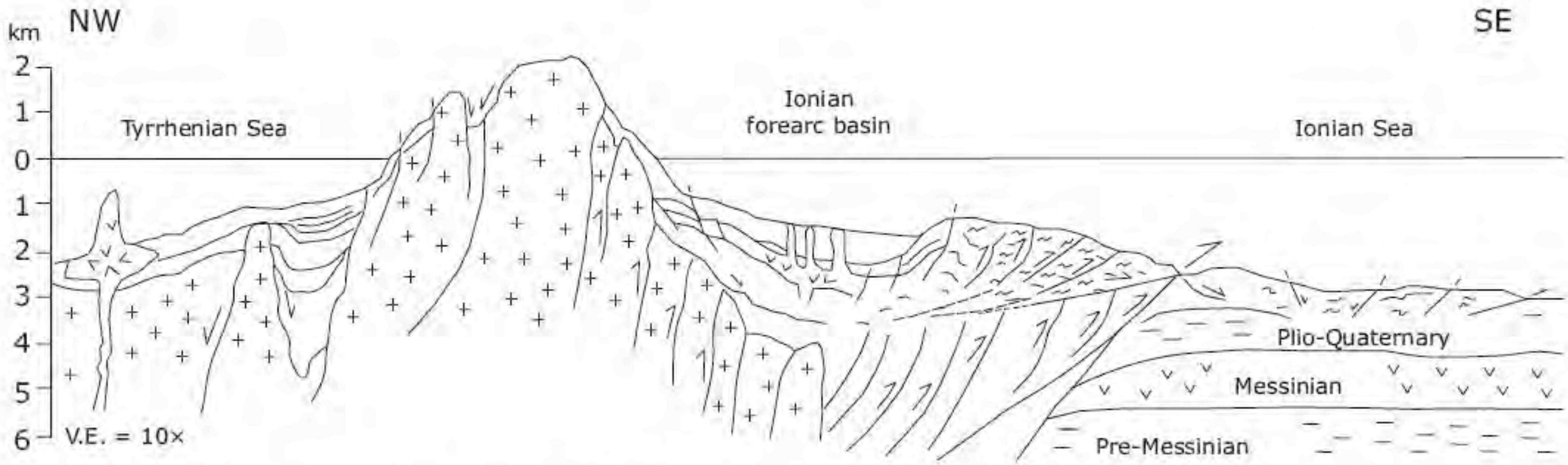

Figure 3. Schematic section across the Calabria-Peloritani terrane (modified after Van Dijk, 1992). See Figure 2 for location. V.E.—vertical exaggeration.

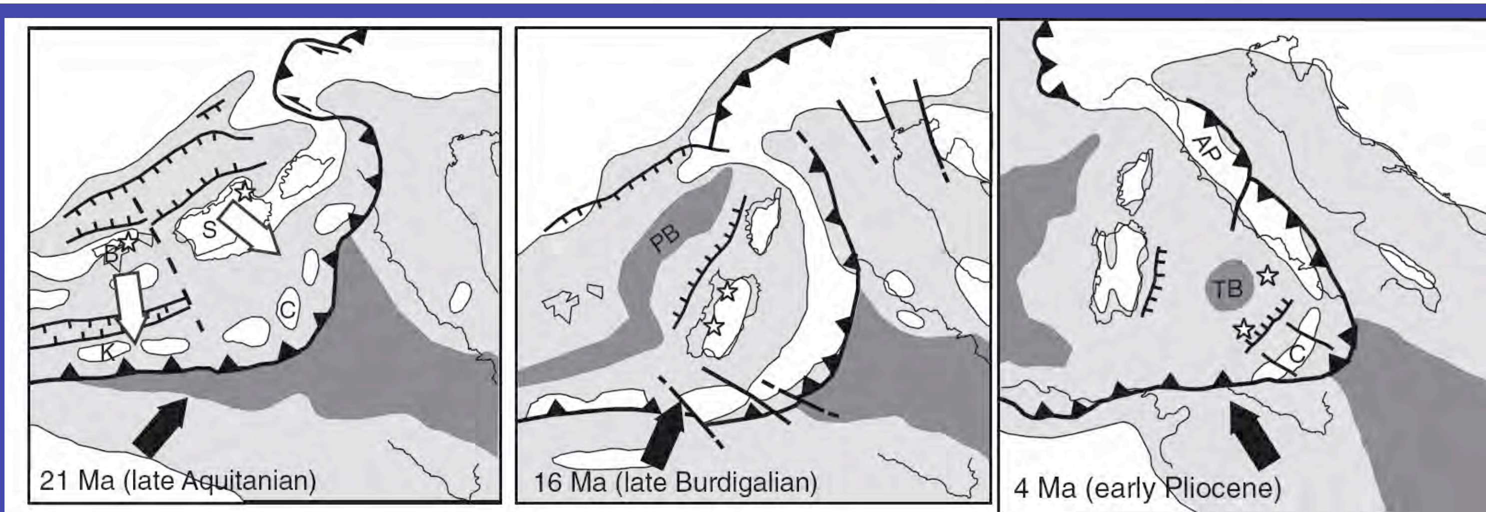

Figure 1. Paleogeographic sketch maps for the western-central Mediterranean (after Cavazza et al., 2004). AP—Apennines; B—Balearic Islands; C—Calabria; K—Kabilides; PB—Provençal Basin; S—Sardinia; TB—Tyrrhenian Basin.

Cavazza & Barone 2010

Cretaceous-Paleocene Contact, Bottaccione Gorge, Near Gubbio

Fig. 1. The Bottaccione Gorge in the mountains behind Gubbio, looking towards the north-east. The large mountainside in the rear is made of Upper Cretaceous and Palaeocene Scaglia rossa, dipping moderately away from the viewer. The horizontal structure is a Mediaeval aqueduct that supplied Gubbio with water.

Alvarez 2009

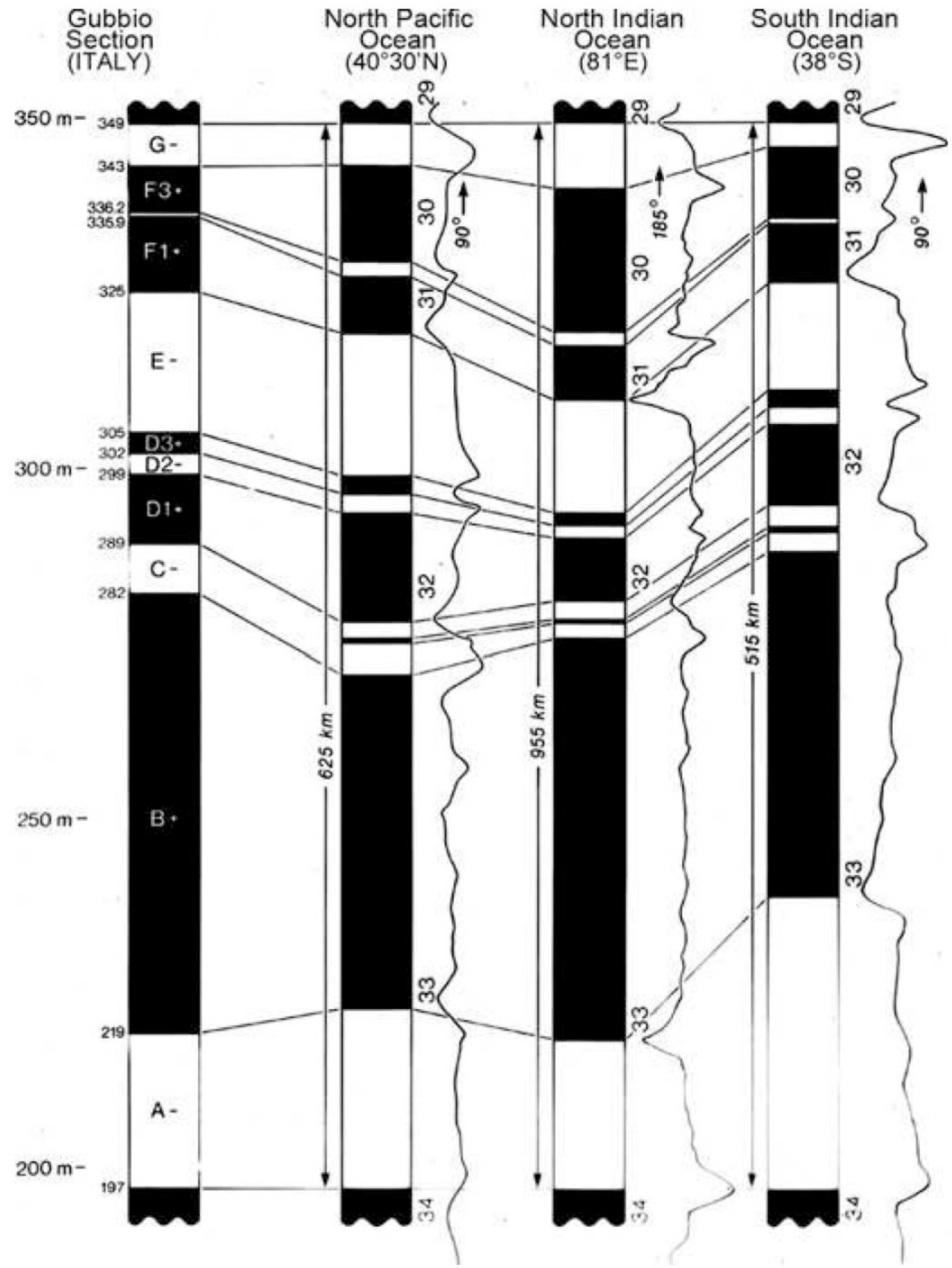

Fig. 2. Comparison between the Upper Cretaceous polarity record (Campanian and Maastrichtian, with the top of the Cretaceous at 347·6 m) from 150 m of pelagic limestone at Gubbio, and the polarity record from several hundred kilometres of sea floor in three different oceans (Lowrie & Alvarez, 1977a). The one thin normal interval missing in zone C at Gubbio was missed between samples in this initial paper; it was found to be present in a more detailed follow-up study (Lowrie & Alvarez, 1977b).

Alvarez 2009

Fig. 3. At the Bottaccione Gorge during the 1976 meeting on palaeomagnetic stratigraphy of pelagic carbonate sediments. Front, from left to right: Roger Larson, Alfred G. Fischer, Walter Alvarez, William Roggenthen, Giampaolo Pialli. Rear, left to right: Roberto Colacicchi, Giovanni Napoleone, William Lowrie. The Cretaceous–Tertiary

Alvarez 2009

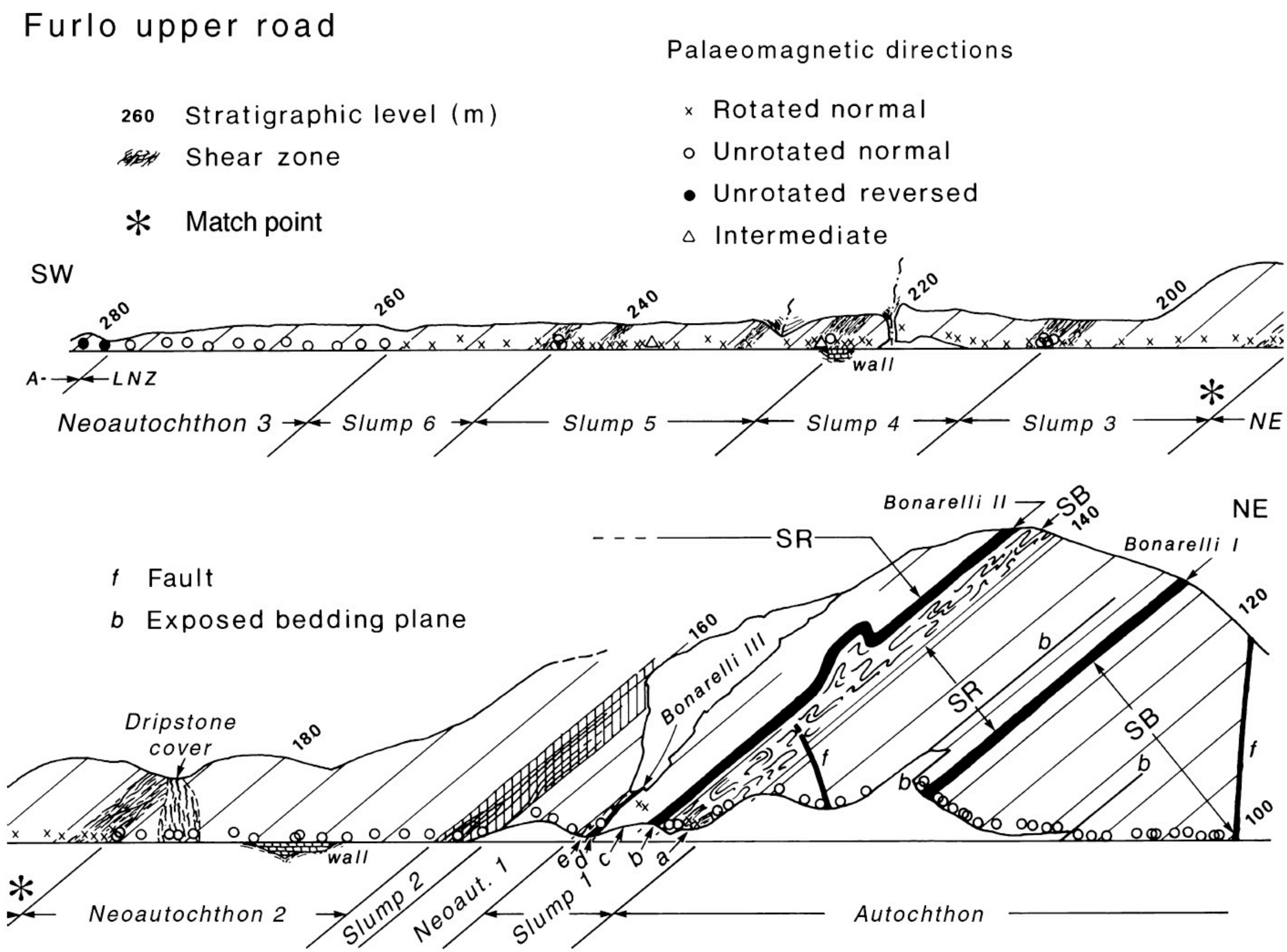

Fig. 5. Exposures of the Scaglia bianca and Scaglia rossa along the upper road at Furlo, in the Marche Apennines north-east of Gubbio. The strongly deformed slump that repeats the anoxic Bonarelli bed close to the Cenomanian–Turonian boundary is clearly visible in outcrop. The more obscure slumps numbered '3' to '6' were found because their palaeomagnetic declinations were rotated during slump movement; once they were located in this way, they were seen to be bounded by subtle sheared intervals in the limestone. From Alvarez & Lowrie (1984).

Alvarez 2009

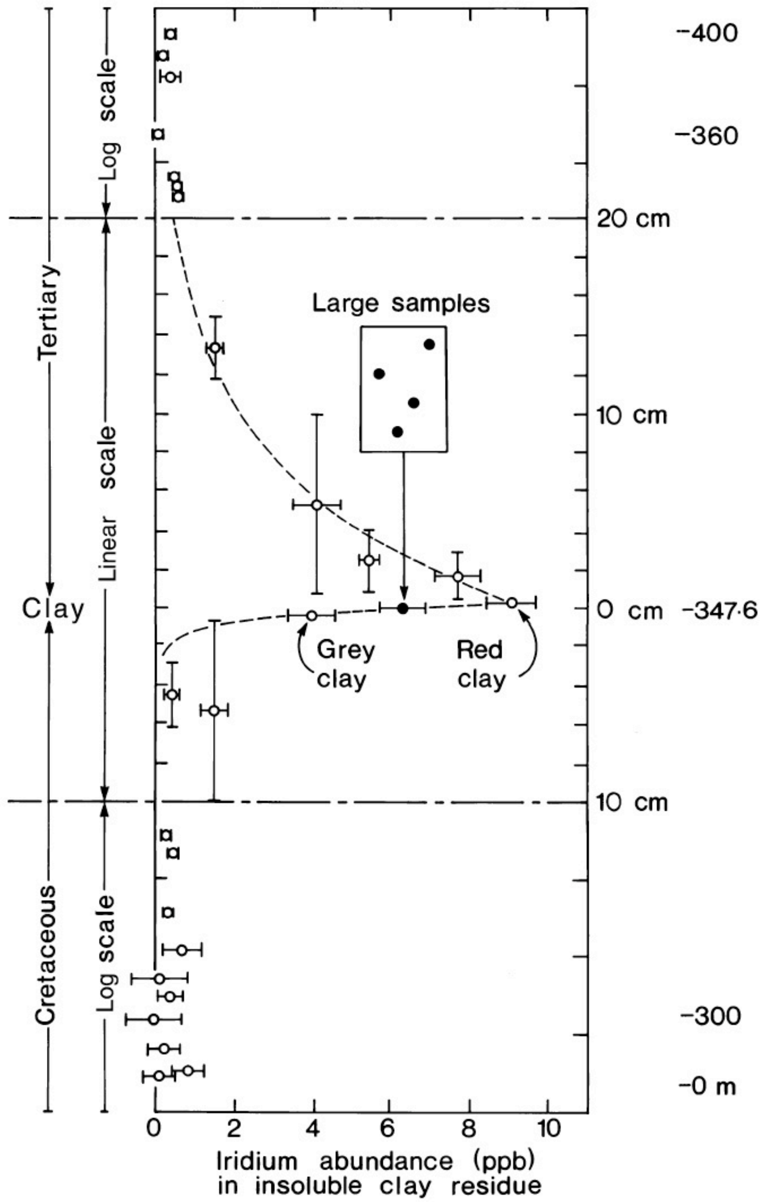

Fig. 7. The first plot of the Cretaceous-Tertiary boundary iridium anomaly from the Bottaccione Gorge at Gubbio and nearby sections, which was slightly modified for publication by Alvarez *et al.* (1980).

Alvarez 2009