Journal of Maps

ISSN: (Print) 1744-5647 (Online) Journal homepage: https://www.tandfonline.com/loi/tjom20

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To cite this article: Alberto Bosino, Luisa Pellegrini, Adel Omran, Massimiliano Bordoni, Claudia Meisina & Michael Maerker (2019) Litho-structure of the Oltrepo Pavese, Northern Apennines (Italy), Journal of Maps, 15:2, 382-392, DOI: 10.1080/17445647.2019.1604438

To link to this article: https://doi.org/10.1080/17445647.2019.1604438

JOURNAL OF MAPS
2019, VOL. 15, NO. 2, 382–392
https://doi.org/10.1080/17445647.2019.1604438

Science

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Litho-structure of the Oltrepo Pavese, Northern Apennines (Italy)

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ABSTRACT
In this article we present a detailed litho-structural map of the Oltrepo Pavese, a sector of the Northern Apennines, Southern Lombardy, Italy. Lithology and geological structures are an important basis for different disciplines of Earth Sciences. In particular, for the assessment of earth surface processes such as soil erosion, mass movements, flooding, etc. The Oltrepo Pavese is characterised by a complex geology and related tectonic settings. In this study, we conducted a comprehensive lithological mapping approach considering existing geological maps, and detailed field surveys. The lithotypes have been subdivided into 11 classes based on the dominant outcropping lithologies. Integrating bibliographic data and a detailed Digital Terrain Analysis of a high-resolution DTM (5 m) we detected faults, folds and tectonic lineaments in the study area. The final result is represented by a litho-structural map of the Oltrepo Pavese-area, consisting in two shape files elaborated in an open source GIS environment.

ARTICLE HISTORY
Received 4 January 2019
Revised 3 April 2019
Accepted 4 April 2019

KEYWORDS
Oltrepo Pavese; lithological map; lithologies; lineament detection

1. Introduction

The Oltrepo Pavese area is located in the Northern Apennines and is belonging to the southern part of Lombardy, Italy (Figure 1a). The Oltrepo Pavese covers about 1110 km^2 dominated by a hilly landscape. The elevation ranges from 60 m.a.s.l. close to the Po River up to 1724 m.a.s.l. at the top of Monte Lesima (Figure 1b). The region is characterised by a typical agricultural land use (Figure 1c) consisting in permanent grassland (12.4%), bushes (12.45%), broad-leave forests, vineyards (13.65%), simple agricultural fields (14.54%) and, bushes in abandoned agricultural areas (14.55%). The Oltrepo Pavese area is one of the most important agricultural and vine-growing regions of Italy (DUSAF, 2015 from GEOPORTALE DELLA LOMBARDIA available at http://www.geoportale.regione.lombardia.it/). From the geological point of view the study area is a mosaic of different Mesozoic and Cenozoic sedimentary formations. The geology of the Oltrepo Pavese has been studied and mapped by several authors in the past (e.g. Bellinzona, Boni, Braga, & Marchetti, 1971; Boni, 1967; Braga et al., 1985; Di Dio, Piccin, & Vercesi, 2005; Marroni, Ottria, & Pandolfi, 2010; Meisina, Zucca, Fossati, Ceriani, & Allievi, 2006; Panini, Fioroni, Fregni, & Bonacci, 2002; SERVIZIO GEOLOGICO D'ITALIA, 1965; SERVIZIO GEOLOGICO D'ITALIA, 1969; SERVIZIO GEOLOGICO D'ITALIA, 2005; SERVIZIO GEOLOGICO D'ITALIA, 2010; SERVIZIO GEOLOGICO D'ITALIA, 2014; Taramelli, 1882; Vercesi et al., 2014). However, there is no accurate and homogeneous subdivision of lithologic formations available or a comprehensive regional litho-structural map for further geological assessments and modelling approaches. Generally, litho-structural maps yield information on different rock types as well as geological structures and play a fundamental role in understanding the history of the study region (Ali & Ali, 2013). Therefore, we generated a new litho-structural map of the Oltrepo Pavese. The Main Map was developed based on historical maps, field surveys and DTM analysis, and represents 11 lithologies as well as the main faults, folds, thrust and tectonic lineament systems present in the study area. Finally, the litho-structural map gives important information about the lithology of the substrates and the structural setting of the study area. Thus, this map provides basic information for the assessment of processes i.e. flooding, soil erosion etc. and features i.e. gully, Badlands etc. related to earth sciences.

2. Geological Setting

2.1. Geology of the study area

The Oltrepo Pavese is located in the northern parts of the Apennines and shows typical features of a fold-thrust belt landscape structure (Carmignani, Conti, Cornamusini, & Meccheri, 2004; Cibin, Spadafora,

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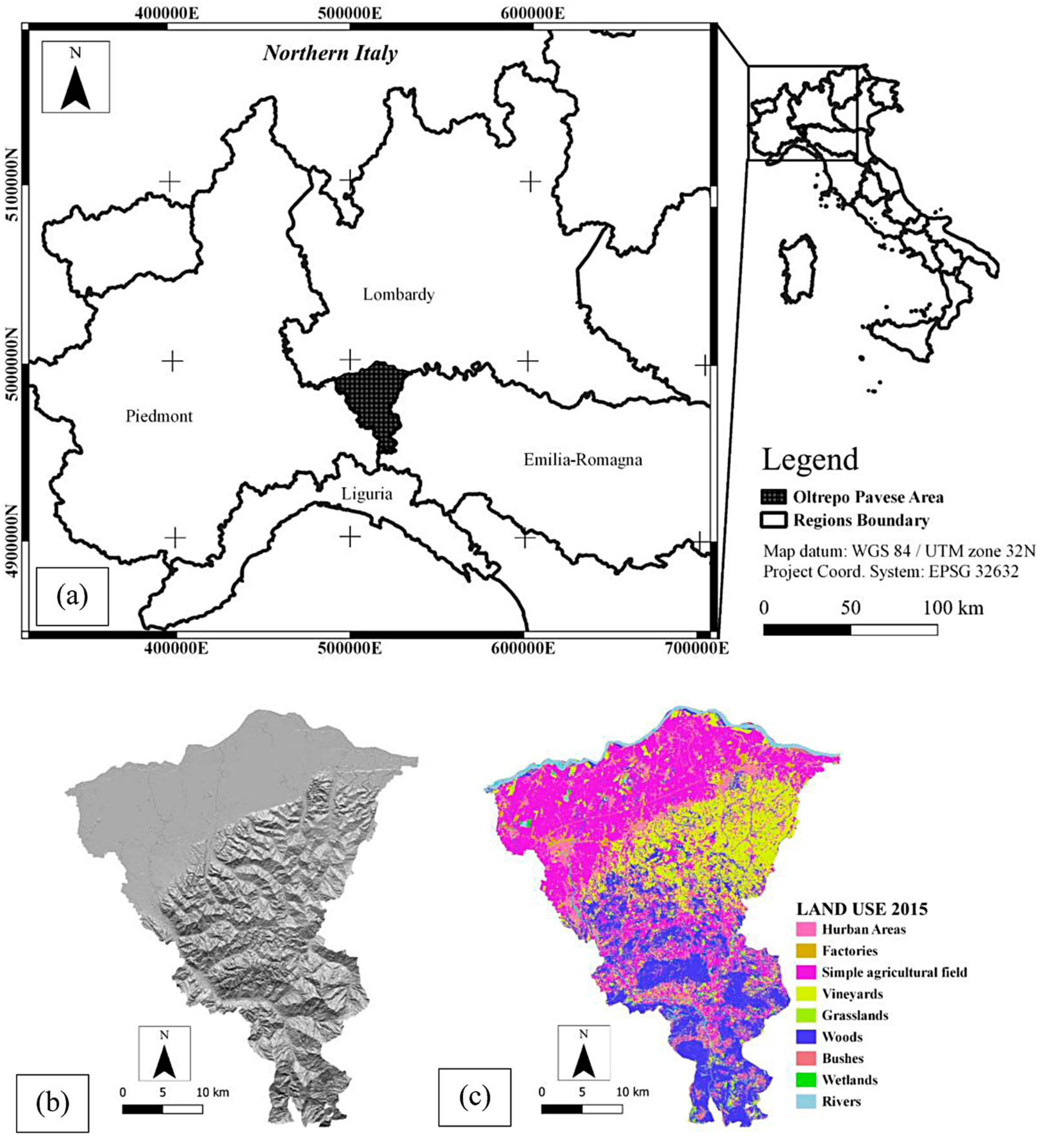

Figure 1. (a) Setting of the Oltrepo Pavese study area. (b) Hillshading of the study area. (c) Land Use of the Oltrepo Pavese, according to CORINE 2015.

Zuffa, & Castellarin, 2001; Toscani, Seno, Fantoni, & Rogledi, 2006). Several authors (e.g. Ciarapica & Passeri, 1998; Decarlis et al., 2014; Finetti et al., 2001; Maino, Decarlis, Felletti, & Seno, 2013) link the evolution of the Apennines with the formation of the Balearic basin. According to this theory the opening of the basin, caused by the anticlockwise rotation of the Corsica-Sardina blocks, is setting up the Apennines orogen (Maino et al., 2013; Maino, Dallagiovanna, Gaggero, Seno, & Tiepolo, 2012). The origin of the Apennines can be associated with two main accretionary steps: (i) the initial Cretaceous western subduction, of the Ligurian Piemonte Ocean, under the European Plate – Eoalpine Phase and (ii) the Eocenic collision between Europe and the Adriatic microplate – Mesoalpine Phase. During these phases the chain acquired its dominant eastward vergence. Finally, during the Oligocene the formation of a double vergence accretionary wedge occurs, which is related to the late eastward subduction of the Adria region (Vercesi et al., 2014).

The Northern Apennines is historically subdivided in several tectono-stratigraphic Units belonging to the two continents (Adria and Europe) and the ocean between them. From the base to the top the relevant Units are structured as follows: Tuscan-Umbrian, Subligurian, Ligurian, and Epiligurian (e.g. Elter, 1975; Elter, Grasso, Parrotto, & Vezzani, 2003; Piazza, Artoni, & Ogata, 2016). In the study area different allochthonous units crop out such as the Subligurian (SUB) and Ligurian Units (LIG), that are often covered by Epiligurian Units (EPI). These, in turn, are sealed by post-Messinian deposits (PMess) and finally covered by Quaternary alluvial deposits (Q).

The Subligurian Units represent the interface between the External Ligurian domain and the Tuscan domain. In the Oltrepo Pavese the Subligurian Units are characterised by the Monte Penice Flysch as well as interstratified limestones; the so called Canetolo clay- and limestones. These Units lay on the thinned boundary of the Adriatic Continent. From a lithological point of view, they are composed by turbiditic deposits of interstratified and massive limestones.

Above the Subligurian Units the Ligurian Units crop out (Elter, Elter, Sturani, & Weidmann, 1966). The latter units were historically subdivided in Internal and External Units. The External Units are widely distributed in Oltrepo Pavese area and are characterised by the presence of resedimented ophiolites. They are considered fragments of the Ligurian-Piemonte ocean (Elter & Marroni, 1991; Molli et al., 2010). The Unit is represented by flysch, terrigenous interstratified rocks and claystones that were deposited between the Adriatic plate and the Ligurian-Piemonte Ocean. The Internal Ligurian Units do not crop out in the Oltrepo Pavese. They are distinguished from the External Ligurian Units by the presence of ophiolites still in their original stratigraphic position with an Upper Jurassic/Lower Cretaceous sedimentary cover (Molli et al., 2010).

The Epiligurian Units, deposited on the top of the Ligurian Units, represent sedimentary depositions in thrust-top basins (Ricci Lucchi & Ori, 1985). These Units are related to the erosion and sedimentation of the Ligurian Units during the Eocene-Miocene uplift phases of the Apennines belt. The synorogenetic deposition of the Epiligurian Units causes the quite complex geology of the area, bringing these Epiligurian Units in stratigraphic and unconformable contact with the Ligurian Units. Subsequently, during the Oligo-Miocene rising phases of the Apennines, the Epiligurian Untis acted like preferential path in the overtrusting bringing the Ligurian Unit in tectonic contact with the Epiligurian one (Figure 2a).

From a lithological point of view the Epiligurian formations are very heterogeneous (Panini et al., 2002). In fact, they are mainly composed by:

- Melange: i.e. *Brecce Argillose di Baiso* representing submarine landslides.
- Marls: i.e. *Monte Piano Marls* pelagic sediments.
- Interstratified rocks: i.e. Ranzano *Formation*, clastic turbidit formations.
- Sandstones: i.e. *Monte Vallassa Sandstone*, platform deposits.

Furthermore, in the Oltrepo Pavese area the sedimentary formations of the Tertiary Piedmont Basin (BTP) crop out. The BTP is an episutural basin like initially described by Bally and Snelson (1980) covering both the Alpine and Apennines Units. These formations are represented by continental and marine rocks consisting of conglomerates, sandstones, flysch and hemipelagic deposits. Moreover, evaporitic and terrigenous formations were deposited during the Messinian in small shallow marine basins. Finally, the area is characterised by Quaternary alluvial, colluvial and landslide deposits. From a geomorphological point of view the area is highly influenced by shallow landslide, in unconsolidated or weakly consolidated substrates. Moreover, Badlands (Calanchi) landforms are present in the soft sedimentary formations and show certain relation to tectonic lineaments.

2.2. Tectonic features of the study area

From a tectonic point of view the Oltrepo Pavese is a very complex mosaic of tectonic units. During the middle Eocene-late Miocene emplacement phases of the Apennines chain the Internal Ligurian Units were thrusted on the External ones and during the same time sin-tectonic deposits, i.e. turbiditic sequences and submarine landslides, were deposited on the underlying Ligurian Units generating the Epiligurian Units. Even if the Oltrepo Pavese represents a delimited study area, it is very difficult to observe directly the above-mentioned sequences in open sections. Thus, especially the available described outcrops reveal important tectonic information.

The faults and tectonic lineaments detected in the field fit to three main directions as defined by Panini et al. (2002): (i) NW/SE directions: defined as 'Apenninic direction' which frequently juxtapose the Epiligurian Units with the Ligurian ones. In other words, these tectonic lineaments follow the direction of the overlapping Apennines strata; (ii) NE/SW directions: defined as 'Anti-Apennines direction' that is orthogonal to the Apennines lineaments and interrupt the lateral continuity of the tectonic Units; and (iii) N/S directions: usually represented by left lateral strike-slip faults.

The main fault of the study area is the Villalvernia-Varzi Line (VVL). The fault is an east-west oriented strike-slip fault (Bellinzona et al., 1971; Cerrina Feroni, Ottria, Martinelli, & Martelli, 2002; Festa, Fioraso, Bissacca, & Petrizzo, 2015; Meisina & Piccio, 2003; Panini et al., 2002) and separates the BTP formations on the Epiligurian Units (Figure 2b).

3. Methods

The detection and identification of the sedimentary formations is a complex task since only a few outcrops are available in the study area. This is caused by the hilly landscape and the rolling morphology, which makes it difficult to observe directly the bedrocks. Furthermore, the bushy vegetation cover does not allow the direct analysis to extract the lithology, such as classic remote sensing i.e. mineral mapping using ASTER data (i.e. Omran, Hahn, Hochschild, El-Rayes, & Geriesh, 2012). However, a complete lithological and structural map is a prerequisite to assess surface earth processes and to simulate these processes through models at local and regional scales. To carry out the

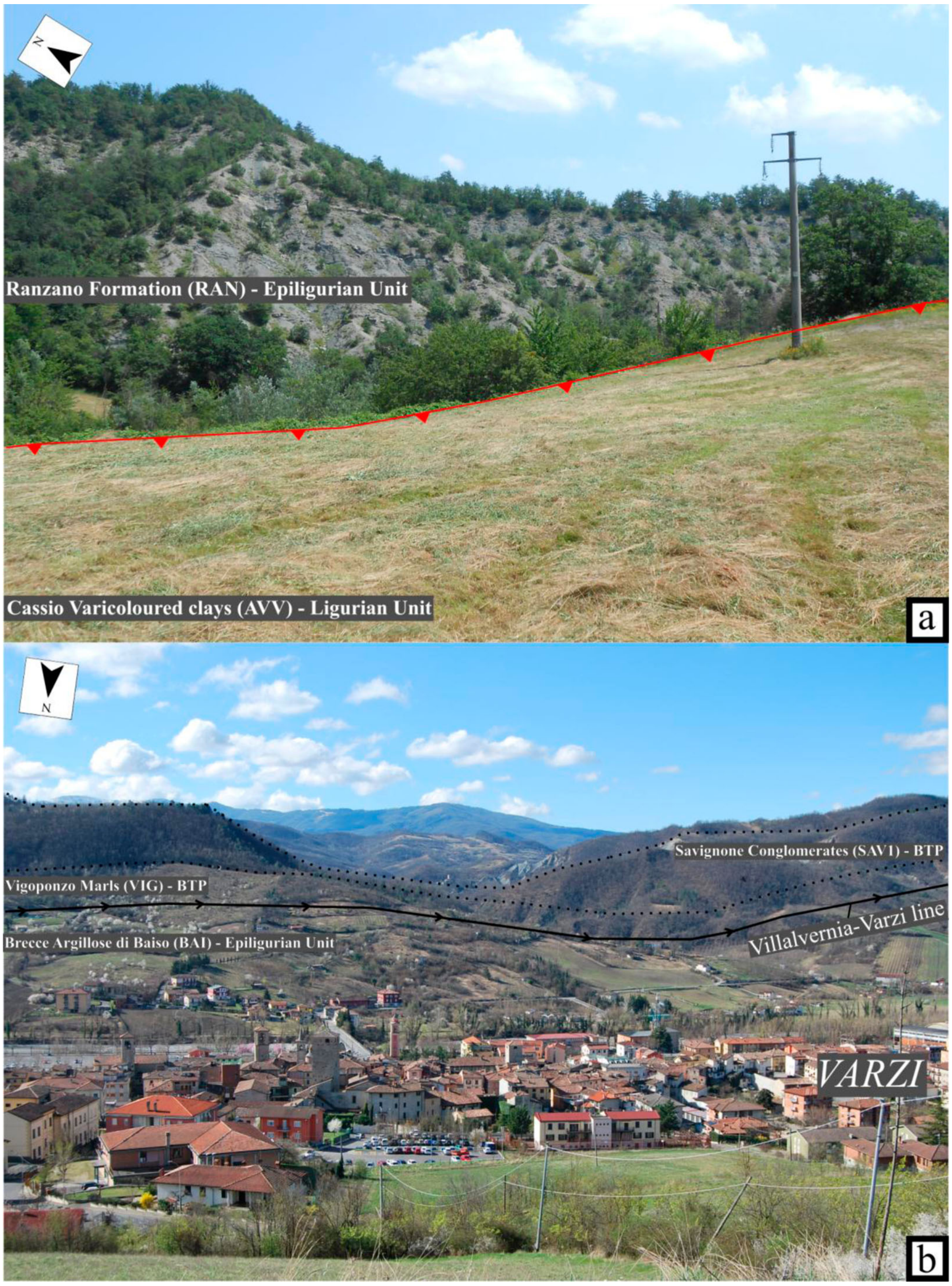

Figure 2. (a) Boundary between the soft Cassio Varicoloured clays (AVV) belonging to the Ligurian Units and the Epiligurian Unit of the more resistive Ranzano Formation (RAN). The Ligurian Units are overthrusting on the Epiligurian ones (44°54′25.26″N - 9° 16′38.60″E). (b) Villalvernia-Varzi fault line close to the town of Varzi separating the Epiligurian Units - Breccie Argillose di Baiso (BAI) from the BTP Formations -Vigoponzo Marls (VIG) and the Savignone Conglomerates (SAV1).

litho-structural map of the Oltrepo Pavese we followed subsequent steps, (Figure 3).

To discriminate the lithologies outcropping in the study area we analysed and combined available geological maps covering different parts of the Oltrepo Pavese. The following maps were used: 1:50.000 geological map (SERVIZIO GEOLOGICO D'ITALIA, 2005; SERVIZIO GEOLOGICO D'ITALIA, 2014), 1:100.000 geological maps (SERVIZIO GEOLOGICO D'ITALIA, 1965; SERVIZIO GEOLOGICO D'ITALIA, 1969), as well as more local information provided by Vercesi and Scagni (1984), Braga et al. (1985), Meisina et al. (2006). Moreover, we mapped areas of the Oltrepo Pavese not covered or that have a too coarse scale, (e.g. areas covered by the old 1:100.000 scale sheets). The geological formations were grouped in 11 classes (Table 1) according to their lithological characteristics and their behaviour in the respects of the processes of degradation. The lithological Units were elaborated in QGIS generating a shapefile with the extent of the Oltrepo Pavese area. Each

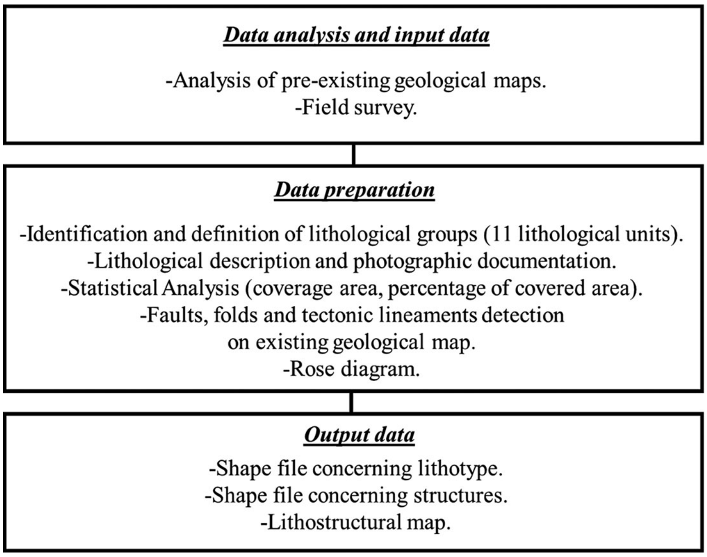

Figure 3. Flow chart of the applied methodology.

lithological unit was described and photo-documented (Figure 4). Moreover, for the 11 lithological classes the coverage area and the percentage of the covered area was determined through statistical analysis.

Finally, faults, thrust, folds and tectonic lineament systems were added to the Main Map. The tectonic elements are based on the bibliography following SERVIZIO GEOLOGICO D'ITALIA (1965), Marchetti, Papani, and Sgavetti (1978), Marchetti, Pellegrini, Perotti, and Vercesi (1979), Boccaletti and Coli (1982), Scagni and Vercesi (1987), Pellegrini and Vercesi (1995), Pellegrini and Arzani (1997), Mantelli and Vercesi (2000), as well as the SERVIZIO GEOLOGICO D'ITALIA (2014). Moreover, we conducted a detailed DTM analysis followed by a visual and semi-automatic elaboration to extract lineaments. The DTM data with 5 m cell size (Regional Topographical Data Base) was downloaded from the geoportal of the Lombardy region (http://www.geoportale.regione.lombardia.it/). The DTM was pre-processed and four hillshadings were generated in a SAGA GIS environment.

Lineaments are defined as 'simple or composite linear features of a surface, whose parts are aligned in a rectilinear or slightly curvilinear way, which differs distinctly from the pattern of adjacent features and presumably reflect a subsurface phenomenon' (O'Leary, Friedman, & Pohn, 1976). However, tectonic lineaments are often represented by linear features of the earth surface usually connected with zones of structural weakness. Moreover, scarps, linear ridges, joints, and faults etc. can be interpreted as lineaments (Pandian, Shruthi, & Pavithra, 2016). Lineaments were traditionally identified and extracted from topographic maps using a visual procedure (Zhumabek, Assylkhan, Alexandr, Dinara, & Altynay, 2017). Despite traditional methods an automatic lineament extraction can be used to identify lineaments, especially at broader scales.

The semi-automatic extraction of lineaments was carried out using the PCI Geomatica software package (PCI Geomatics Ltd., 2017). The combination of the semi-automatic extraction was refined with a visual interpretation and lineament identification. Initially, the DTM is pre-processed and clipped to the extent of the Oltrepo Pavese study area. The pre-processing was performed with SAGA GIS and consists in the application of a simple filter and fill sink algorithm (Planchon & Darboux, 2002) to correct the DEM hydrologically and to eliminate major artefacts. Furthermore, four hillshadings were generated using four illumination angles (0°, 45°, 90°, 135°) and a vertical exaggeration of 4. We chose the following parameter setting for the PCI analysis: Filter Radius = 20; Edge Gradient Threshold = 200; Curve length Threshold = 10; Line fitting Error threshold = 3; Angular difference threshold = 30; and Linking Distance Threshold = 20.

Subsequently, a rose diagram of faults and tectonic lineaments was derived using GeoRose (version 0.5.0). The final step consists in the QGIS elaboration of the main map.

4. Results

We identified, homogenised and classified the main formations outcropping in the Oltrepo Pavese based on the different lithotypes. The main geological formations are illustrated in (Table 1). They are described with the common abbreviations and the geological Units they belong to, as reported in Boni (1967), Di Dio et al. (2005), Marroni et al. (2010), and Vercesi et al. (2014). In total 11 lithological units were identified, documented and described as follows:

(1) Alluvial Deposits (Figure 4a): The unit is lithologically composed by rounded gravel, sand, silt, and clay deposited by the Po river and its

Table 1. Lithological and geological subdivision.

ID	Formation/abbreviation	Units
(1) Alluvial Deposits	Voghera Synthem (VOH)	Q
	Rivazza Synthem (RVX)	Q
	Rivanazzano Unit (URV)	Q
	Torretta Unit (TTS)	Q
	Varzi Unit (VRZ)	Q
	Ardivestra Unit (ADV)	Q
	Nizza Unit (NIZ)	Q
	Other alluvium South of the Po River (ALL)	Q
(2) River Terrace Deposits	Cà D'Andrino Group (GD)	Q
	Codevilla Unit (LLX)	Q
	Torrazza Coste Group (TZ)	Q
	Diluvium (Q1m), (Q1a), (Q1b)	Q
(3) Colluvial Deposits	Retorbido Group (RE)	Q
	Other colluvial deposits (COL)	Q
(4) Landslide Deposits	Po Syntem (POI)	Q
	Other gravitational deposits (POI1)	Q
(5) Conglomerates	Bagnaria Conglomerates (UBG)	Q
	Cassano Spinola Conglomerates (CCS)	Pmess
	Argille Azzurre, Mondondone Conglomerates (FAAa)	Pmess
	Salti del Diavolo Conglomerates (AVV1)	LIG
(6) Melange	Brecce Argillose di Baiso (BAI)	EPI
	Brecce Argillose della Val Tiepido Canossa (MVT)	EPI
	Brecce Argillose di Costa Pelata (BPE)	EPI
	Palombini Claystone (Ap)	LIG
	Serpentinites (Sr)	LIG
(7) Sandstones	Cassano Spinola Conglomerates, Member of Monte Arzolo Sandstone (CCS1, aA)	PMess
	Corvino S. Quirico Formation (fQ)	PMess
	Asti sand (AST)	PMess
	Martinasca Formation (fM)	PMess
	Gremiasco Formation, Member of Nivione (GEM2a)	BTP
	Monte Vallassa Sandstone (AVL)	EPI
	Montù Beccaria Formation (fB)	EPI
(8) Claystones	Argille Azzurre (FAA)	Pmess
	Sparano Formation (fS)	Pmess
	Cassio Varicoloured clays (AVV)	LIG
	Montoggio claystone (MGG)	LIG
(9) Interstr. Rocks	Monastero Formation (MST)	BTP
	Castagnola Formation (FCA)	BTP
	Savignone Conglomerates, Monte Rivalta Member (SAV1)	BTP
	Ranzano Formation (RAN)	EPI
	Scabiazza Sandstone (SCB) Val Luretta Formation, Poviago	LIG
	Member (VLU1) and Monteventano Member (VLU2)	LIG
	Monte Ragola Complex (MRA)	LIG
(10) Interstr. Limestones and Limestones	Dernice Formation (DRN)	BTP
	Pietra dei Giorgi Limestone (cG)	EPI
	Monte Antola Formation (FAN)	LIG
	Flysch di Bettola (BET)	LIG
	Flysch di Monte Cassio (MCS)	LIG
	Flysch di Monte Penice (PEN)	SUB
	Canetolo Clay and Limestone (ACC)	SUB
(11) Interstr. Marls and Marls	Sapigno Formation (GNO)	PMess
	Gessoso Solfifera Formation (fgs)	PMEss
	Monte Brugi Marls (BGU)	BTP
	Vigoponzo Marls (VIG)	BTP
	Gremiasco Formation, Nivione Member (GEM2c)	BTP
	Monastero Formation (MSTd)	BTP
	S. Agata Fossil Marls (SAF, mA)	EPI
	Contignaco Formation (CTG)	EPI
	Monte Piano Marls (MMP)	EPI
	Antognola Formation (ANT)	EPI
	Val Luretta Formation, Genepreto Member (VLU3)	LIG

Notes: (SUB): Subligurian Units. (LIG): Ligurian Units. (EPI): Epiligurian Units. (BTP): Tertiary Piedmont Basin. (PMess): Post Messinian Units. (Q): Quaternary deposits.

tributaries. It consists in rounded gravel in a sandy matrix and is often orientated.

(2) River Terrace Deposits (Figure 4b): The unit is lithologically composed by flat and rounded centimetric pebbles scattered in a brown silt, sandy silt and clay silt matrix. Usually gravel layers are found at the base of the group or layers of red fine sediments. Pedogenetic processes occurred generating a sandy clay loam texture. The average colour is defined by a Munsell soil colour chart of 2.5Y4/3. This deposit can be associated to river terrace deposits, from local river system at the margins of the Apennines.

(3) Colluvial Deposits (Figure 4c): The unit is lithologically composed by sandy silt, silt and clay silt deposits. The parental material is already

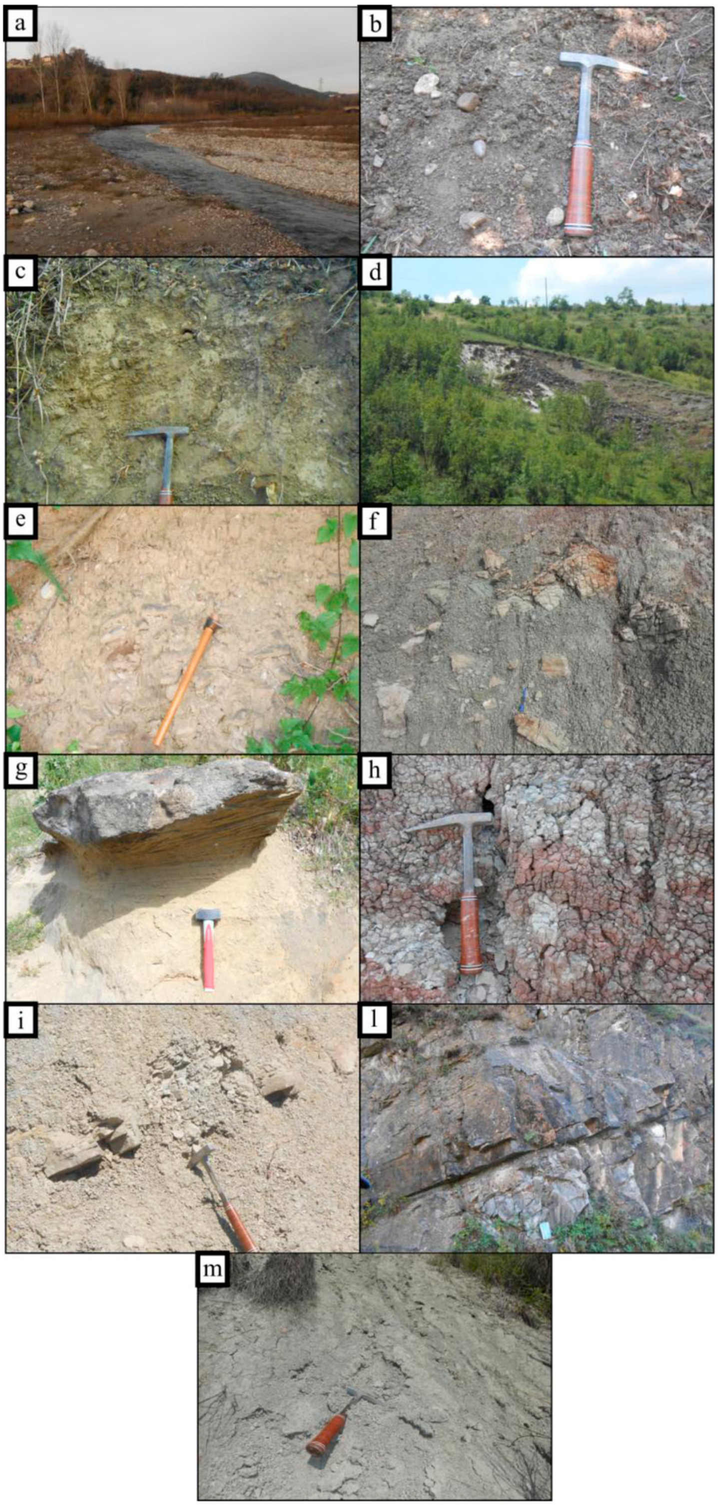

Figure 4. Examples of lithological units. (a) Alluvial Deposits Staffora River. (b) River Terrace Deposits. (c) Colluvial Deposits. (d) Landslide Deposits. (e) Conglomerates. (f) Melange. (g) Sandstones. (h) Claystones. (i) Interstratified rocks. (l) Interstratified limestones and limestones. (m) Marls and interstratified marls.

pedogenetically modified. In outcrops diffuse planar layers are visible. The average Munsell soil colour range between 7.5YR and 10YR (e.g. 10YR5/4 represented in Figure 3l). This deposit can be associated with colluvial and mass flow processes.

(4) Landslide Deposits (Figure 4d): The unit is lithologically composed by unlithified deposits generated by landslides and denudation processes. The unit is characterised by incoherent material without stratification, metric and centimetric blocks in fine matrix.

(5) Conglomerates (Figure 4e): The unit is lithologically composed by rounded centimetric pebbles, usually orientated (imbricated) often interbedded with grey/light grey sand and silt lens. In outcrops two main types of conglomerates are found: (i) grain dominated conglomerates

(Orthoconglomerate) and (ii) matrix dominated conglomerates (Paraconglomerate) characterised by a sandy/silty matrix. The pebbles are mainly composed by limestones and sandstones with variable size, from sub centimetric to centimetric size. These deposits represent the river sediments.

(6) Melange (Figure 4f): The unit is lithologically composed by centimetric to metric chaotic blocks in a fine grey or reddish clay matrix. The blocks are mainly composed by sandstone, limestone and conglomerates, corresponding to the Ligurian and Epiligurian Formations. The smectite clay matrix comprises minerals like montmorillonite, and illite. Moreover, low percentages of fine silt are present. The texture appears chaotic without stratifications. These deposits represent submarine landslides (Olistrostroms).

(7) Sandstones (Figure 4g): The unit is lithologically composed by stratified or massive deposits of yellow to grey bioclastic sandstones, biocalcarenites, rich in fossils (i.e. foraminifers and platform dweller). These rocks are more or less cemented and represent platform deposits. The fluvial sandstones of this group occasionally are interbedded with silty claystones usually characterised by cross beddings or a poorly defined stratification.

(8) Claystones (Figure 4h): The unit is lithologically composed by dark red, dark grey, grey and violet claystones, with subordinated siltstones and sandstones. In outcrops usually, pop-corn structures appear or other desiccation forms like mud cracks. Generally, typical characteristics of run off processes are present. In outcrops alternated bands of coloured clays are often visible, representing a zonal change in chemical composition. In general, the inherited stratification is not preserved due to the high tectonic deformation and shrinking-swelling phenomena of active layer clays. These rocks represent ocean floor sediments.

(9) Interstratified rocks (Figure 4i): The unit is lithologically composed by an alternation of conglomerates, sandstones and pelites in variable proportions. In general, we found centimetric to sub-metric grey or light brown sandstones interbedded with grey silty marly siltstones. Groove cast, flute cast and sparse bioturbation on the top of the strata can be observed. Run off processes are evident in the outcrops characterised by thick fine-grained strata interbedded with thin sandstone layers. These rocks might crop out in a folded and deformed way due to tectonic activity. These deposits can be associated with terrigenous turbiditic sediment deposited in small basins.

(10) Interstratified limestones and limestones (Figure 4l): The unit is lithologically composed by yellow or white massive limestone, and limestone interbedded with calcareous marls and pelites. Centimetric and metric strata of limestone are observed occasionally with sandstone layers at the base. Ripple and flute cast rarely occur. This unit can be associated with calcareous turbiditic sediments deposited in small basins.

(11) Marls and Interstratified Marls (Figure 4m): The unit is lithologically composed by grey, light blue to greenish marls, chalky marl, marls interbedded with silty marls, flint, pelites and clayey marls. The lithology crops out with a typical conchoid or flaked fracturing. On the exposed surface weathering processes and runoff features are presents. Usually scarce bioturbations are evident. These deposits represent pelagic sediments deposited regularly in shallow basins, often combining the marine sedimentation with evaporitic conditions.

Once the lithological units were classified, we determined the coverage area and the percentage of coverage area for each lithological unit (see Table 2).

The final map (Main Map) was completed adding the faults, folds and tectonic lineaments. Even though faults and folds have been reported partly in bibliography we identified the tectonic lineaments with a combination of visual (DTM interpretation) and semi-automatic procedures (analysis PCI output). The PCI output was combined with a classic visual method modifying the lineaments in QGIS in order to extract only the major tectonic lineaments.

The direction of the main faults and tectonic lineaments is represented in a rose diagram. Basically, two main directions: NW/SE-NE/SW and N/S are highlighted in the rose diagram. These directions correspond to the main Apennines and anti-Apennines directions. Moreover, a N/S direction typically represents strike-slip faults (Figure 5).

Finally, the main map was elaborated in QGIS joining lithology and structural elements.

Table 2. Coverage area and percentage of coverage area of the Oltrepo Pavese lithologies.

ID	Coverage area (Km^2)	Percentage of coverage area (%)
(1) Alluvial Deposits	423	38
(2) River Terrace Deposits	36	3
(3) Colluvial Deposits	33	3
(4) Landslide Deposits	66	6
(5) Conglomerates	9	1
(6) Melange	67	6
(7) Sandstones	53	5
(8) Claystones	35	3
(9) Interstr. Rocks	151	13
(10) Interstr. Limestones and Limestones	84	8
(11) Interstr. Marls and Marls	153	14

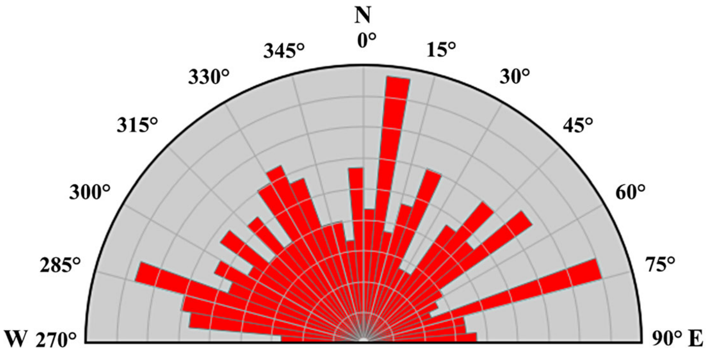

Figure 5. Rose diagram show the main direction of faults and tectonic lineaments.

5. Conclusions

In the complex landscape of the study area, characterised by a dense vegetation cover, a consistent lithologic classification was not existing and hence, also a corresponding homogeneous map was missing so far. Thus, in this paper we present a litho-structural map of the Oltrepo Pavese area. The main lithologies were obtained combining bibliographic information and own field surveys. The lithologies are grouped in 11 representative classes based on their intrinsic characteristics. The map is enhanced with the main structural elements (faults, folds and tectonic lineaments) present in the study area. The latter were derived with a combination of a semi-automatic GIS-based method and a traditional visual method. The lineaments extracted can be associated with faults and disturbance zones. The final map (Main Map) represents the litho-structure of the study area. Moreover, we provide two vector files characterising the lithology and the linear structures of for the Oltrepo Pavese. This study provides basic information for further assessment of earth surface processes in the Oltrepo Pavese Area.

Software

The maps were generated and realised using open source GIS (QGIS 3.0). The DTM was elaborated with SAGA GIS and PCI Geomatica. The Rose diagram was generated with GeoRose (version 0.5.0). The statistical analysis has been conducted in Microsoft Excel.

Acknowledgements

The authors are grateful to Prof. Pier Luigi Vercesi for the valuable comments and support.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This research was conducted with the financial support of the Università degli Studi di Pavia.

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References

Ali, S. A., & Ali, U. (2013). Litho-structural mapping of sind catchment (Kashmir basin), NW Himalaya, using remote sensing & GIS techniques. *International Journal of Science and Research (IJSR)*, *4*(7), 1325–1330.

Bally, A. W., & Snelson, S. (1980). Realms of subsidence. In A. D. Miall (Ed.), *Factors and Principles of world petroleum occurrence* (Vol. 6, pp. 9–75). Calgary: Can. Soc. Petrl. Geol. Mem.

Bellinzona, G., Boni, A., Braga, G., & Marchetti, G. (1971). *Note Illustrative della Carta Geologica D'Italia in scala 1:100,000 – Foglio 71 Voghera* (p. 121). Roma: Serv. Geol. d'It.

Boccaletti, M., & Coli, M. (1982). *Carta Strutturale dell'appennino Settentrionale*. Firenze: P.F.G. -Sottoprogetto 5 -Modello Strutturale, 4 Tavv. Selca.

Boni, A. (1967). *Note Illustrative della Carta Geologica D'Italia in scala 1:100,000 – Foglio 59 Pavia* (p. 68). Roma: Serv. Geol. d'It.

Braga, G., Brasschi, G., Calculli, S., Caucia, F., Cerro, A., Colleselli, F., … Veniale, F. (1985). *I fenomeni franosi nell'Oltrepo Pavese: tipologie e cause*. Geologia Applicata e Idrogeologia. Volume XX Parte II.

Carmignani, L., Conti, P., Cornamusini, G., & Meccheri, M. (2004). *The internal Northern Apennines, the Northern Tyrrhenian sea and the Sardinia- Corsica Block*. Special Volume of the Italian Geological Society for the IGC 32 Florence.

Cerrina Feroni, A., Ottria, G., Martinelli, P., & Martelli, L. (2002). *Carta geologico-strutturale dell'Appennino emiliano – romagnolo alla scala 1:250.000*. Firenze: Regione Emilia-Romagna, C.N.R., Ed. S.EL.CA.

Ciarapica, G., & Passeri, L. (1998). Evoluzione paleogeografica degli Appennini. *Atti Ticinensi di Scienze delle Terra*, *40*, 233–290. 13 figg.

Cibin, U., Spadafora, E., Zuffa, G. G., & Castellarin, A. (2001). Continental collision history from arenites of episutural basin in the Northern Apennines, Italy. *Geological Society of America Bulletin*, *113*(1), 4–19.

Decarlis, A., Maino, M., Dallagiovanna, G., Lualdi, A., Masini, E., Toscani, G., & Seno, S. (2014). Salt tectonics in the SW Alps (Italy–France): From rifting to the inversion of the European continental margin in a context of oblique convergence. *Tectonophysics*, *636*, 293–314. doi:10.1016/j.tecto.2014.09.003

Di Dio, G., Piccin, A., & Vercesi, P. L. (2005). *Carta Geologica d'Italia alla scala 1:50,000. Foglio 179* '*Ponte dell'Olio*' (p. 108). Roma: APAT – Dipartimento Difesa Del Suolo - Servizio Geologico D'Italia.

Elter, G., Elter, P., Sturani, C., & Weidmann, M. (1966). Sur la prolongation du domaine ligure de l'Apennin dans le Monferrat et les Alpes et sur l'origine de la Nappe de la Simme s.l. des Prealpes romandes et chablaisiennes. *Arch. Sciences de Geneve*, *19/3*, 279–378. Geneve.

Elter, P. (1975). Introduction a la geologie de l'Apennin Septentrional. *Bulletin de la Societe Geologique de France*, *17*, 956–962. Paris.

Elter, P., Grasso, M., Parrotto, M., & Vezzani, L. (2003). Structural setting of the Apennines-Maghrebian thrust belt. *Episodes*, *26*, 205–211.

Elter, P., & Marroni, M. (1991). Le unità Liguri Dell'Appennino Settentrionale: sintesi dei dati e nuove interpretazioni. *Mem. Descr. Carta Geol. D'It*, *XLVI*, 121–138.

Festa, A., Fioraso, G., Bissacca, E., & Petrizzo, M. R. (2015). Geology of the Villalvernia – Varzi Line between Scrivia and Curone valleys (NW Italy). *Journal of Maps*, *11*(1), 39–55. doi:10.1080/17445647.2014.959569

Finetti, I. R., Boccaletti, M., Bonini, M., Del Ben, A., Geletti, R., Pipan, M., & Sani, F. (2001). Crustal section based on CROP seismic data across the North Tyrrhenian–Northern Apennines–Adriatic Sea. *Tectonophysics*, *343* (2001), 135–163.

Maino, M., Dallagiovanna, G., Gaggero, L., Seno, S., & Tiepolo, M. (2012). U-Pb zircon geochronological and petrographic constraints on late to post-collisional Variscan magmatism and metamorphism in the Ligurian Alps, Italy. *Geological Journal*, *47*(6), 632–652. doi:10.1002/gj.2421

Maino, M., Decarlis, A., Felletti, F., & Seno, S. (2013). Tectono-sedimentary evolution of the Tertiary Piedmont basin (NW Italy) within the Oligo-Miocene central Mediterranean geodynamics. *Tectonics*, *32*(3), 593–619. doi:10.1002/tect.20047

Mantelli, L., & Vercesi, P. L. (2000). Evoluzione Morfostrutturale Recente del Pedeappennino Vogherese-Tortonese. *Atti Ticinensi di Scienze della Terra*, *41*, 49–58.

Marchetti, G., Papani, G., & Sgavetti, M. (1978). Evidence of Neotectonics in the North-West Apennines-Po side. In H. Closs, D. M. Order e K. L. Shmidt (Eds.), *Alps, Apennines, Hellenide-Geodynamic investigations along Geotraverses by an International Group of Geoscientis*. Stuttgard.

Marchetti, G., Pellegrini, L., Perotti, C., & Vercesi, P. L. (1979). L'evoluzione morfo-strutturale dell'Appennino piacentino: proposta di uno schema interpretativo. C.N.R. Estratto da: Contributi preliminari alla realizzazione della Carta Neotettonica d'Italia, Pubbl. n. 251 del Progetto Finalizzato Geodinamica, pp. 449–461.

Marroni, M., Ottria, G., & Pandolfi, L. (2010). *Note illustrative della Geologica d'Italia alla scala 1:50,000. Foglio 196* '*Cabella Ligure*'. ISPRA, Istituto Superiore per la Protezione e la Ricerca Ambientale.

Meisina, C., & Piccio, A. (2003). River dynamics and slope processes along a sector of the Villalvernia-Varzi Line (Northern Italy). *Quaternary International*, *101–102*, 179–190.

Meisina, C., Zucca, F., Fossati, D., Ceriani, M., & Allievi, J. (2006). Ground deformation monitoring by using the permanent scatterers technique: The example of the Oltrepo Pavese (Lombardia, Italy). *Engineering Geology*, *88*, 240–259.

Molli, G., Crispini, L., Malusà, M., Mosca, P., Piana, F., & Federico, L. (2010). Geology of the Western Alps-Northern Apennine junction area: A regional review. *Journal of the Virtual Explorer*, *36*, paper 9. doi:10.3809/jvirtex.2009.00215

O'Leary, D. W., Friedman, J. D., & Pohn, H. A. (1976). Lineament, linear, lineation: Some proposed new standards for old terms. *Geological Society of America Bulletin*, *87*, 1463–1469.

Omran, A., Hahn, M., Hochschild, V., El-Rayes A. H., & Geriesh, M. (2012). Lithological mapping of Dahab Basin, South Sinai, Egypt, using ASTER Data. Geoinformation 6/2012.

Pandian, M., Shruthi, N., & Pavithra, K. (2016). A Geomatics approach – structural mapping and automatic lineament extraction in parts of central Tamil Nadu. *International Journal of Geology and Earth Sciences*, *2*(4), 11–18.

Panini, F., Fioroni, C., Fregni, P., & Bonacci, M. (2002). Le rocce caotiche dell'Oltrepo pavese: Note illustrative della carta geologica dell'Appennino Vogherese tra Borgo Priolo e Ruino. *Atti Ticinensi di Scienze delle Terra*, *43*, 83–109.

PCI Geomatics Ltd. (2017). https://www.pcigeomatics.com/.

Pellegrini, L., & Arzani, C. (1997). Evoluzione morfoneotettonica nel basso Appennino Pavese-Piacentino: l'esempio del T. Gualdora, affluente del T. Tidone (Piacenza, Italia Settentrionale). *Italian Journal of Quaternary Sciences*, *10*(2), 603–608.

Pellegrini, L., & Vercesi, P. L. (1995). Considerazioni morfoneotettoniche sulla zona a sud del Po tra Voghera (PV) e Sarmato (PC). *Atti Ticinensi di Scienze delle Terra*, *38*, 95–118. 7 figg., 4 tav. f.t.

Piazza, A., Artoni, A., & Ogata, K. (2016). The Epiligurian wedge top succession in the Enza Valley (Northern Apenniens): evidence of a syn-depositional transpressive system.

Planchon, O., & Darboux, F. (2002). A fast, simple and versatile algorithm to fill the depressions of digital elevation models. *Catena*, *46*, 159–176.

Ricci Lucchi, F., & Ori, G. G. (1985). Syn-orogenic deposits of migrating basin systems in the NW Adriatic Foreland. In P. Allen & P. Homewood (Eds.), "Foreland Basins Symp. Excursion Guidebook", IAS, pp. 137–176.

Scagni, G., & Vercesi, P. L. (1987). Il messiniano tra la Valle Versa e la Valle Staffora (Appennino pavese-vogherese) Considerazioni Paleogeografiche. *Atti Ticinensi di Scienze delle Terra*, *31*, 1–20. 2 ff., 3 tavv.

SERVIZIO GEOLOGICO D'ITALIA. (1965). Carta Geologica d'Italia alla scala 1:100.000, Foglio 59 Pavia, II edizione. Roma.

SERVIZIO GEOLOGICO D'ITALIA. (1969). Carta Geologica d'Italia alla scala 1:100.000, Foglio 71 Voghera, II edizione. Roma.

SERVIZIO GEOLOGICO D'ITALIA. (2005). Carta Geologica d'Italia alla scala 1:50.000, Foglio 179 Ponte dell'Olio. Roma.

SERVIZIO GEOLOGICO D'ITALIA. (2010). Carta Geologica d'Italia alla scala 1:50.000, Foglio 178 Cabella Ligure. Roma.

SERVIZIO GEOLOGICO D'ITALIA. (2014). Carta Geologica d'Italia alla scala 1:50.000, Foglio 178 Voghera. Roma.

Taramelli, T. (1882). Descrizione geologica della Provincia di Pavia, con annessa Carta Geologica. *Stab. Civelli G.*, 1–163. Milano.

Toscani, G., Seno, S., Fantoni, R., & Rogledi, S. (2006). Geometry and timing of deformation inside a structural arc; the case of the western Emilian folds (Northern Apennine front, Italy). *Bollettino Della Società Geologica Italiana*, *125*(1), 59–65.

Vercesi, P. L., Falletti, P., Pasquini, C., Perotti, C., Tucci, G., & Papani, L. (2014). *Carta Geologica d'Italia alla scala 1:50,000. Foglio 178 'Voghera', note illustrative InfoCartoGrafiche – Picenza*. ISPRA, Istituto Superiore per la Protezione e la Ricerca Ambientale.

Vercesi, P. L., & Scagni, G. (1984). Osservazioni sui depositi conglomeratici dello sperone collinare di Stradella. *Rend. Soc. Geol. It.*, *7*, 23–26.

Zhumabek, Z., Assylkhan, B., Alexandr, F., Dinara, T., & Altynay, K. (2017). Automated lineament analysis to assess the geodynamic activity areas. *Procedia Computer Science*, *121*, 699–706.