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ADVANCES IN ANALYSING METROPOLITAN AREAS SUBSURFACE GEOLOGY

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Subsurface geology of the Torino metropolitan area (Westernmost Po Plain, NW Italy)

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ABSTRACT

The 1:100,000 subsurface geological map of the Torino metropolitan area covers ~900 km^2 in the westernmost Po Plain, an area of great relevance being crossed by the late Neogene to Quaternary 'Torino Hill Front' (THF), a tens of kilometers long, NW-verging buried and blind thrust. The map provides an updated representation of the bedrock geology below the late Early Pleistocene-Holocene Alpine-sourced fluvial blanket, relying on novel correlation of shallow water well and borehole logs. The map describes how the syn-depositional thrust-related folding pulses affected the early Piacenzian-early Middle Pleistocene tectono-stratigraphic evolution of this sector. Our results demonstrate that the deposition of the lower Piacenzian shallow marine succession and then of the Piacenzian to Calabrian alluvial record was controlled by the stepwise propagation of the THF, and suggest that this thrust was apparently sealed by the late Early Pleistocene unconformity. Gentle folding characterized the late Early Pleistocene-early Middle Pleistocene time interval.

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1. Introduction and aims

The Torino metropolitan area is located between the Western Italian Alps and the Torino Hill (Figure 1) and represents one of the most populated and industrialized areas of Northern Italy. From the geological point of view, this area is of great interest developing at the westernmost termination of the Torino Hill thrust Front (THF), which tectonically superposes the northwestern part of the Tertiary Piemonte Basin (TPB) and the unconformably overlying late Messinian-Pleistocene Savigliano Basin onto the coeval Western Padane Foredeep (present-day Po Plain) (Ghielmi et al., 2019; Mosca et al., 2010, Piana et al., 2017a,b). In the hanging-wall of the THF, which is buried by Quaternary continental deposits of the Western Padane Foredeep, the geologic setting of the exhumed, northeastern part of the Torino Hill anticline (Figures 1 and 2(a)) was mapped in detail by Festa et al. (2009), and its pre-Pliocene tectono-stratigraphic evolution was studied by Festa et al. (2005). On the contrary, the geologic architecture of its buried southwestern counterpart as well as that of the adjacent depocentres, and their Pliocene-Quaternary tectono-stratigraphic evolution were only partly depicted by small-scale (1:200,000-1:250,000) subsurface maps (see Balestro et al., 2009; Forno et al., 2018; Lucchesi, 2001), and by the interpretation of a few industrial seismic profiles, (e.g. Comerci et al., 2021; Ghielmi et al., 2019; Mosca, 2006).

Throughout the analysis of well logs, drilled cores, and published seismic transects (Figure 2) and their mutual correlation, this paper aims to define and reconstruct the architecture and the late Pliocene-early Middle Pleistocene tectono-stratigraphic evolution of the subsurface geology of the Torino metropolitan area throughout a new 1:100,000 geological map (Main Map). The latter illustrates the bedrock geology below the late Early Pleistocene regional unconformity (hereafter 'LEP' unconformity), corresponding to the base of the late Early Pleistocene-Upper Pleistocene alluvial succession (Figure 2(a)), related to the Alpine glacio-fluvial fans. The map would also represent a geological base reference for future researches and applications (e.g. groundwater exploration and seismic hazard assessment), and a complementary document for public administrations, geo-practitioners, and stakeholders.

2. Methods and map representation

The Main map covers an area of approximately 890 km^2, representing the original cartographic output of a GIS-assisted subsurface geodatabase (Marcelli

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Supplemental map for this article is available online at https://doi.org/10.1080/17445647.2024.2391963.

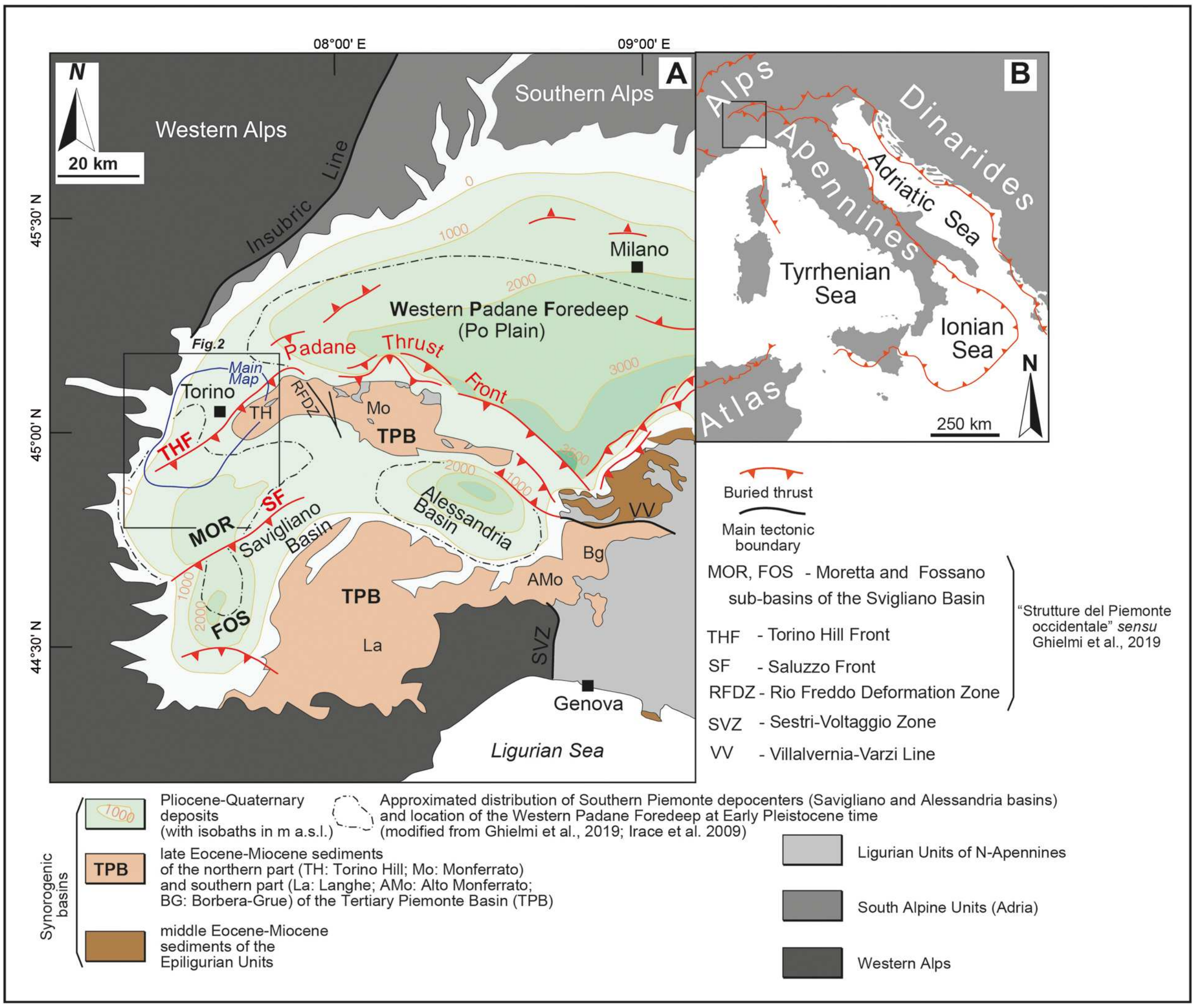

Figure 1. Regional structural sketch map (a) of Northwestern Italy (modified from Bigi et al., 1983; Festa et al., 2015; Irace et al., 2010). (b) Location of Figure 1 (a) (modified from Festa et al., 2015).

et al., 2021) in part developed in the frame of a research project, carried out over a two-year period (2019–2020) by researchers of the CNR-IGG and SMAT (Società Metropolitana Acque Torino) to improve a sustainable use and safeguard of aquifers in the Torino metropolitan area. It consists of an isobaths map, contoured at 10 m intervals, of the LEP unconformity beneath the late Early Pleistocene-Holocene alluvial plain cover. The map was compiled by novel analyses, interpretation, and detailed correlation of over 500 selected key water well and borehole logs, collected from the geotechnical database of the Regional Agency for Environment Protection (ARPA Piemonte), the National Geological Cartography (CARG project) and SMAT archives. Logs interpretation consisted in the lithofacies analysis, supported by original photographic documentation of some recovered continuous drilled cores and, in a few cases, by their direct observations, and also by targeted biostratigraphic analyses.

Logs were correlated through a dense network of detailed cross-sections with an average investigation depth of 200 m below ground surface, leading to a shallow subsurface fence diagram (see Marcelli et al., 2021, for more details), which is also supported by the deep tectono-stratigraphic relationships recognized in the regional seismic stratigraphy (Figure 2(b)). Integration of all data allowed a well-constrained 3D reconstruction of both the LEP unconformity and buried Pliocene-Pleistocene sedimentary units and geological contacts, which were excerpted and summarized in three geological cross-sections in the Main Map, striking sub-parallel to the seismic transects of Figure 2(b) and perpendicular to the main direction of tectonic transport.

The basic architectural elements of the legend are represented by lithostratigraphic units, and grouped into synthems, bounded by regional unconformities (Salvador, 1994). The names of lithostratigraphic units and synthems, and tags of the regional unconformities (D1 to D9) correspond to those adopted in the GeoPiemonte Map (Piana et al., 2017a,b) for the Eocene-Early Pleistocene syn-orogenic basins.

The map is represented on a vectorial topographic base derived by the Digital Elevation Model of Regione

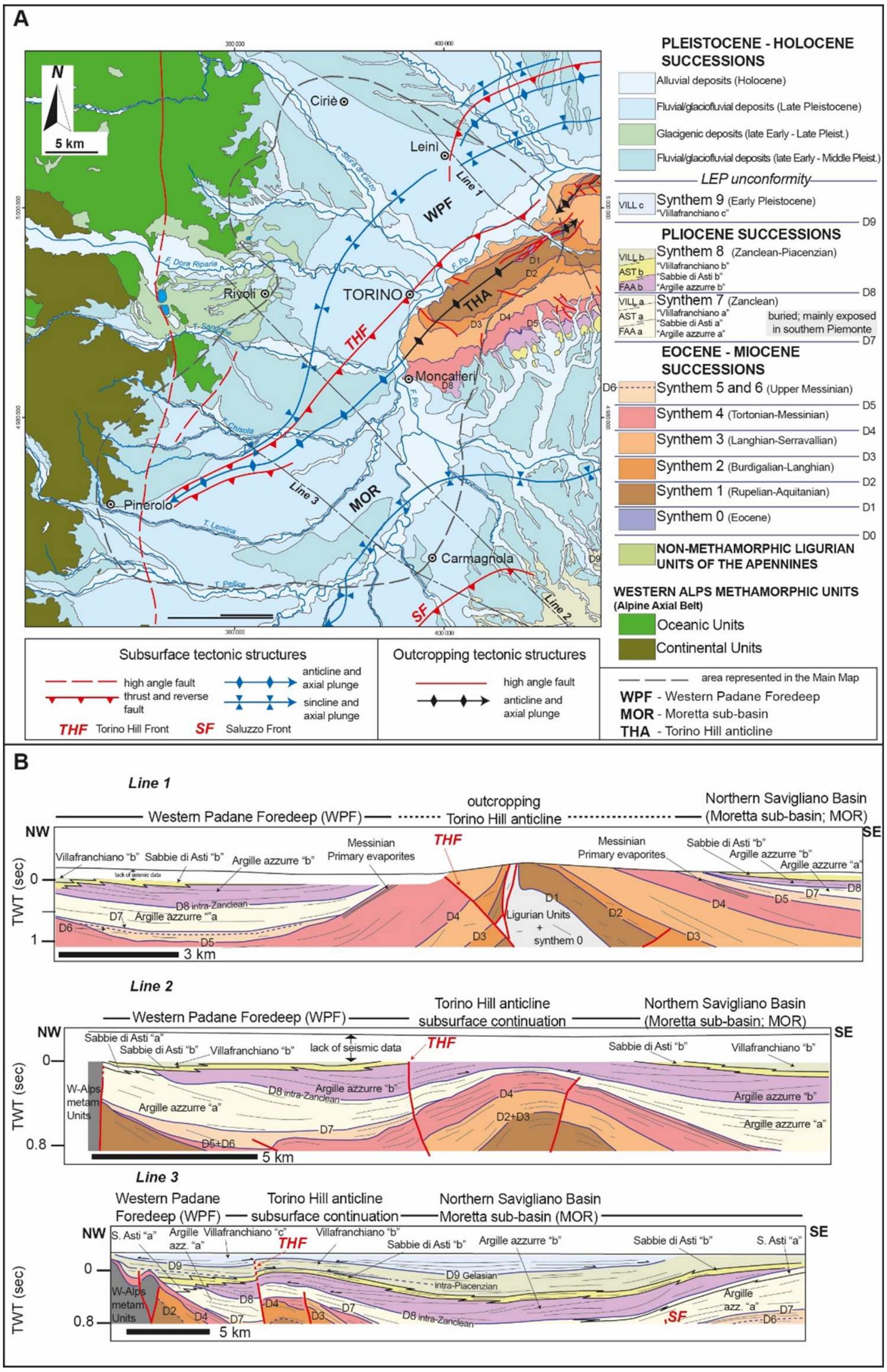

Figure 2. (a) Location of the study area in the geological sketch map of Western Piemonte (modified from Piana et al., 2017a,b). Outcropping tectonic structures located from Festa et al. (2009), Balestro et al. (2009); buried thrusts and folds simplified from Ghielmi et al. (2019). (b) Line drawings of seismic lines across the Torino Hill Front (THF) and thrust-related folds (line 2 after Comerci et al., 2021; line 3 from Ghielmi et al., 2019; line 1 from Mosca, 2006 and Mosca et al., 2010 and Comerci et al., 2021) reinterpreted according to the unconformity and synthem codes mapped in the GeoPiemonte Map (Piana et al., 2017a,b). A lithostratigraphic interpretation of the Pliocene-lower Pleistocene seismic sequence is also reported. Note that seismic data above the datum plane (0 m a.s.l.) are often lacking (e.g. profile 1 and 2). Traces of seismic lines are in Figure 2(a).

Piemonte (DTM 2009–2011 Piemonte, ICE 5 m grid resolution). In particular, the shaded DTM was combined with hydrographic data, trigonometrical and elevation points, as well as anthropic data (highways, roads, railways, urban areas).

3. Regional geological setting

The subsurface of the westernmost part of the Po Plain consists of Cenozoic synorogenic basins: the Eocene-Messinian Tertiary Piemonte Basin (TPB) and the Pliocene-Quaternary basins (Figure 1). They recorded the syn-collisional tectonic evolution of the Alps-Apennines orogenic system, whose evolutionary stages are mostly represented by regional-scale unconformities (e.g. Balestro et al., 2022; Dela Pierre et al., 2003; Festa et al., 2009, Piana et al., 2017a,b), and classically subdivided into seven main contractional stages during the Rupelian, late Oligocene to pre-late Burdigalian, late Burdigalian-early Langhian, late Serravallian-early Tortonian, late Messinian (see Dela Pierre et al., 2003, 2007; Festa et al., 2005, 2009; Mosca et al., 2010; Piana, 2000), Zanclean and early Gelasian (see Ghielmi et al., 2010; Ghielmi et al., 2013; Ghielmi et al., 2019; Irace et al., 2010; Irace et al., 2017; Vigna et al., 2010). Since Serravallian-early Tortonian times, the NE-trending Torino Hill anticline began to develop in the hanging wall of the NW-verging THF (Festa et al., 2005, Figure 2), which represents the westernmost prolongation of the more external thrust fronts of the northern Apennine (i.e. the Padane thrust front; Costa, 2003; Pieri & Groppi, 1981). This anticline, which is characterized by a double plunging fold axis toward SW and NE, is displaced by transfer faults, about NW-SE striking, that accommodated the northwestward migration of the THF (Costa, 2003; Festa et al., 2009; Figure 2 (a)). During the Messinian a major NW – to N-ward migration of the THF induced a significant uplift and erosion of the Torino Hill anticline (Festa et al., 2005, 2009; Piana, 2000), temporarily interrupting the communications between the main depocentral areas (Ghielmi et al., 2019; see Figure 1). Part of these depocentral areas (e.g. the Western Padane Foredeep and the Moretta sub-basin, see Figures 1 and 2(a)) were first reconnected one to each other above the SW buried prolongation of the Torino Hill anticline during the Pliocene Epoch (Ghielmi et al., 2019), and later again separated by the reactivation of the THF during the Pliocene-Pleistocene transition (Piana et al., 2017b).

The stratigraphic succession of the Torino Hill sector of the TPB consists of seven synthems (synthem 0–6), separated by regional unconformities (from D0 to D6), and ranging in age from late Eocene to late Messinian (Festa et al., 2009; Piana et al., 2017a,b). The Miocene succession is followed, through the abrupt drowning at the end of the Messinian salinity crisis (D7 unconformity), by three synthems (7, 8 and 9; Figure 2 (b)) whose complete section is now buried in the depocentres of the Savigliano basin and Western Padane Foredeep (see Figure 1). Seismic and outcrop data show that the Zanclean to Early Pleistocene synthems are separated by two main regional angular unconformities (D8 and D9), corresponding to basin-wide modifications related to the intra-Zanclean and early Gelasian major compressional tectonic phases, respectively (Ghielmi et al., 2019; Irace et al., 2010; Piana et al., 2017a,b; Vigna et al., 2010). Between the D8 and D9, a lower rank angular unconformity, corresponding to the lower magnitude intra-Piacenzian tectonic phase (*sensu* Ghielmi et al., 2010, 2013 and Amadori et al., 2019), is seismically detectable to the southwest, mostly close to the THF (i.e. Ghielmi et al., 2019; see line 3 in Figure 2 (b)). The regressive synthems 7 and 8 both testify opposite (NW – and SE-ward) progradation directions of basin/slope (Argille azzurre) and shelfal/coastal (Sabbie di Asti) depositional systems, becoming progressively continental upward ('Villafranchiano' *Auct.*). The synthem 7 includes the Zanclean Argille azzurre 'a', Sabbie di Asti 'a' and Villafranchiano 'a' informal units *sensu* Ghielmi et al. (2019). Likewise, the synthem 8, spanning the late Zanclean-Piacenzian time interval, is informally subdivided into the Argille azzurre 'b', Sabbie di Asti 'b' and Villafranchiano 'b' units, allowing the distinction from similar, but older, units belonging to the synthem 7. Although the term 'Villafranchiano' should be abandoned in the future, as it refers to a Mammal Age (Rook & Martínez-Navarro, 2010 and references therein), corresponding to the Piacenzian (from 3.5–2.6 Ma) and Gelasian and Calabrian *p.p.* (from 2.6 up to 1.1 Ma, near to the base of the Jaramillo subchron), it has been still maintained in this paper in agreement with the litostratigraphic nomenclature of Piana et al. (2017b) and Ghielmi et al. (2019).

The high-rank Gelasian angular unconformity (D9; Figure 2(b)) separates the more deformed Pliocene prograding prisms from the upper less deformed lower Pleistocene synthem 9 (Ghielmi et al., 2019; Irace et al., 2017), consisting of continental deposits referred to the Villafranchiano 'c' informal unit. Its mainly aggradational architecture preceded the deposition of the typical terraced fluvial/glaciofluvial megafans, late Early Pleistocene-to-Late Pleistocene in age, fed by the Stura di Lanzo, Dora-Riparia, Sangone, Chisone and Pellice rivers (Figure 2 (a)). These proglacial braidplain successions, which in the studied area are not resolved by seismic profiles, are correlative to the end moraine systems along the Alpine margin (Fioraso et al., 2021) and lie above the LEP unconformity. This coincides with the 'Red' (R) surface traced across the Po Plain subsurface (Ghielmi et al., 2010, 2013, 2019; Muttoni et al., 2003; Scardia et al., 2006; Scardia et al., 2012). Its shaping, primarily ascribed to the onset of major Pleistocene glaciations in the Alps, was locally influenced by the uplift of northern Apennine blind-thrusts and/or anticlines (Amadori et al., 2019; Zuffetti & Bersezio, 2021).

4. Data

The stratigraphic succession (Subsection 4.1) and the map scale tectonic setting (Subsection 4.2), characterizing the subsurface of Torino metropolitan area, are presented in the following.

4.1. Subsurface stratigraphy

The lithological, sedimentological and stratigraphic characters of the Pliocene-Quaternary litostratigraphic units are here described, from the older unit to the younger one (see Figure 3 and cross sections in the Main Map).

4.1.1. The Pliocene succession

- *Argille azzurre (Zanclean – earliest Piacenzian)*: this unit (FAA in the Main Map) consists of a basin to outer shelf muddy succession, composed by grey to light blue, poorly bedded and bioturbated marls and clayey marls, alternating with thinly laminated silty clays (Figure 3), which locally pass laterally and in continuity to sandy and sandstone interbeds, about 10–15 m in thickness. The fossil content consists of rare gastropods and bivalves, abundant planktonic and benthic foraminifera, and plant fragments. The upper part of the succession shows a gradual regressive facies transition to the Sabbie di Asti 'b'.
- *Sabbie di Asti 'b' (early Piacenzian)*: this unit (ASTb in the Main Map) consists of shelf to nearshore deposits represented by yellowish to grey colored, fine to coarse homogeneous sands and sandstones, showing peculiar concentrations of marine bivalves and gastropods (Figure 3). Several lenticular bodies of clayey silts, kilometers-wide and up to 20 m-thick, occur at different stratigraphic levels. The thickness of ASTb changes from about 30 m to about 80 m from the hangingwall to the footwall of the THF, respectively (see 'Map scale tectonic setting' below; see also section B-B' in the Main Map). The top of the unit is cut by a slight angular unconformity named here D8.1, following the nomenclature of Piana et al. (2017a,b). The D8.1 documents a sharp change to a continental environment (see below), and it likely correlates to the tectonic-driven, intra-Piacenzian local unconformity reported by Ghielmi et al., 2019 (see line 3 in Figure 2 (b)).
- *Villafranchiano 'b' (Piacenzian)*: this unit (Vb in the Main Map) is characterized by a cyclical pattern, evidenced by the rather regular alternation of 20–60 m thick clay–silt deposits, and 10–20 m thick gravel-sand intervals, both showing a great lateral persistence. The clay–silt deposits, which predominate toward SE, are massive and bioturbated to laminated and include lignite coal beds and abundant plant remains (e.g. Robassomero-Venaria sector; Martinetto et al., 2007). The gravel-sand intervals consist of clast – to sand matrix-supported, moderately sorted to sorted, pebbly gravels, with sub – to well-rounded polygenic clasts, grading upward and laterally to well sorted sands. The Vb sediments are characterized by different colors varying from grey/blue/greenish to yellowish and brown ochre, reflecting increasing degrees of oxidation (Figure 3), in turn related to growing drainage conditions and/or time of subaerial exposure. The Vb thickness varies largely in a NW-SE direction, passing from major estimated values of 150–200 m to the northwest of the THF, up to limited values of about 10–30 m to the southeast of the Torino Hill anticline (see 'Map scale tectonic setting' below; see also section B-B' in the Main Map). These sediments locally crop out along the thalwegs and terrace scarps of the Casternone-Ceronda and Stura di Lanzo rivers (Balestro et al., 2009), at the northwestern border of the study area, where they were constrained to the Piacenzian subchron Kaena by Martinetto et al. (2007). The depositional setting was a low-gradient distal floodplain, with dominant palustrine/lacustrine to overbank deposition punctuated by recurrent avulsive shifting of braided channels across the Pliocene piedmont open alluvial plain (Ghielmi et al., 2019; Martinetto et al., 2007).

4.1.2. The Quaternary succession

- *Villafranchiano 'c' (Gelasian – Calabrian)*: this unit (Vc in the Main Map) starts with the D9-Gelasian erosional surface, comprising a subtle angular unconformity, which downcuts the Vb succession. Its upper boundary corresponds to the LEP unconformity. The Vc is limited to the central and southern sectors of the mapped area and shows a south-westward thickness increase from 0 to about 60 m. Abrupt stratigraphic thickness variations, also occur in the NW-SE direction (sections B-B', C-C'). The Vc displays a different stratigraphic architecture in comparison to the Vb, recording a decreasing of silty-clayey intervals. These latter are thinner, laterally more discontinuous and more weathered than those in the Vb (Figure 3), and show episodic lignite layers. Furthermore, Vc records the increase of poorly sorted coarse to very coarse gravel (up to 20 m thick), filling concave-up erosive surfaces, which are indicative of a proximal braidplain with sedimentation likely confined in depocentres, as suggested by Ghielmi et al. (2019). Despite the lack of chronological constraints, a Gelasian-Calabrian age is suggested for Vc by the stratigraphic correlation with informal stratigraphic units, previously mapped to the east (Carraro, 1996; Forno et al., 2015) and drilled by deep-wells to the south (Ghielmi et al., 2019).

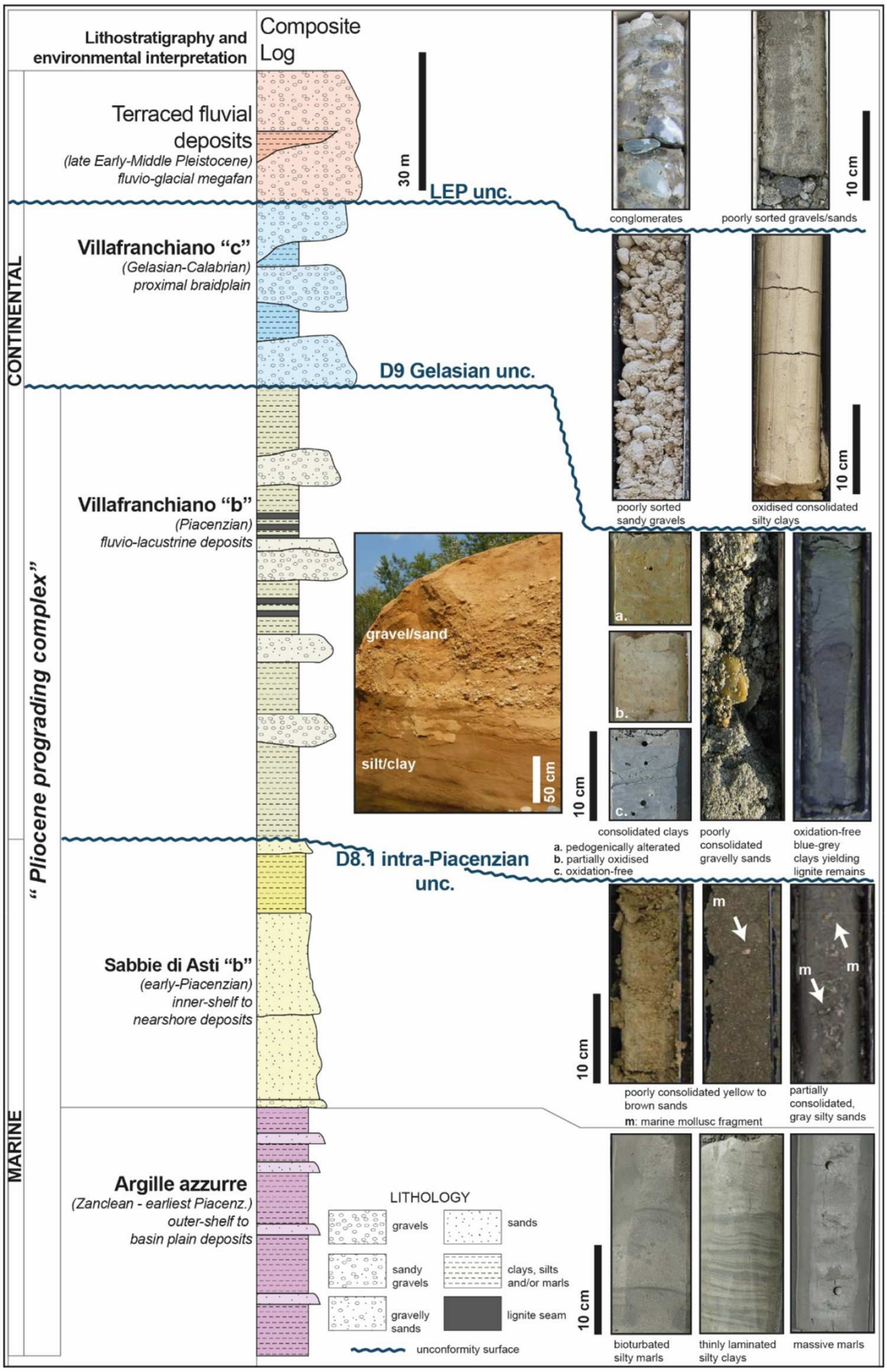

Figure 3. Summary stratigraphic log and core expression of the Zanclean-Quaternary succession in the Torino thrust-propagation fold system. A photograph of the Villafranchiano 'b' outcrop-analogue along the Stura di Lanzo river bed (Robassomero sector, northwestern border of the study area) is also reported; notice the characteristic ochre color.

– *Terraced alluvial deposits (late Early–Late Pleistocene and Holocene)*: above the smooth angular LEP unconformity, the terraced alluvial successions of the present-day alluvial plain display an even more proximal trend of braided fluvial deposits than the Vc. The terraced deposits, whose detailed analysis is out of the aim of this paper, consist of thick packages of poorly sorted, very coarse gravels/sands (locally cemented; Figure 3) and subordinate sandy-clayey lenses. These successions, which were represented only in cross-sections to give a better map representation of the buried geology, include:

– the coalescing glaciofluvial and fluvial megafan deposits, which are coeval to the *late Early* – Late Pleistocene glacigenic deposits occurring at the western border of the study area;

– the Holocene fluvial deposits of the present-day major rivers (Po and left tributaries; see also Forno et al., 2024; Forno & Gianotti, 2021) entrenched into the older megafans through the erosive surface shaped during the latest downcutting of the river network.

4.2. Map scale tectonic setting

The tectonic setting is characterized by the NE-striking and SE dipping THF, which separates a regional scale fold system, NE – to NNE-trending, represented by the couple Torino Hill Anticline (THA) – Moretta Syncline (MOS), and the Leinì-Piscina Syncline (LPS), in the hanging wall and footwall, respectively (see Main Map and Figure 4(a)).

The THF is a blind thrust unconformably sealed by the late Early–Late Pleistocene succession. Its north-eastern segment superposes the Langhian-Messinian succession onto the Pliocene sediments (see section A-A’ in the Main Map), while its southwestern part

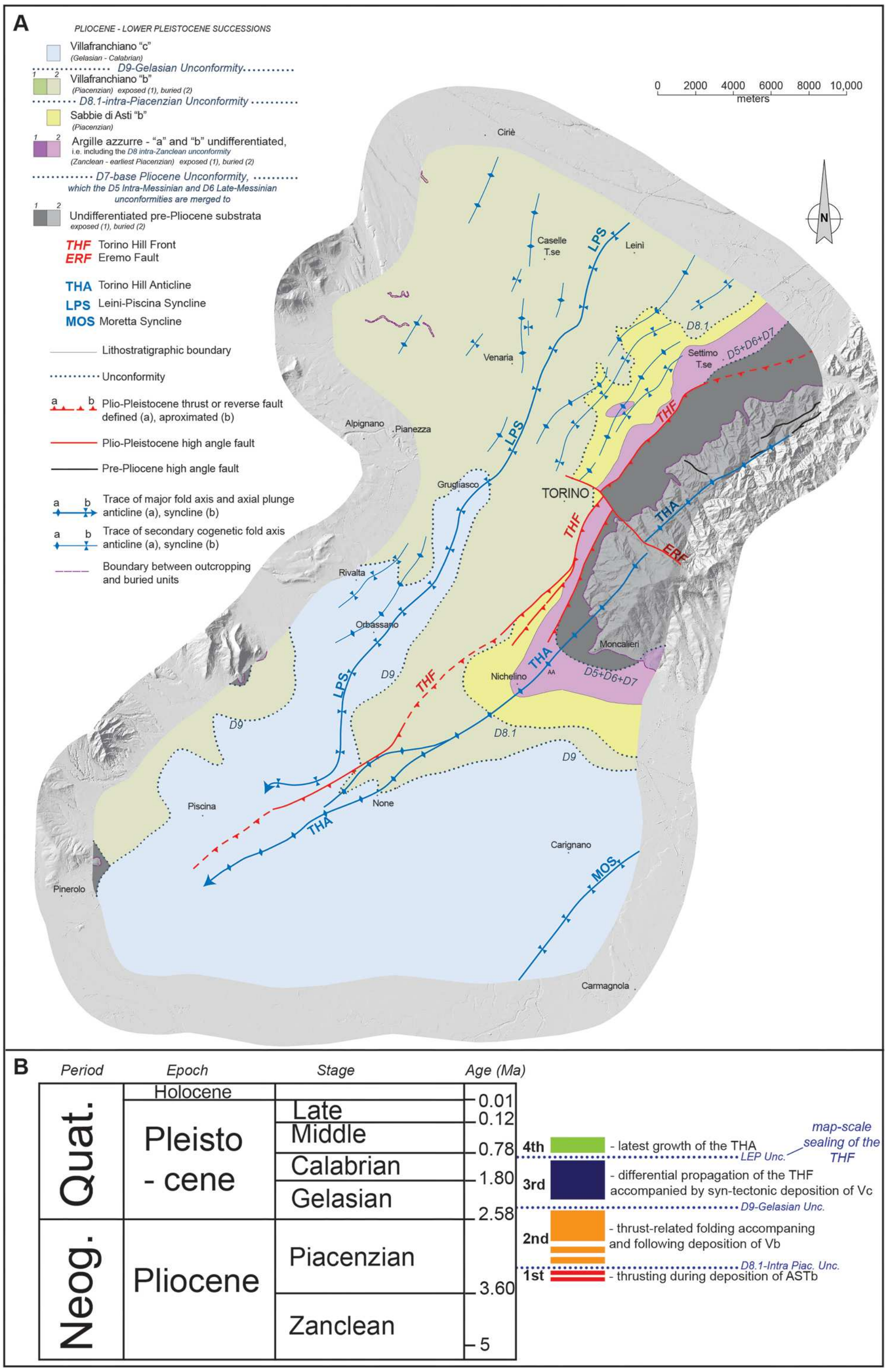

Figure 4. (a) Structural scheme of the studied sector, showing the location of main mapped structural elements, by ideally removing the late Early Pleistocene-Holocene sediments of the present-day alluvial plain. (b) Time column summarizing the four tectonic pulses, inferred from tectono-stratigraphic relationships.

dissects the Pliocene-Lower Pleistocene succession (sections B-B', C-C' in the Main Map), showing a southwestward decrease in displacements. Locally, between Torino and Nichelino (see section B-B' in the Main Map), two thrust splays characterize the hanging-wall of the THF, displacing the Miocene-Pliocene marine succession.

In the hanging-wall of the THF, the THA is characterized by a southwestward axial plunge, which is documented by the exhumation of the Eocene-Messinian marine succession in the northeastern sector of the mapped area (i.e. the Torino Hill *Auct.*), and by the fold-related deformation of progressively younger terms toward SW, up to the Pliocene-Lower Pleistocene succession (see Main Map and Figure 4(a)). In the latter sector, between Moncalieri and None, the D8.1-Intra-Piacenzian unconformity depicts an antiform geometry, and the Vb deposits show onlap terminations on the southeastern limb of the THA (section B-B' in the Main Map). Similarly, the Vc succession (section C-C' in the Main Map) onlaps onto the folded D9-Gelasian unconformity, which truncates the Vb deposits, marking the growth geometry of the fold. This is also supported by evidence that the Vc and locally the late Early–Late Pleistocene deposits thin toward the anticlinal crest (section C-C' in the Main Map).

In the footwall of the THF, the LPS consists of a WNW-verging gentle to very gentle fold with a SW-low angle plunging axis, whose strike is slightly oblique to that of THA with a lateral continuity of about 35 km (see Main Map). The northeastern part of the LPS (Grugliasco-Leinì sector) deforms the Pliocene succession up to the Vb deposits, which progressively thin toward the ESE (i.e. toward the THF) as shown by eastward onlap terminations associated with the D8.1-Intra-Piacenzian unconformity above the ASTb (sections A-A', B-B'). Between the LPS and the northeastern part of THF, the Pliocene succession is also deformed in a minor fold system with fold axes parallel to the LPS, and a lateral continuity of about tens of kilometers along strike. To WSW (Grugliasco-Piscina sector), the LPS also deforms the D9-Gelasian unconformity, which in Section B-B' is sub-parallel to the D8.1 unconformity. Above the D9 the deposition of Vc shows subtle angular relationships with the Vb on the syncline limbs.

To the E, the LPS and the stratigraphic succession up to the Vb deposits are displaced, with normal to transtensional left-lateral movements, by the northwestern prolongation of the high-angle Eremo Fault (ERF), NW-striking, previously described by Festa et al. (2009) for the exhumed Burdigalian-Langhian succession. The above-described subsurface tectonic features (i.e. THF, THA, LPS) of the Torino metropolitan area are unconformably overlain by the LEP unconformity. However, the latter locally shows gentle folds close to the hinge zone of the THA (see section C-C' in the Main Map), which is accompanied by the thinning of overlying late Early–Late Pleistocene alluvial deposits.

5. Discussion: multistage tectono-stratigraphic evolution of the Torino metropolitan area

The crosscutting relationships between the mapped stratigraphic unconformities and tectonic features (i.e. folds and thrust faults), as well as the different degrees of deformation within the different units, allow defining the following subsequent tectonic pulses, related to the progressive NW-ward migration of the THF: (Figure 4(b)):

- *Early Piacenzian*: although only minor evidences of this pulse are preserved in the mapped area, the NW-SE change in thickness of the ASTb deposits across the THF (see section B-B' of the Main Map) suggests that thrust tectonics could have controlled the deposition in early Piacenzian time. The time constrain to this tectonic pulse is provided by the D8.1-Intra-Piacenzian unconformity, which seals the ASTb succession.
- *Late Piacenzian-earliest Gelasian(?)*: evidence that the lower part of the Vb floodplain deposits (Piacenzian) onlap the top the ASTb succession through the D8.1-intra-Piacenzian angular unconformity (sections A-A', B-B') and that both this unconformity and the overlying Vb succession are folded (i.e. THA and LPS) with fold axes subparallel to the THF, suggest that NW-SE-directed shortening, likely consistent with the northwestward migration of the THF, was active in late Piacenzian time. The different thickness of the Vb deposits in the hanging-wall and footwall of the THF (see Cross section B-B' in the Main map) and/or on the different limbs of the THA, also support the occurrence of a thrust activity during this time interval with the THF displacing the Pliocene succession (FAA, ASTb and Vb) with apparent reverse movements. The uppermost temporal constrain to this tectonic pulse is provided by the age of the D9 Gelasian unconformity which seals the Vb deposits.
- *Gelasian-Calabrian*: evidence that the THF displaces the lower part of the Quaternary succession (i.e. the Vc; see section C-C' in the Main Map) and it is uncomformably overlain by the LEP unconformity, document that the thrust activity protracted up to the Gelasian-Calabrian time, at least with offsets mappable at the scale of this work. This thrusting activity controlled the physiography of the Gelasian-Calabrian fluvial basin as highlighted by the lateral wedging of the Vc

between folded structures, and the onlap of Vc deposits onto the folded D9 Gelasian unconformity (see sections B-B', C-C'). This pulse is in line with the Early Pleistocene reactivation of the THF that drove the NW-ward migration of Torino Hill-Moretta folds pair over the LPS. The fact that Vc sediments are confined in the south-western part of the study area may be explained with the SW-ward plunging of the THA and LPS, which is likely related to the decrease of displacement along the THF in the same direction. The normal to left-lateral NW-striking Eremo Fault, which displaces the lateral continuity of the THF and of some fold structures, possibly worked as transfer fault, accommodating the NW-ward movement of the THF closer to the northeast. The uppermost temporal constrain to this tectonic pulse is provided by the LEP unconformity that seals the Vc deposits.

– *late Early Pleistocene-early Middle Pleistocene*: the local, very gentle folding of the LEP unconformity and the thinning of overlying deposits at the THA crest (section C-C') likely suggest a late phase of late Early Pleistocene-early Middle Pleistocene syn-depositional growth for this structure without mappable thrust-related offsets.

6. Conclusions

Subsurface geological mapping of the Torino metropolitan area, based on highly detailed correlations between stratigraphic logs, allowed us to provide new constraints for the reconstruction of the Piacenzian-early Middle Pleistocene tectono-sedimentary evolution of the westernmost termination of the Po Plain. This work allowed the definition of four main subsequent tectonic pulses (i.e. early Piacenzian, late Piacenzian – earliest Gelasian, Gelasian – Calabrian, late Early Pleistocene-early Middle Pleistocene) resulting in the syn-depositional NW-ward propagation of the THF, related to the continuous NW-SE directed regional shortening, which incorporated progressively younger Po Plain successions during Plio-Pleistocene times.

In conclusion, the 1:100,000 subsurface geological map of the Torino metropolitan area represents a new stratigraphic and structural geological base for future researches, and a complementary document to better address some 'challenging' issues such as i) the analysis, sustainable use and protection of subsurface geo-resources (e.g. groundwater) and ii) the seismic hazard assessment in the Torino urban area, where our map may potentially represents the starting point for planning new high-resolution geophysical investigations (integrated with chronologically constrained cores) to better define and detail the relationships between the buried THF and the shallow late Early Pleistocene-Holocene successions, which are not or poorly resolved by current industrial seismic profiles.

Software

The topographic and geological maps and the related database were edited with QGIS 3.4.8 Madeira. 3D modeling of the subsurface geology was performed with GMS – Groundwater Modeling System 9.2. The final map layout was edited with Adobe® Illustrator® CS5. Photos were managed and compiled using Adobe® Photoshop® CS2.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

The authors confirm that the geological data supporting the findings of this study are available within the article and its supplementary materials.

The topographic data that support the findings of this study are openly available in https://www.regione.piemonte.it/web/temi/ambiente-territorio/territorio/infrastruttura-geografica-cartografia at http://www.geoportale.piemonte.it/geocatalogorp/index.jsp, reference numbers r_piemon:2e02fda6-24ee-45bb-a36e-a2fab030b9e1 (vector files) and r_piemon:224de2ac-023e-441c-9ae0-ea493b217a8e (DTM).

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