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QUATERNARY EVOLUTION OF THE PLAIN BETWEEN CASALE MONFERRATO AND VALENZA: IMPLICATIONS FOR THE TECTONICS OF THE MONFERRATO THRUST FRONT (PIEDMONT, NW ITALY)

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ABSTRACT: The present paper highlights the Quaternary evolution of the plain which lies on the eastern portion of the Monferrato Thrust Front, in order to identify and provide evidence of recent tectonic deformations. The study has made it possible to detect and date late Middle Pleistocene or early Upper Pleistocene tectonic deformations related to the activity of the front, and to suggest the hypothesis of more recent ones. It can be observed that some parts of the plain, located north of the thrust fronts and the area corresponding to some buried synclines, mainly subsided during the Quaternary. On the other hand the area of the isolated hills and terraces suffered an almost continuous uplift until the late Middle Pleistocene or early Upper Pleistocene. The areas where the uplift prevailed were affected by faults both transversal and parallel to the thrust fronts. The overall interpretation of the tectonic structures lying below the plains and on the hills has enabled us to assume that there are two deformation zones where strike-slip or oblique-slip displacements took place. In the first one (Giarole-Lu Deformation Zone) some left-slip tectonic deformations should exist, while in the second one (Valenza Deformation Zone) some right-slip displacements may be present. The movements along the two deformation zones would result in an advance towards the north of the thrust front near the isolated Pomaro-Montevalenza Hill.
In the Eastern Monferrato contractional tectonics related to the Monferrato Thrust Front was more recent than in the Central and Western Monferrato.
The subsidence of the northern Alessandria piggyback basin, that lasted until the late Middle Pleistocene or the early Upper Pleistocene, would be a consequence of the shift towards the north of the thrust front.
The horizontal and vertical deformation rates obtained by the Alessandria GPS station seem compatible with the hypothesis of a shift to the north and with a subsidence still in progress. The morphology and distribution of the most recent terraces suggest that part of the Po Plain may have been affected by Upper Pleistocene and Holocene tectonic movements. These areas include Casale Monferrato, which underwent a remarkable aseismic uplift during the twentieth century.

KEYWORDS: Terraces, Quaternary evolution, Monferrato thrust front, transverse fault, Po Plain, Piedmont, Italy.

1. INTRODUCTION

Recent studies on the buried tectonic structures covered by fluvial sediments of the Po Plain have suggested that the Monferrato Thrust Front, despite being subject to very low seismic activity, may be considered a seismogenic structure capable of producing earthquakes of high magnitude.

According to Burrato et al. (2012) and Michetti et al. (2012), the present seismicity of the area could be characterized by earthquakes with long return periods. However, according to other authors (Costa, 2003; Pieri & Groppi, 1981; Cassano et al., 1986; Galadini et al., 2012; Galli et al., 2012), the compressive tectonics of the Monferrato front ended in the Lower or Middle Pleistocene.

In order to verify which of the two hypotheses is more reliable, a detailed study (Giraudi, 2014) has already been conducted on the evolution of the Vercelli Plain, below which the central portion of the Monferrato Front is present.

The data have indicated that the compressive tectonics could have ended before 280-300 ka BP, probably around 400 ka BP, but that tectonic movements, related to structures transversal to the front, probably lasted until the late-Holocene.

The present paper is intended to highlight the evolution of the plain lying on the eastern portion of the Monferrato Thrust Front (Fig. 1), in order to identify and provide evidence of recent tectonic deformations and to check whether tectonic mobility is comparable to that of the Vercelli Plain. The investigated area is located south of the Po river between Casale Monferrato and the area SE of Valenza and lies almost entirely between the buried Monferrato Thrust Fronts, to the north, and the Monferrato Hills to the south. The presence of some large terraces makes the plain of the study area markedly different from the plain lying on the northern slope of the westernmost Monferrato-Turin Hills system.

The geomorphological and geological characteristics of the Casale Monferrato-Valenza area, therefore, may have been conditioned by a different tectonic mobility. For this reason, the geological structure of the tertiary bedrock lying below the Quaternary cover and some peculiar geomorphological and geological features of the Eastern Monferrato Hills are presented and discussed before the data on Quaternary sediments.

The interpretation of the evolution of the plain reveals Quaternary tectonic deformations, related to the activity of fronts, which are difficult to prove in the Monferrato Hills because the outcrops are very scarce and of poor quality.

2. GEOLOGICAL CHARACTERISTICS OF THE BEDROCK

The Monferrato, together with the Turin Hills, represents the northernmost part of the Apennines and is formed by folded marine Tertiary formations. The Monferrato Hills overlie the Plio-Quaternary thrust belt separating the Tertiary Piedmont Basin from the Mesozoic and Cenozoic succession underlying the fluvial Po Plain (Fig. 1).

To the north of the Monferrato, the Po Plain corresponds to a foredeep developed as a result of the propagation of north-verging tectonic fronts located on the southern side. According to Dela Pierre et al. (1995) the Po Plain foredeep was subject, until the Quaternary, to subsidence which reflects the deformation of the front of the Apennine thrust belt.

The sedimentary sequences lying south of the Turin and Monferrato Hills were deposited inside piggyback basins (Irace et al., 2009; Mosca et al., 2010). South of the study area, a deep piggyback basin was formed around Alessandria.

2.1. Stratigraphy and tectonics of the tertiary sediments forming the bedrock of the plain and the isolated hills based on bibliographic data

The bedrock lying below the fluvial sediments of the plain, i.e. the sediments that form the buried Monferrato Thrust Front, consists of the same tertiary marine sediments (Braga & Ragni,1969; Corsi et al., 1969) that form the adjacent hills and outcrop in the three isolated hills of Occimiano (RIO), Mirabello (RIM), and Pomaro-Montevalenza (RIP).

Some seismic sections (Corsi et al., 1969; Montrasio et al.,1969; Pieri & Groppi, 1981; ENEL, 1984; Cassano et al., 1986) indicate the position of the Monferrato Thrust Fronts buried below the Quaternary deposits (Fig. 2). The northernmost and oldest front was active during the Lower Pliocene while others are known to have been active also during the Quaternary (ENEL, 1984).

The northernmost front is always placed beyond the Po river, that is, outside the study area, except in a small stretch. One of the seismic sections (Corsi et al., 1969) shows the presence of a buried (thrust?) fault near Occimiano (Occimiano Fault, FO in Fig. 2), linked to the structures of the front. Costa (2003) suggests that in the subsurface of the plain of the area studied there is also a SW-NE trending transcurrent or transpressive fault crossing the Monferrato Front (Giarole Fault, FG in Fig. 2).

Cassano et al. (1986) show, in their section N. 4, a syncline (called Villabella Syncline in the present paper, VS in Fig. 2) involving Tertiary and Quaternary sediments lying in the area between the RIP and the Monferrato Hills. The syncline is also proved by the geological structure of the RIP, which forms its northern margin (Casnedi, 1975), and by the Late Messinian-Early Pliocene (?) “Conglomerati di Cassano Spinola” sediments, outcropping on the slope of the Valenza Plateau at Castel Menada (NE of Valenza; Fig. 2), which are part of the southern margin.

The studies reported in ENEL (1984) exclude that the sediments exposed at the base of the escarpment of the Valenza Plateau, at least from Castel Menada eastwards, are marine, as supposed in previous papers (Martinis, 1954; Corsi et al., 1969) but suggest that they are continental and can be correlated to the Villafranchian succession.

The bedrock of the isolated hills located west and east of the Giarole Fault is made up of different sediments (Corsi et al., 1969). The isolated hills RIO and RIM, located to the west of the fault, are formed by Pliocene marine sediments while the isolated hill RIP, located to the east, consists, according to Casnedi (1975), of Tortonian, Messinian and Pliocene sediments. The area where Pliocene and Messinian deposits outcrop at the SE slope of the RIP is very small and cannot be represented at the scale of Fig. 2.

From subsurface data, reported in the Structural Model of Italy (Bigi et al., 1990), it is possible to estimate the depth of the bottom of the Pliocene in the area between the hills of the Eastern Monferrato and the Po river. Fig. 3 shows the contour lines of the depth of the Pliocene base, modified according to surface data and the interpretation in section 4 of Cassano et al. (1986) showing that the Pliocene is lacking in the area just

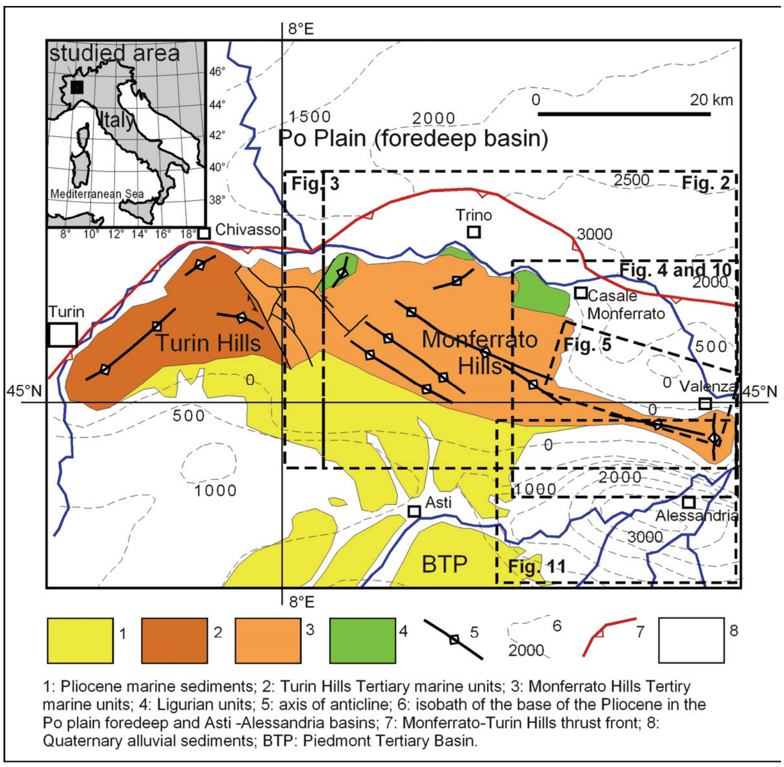

Fig. 1 - Geological sketch of the Monferrato-Turin Hills and depth of the base of the Pliocene (redrawn from Dela Pierre et al., 2003a).

north and NE of the RIP.

The base of the Pliocene reaches a depth of about 3000 m north of the outermost and older thrust front, while the depth slightly exceeds 500 m south of the front. The contour lines reported by Bigi et al. (1990) show that the Pliocene base is deeper in correspondence with the axis of the Villabella Syncline and that the axis trends NW-SE and W-E. The contour lines assume a SW-NE direction in correspondence with the SW-NE trending Giarole Fault, which crosses the Monferrato Front.

2.1.1. Extended tectonic interpretation based on the contour lines of the base of the Pliocene

The trend of the contour lines of the Pliocene base (Fig. 3) can be interpreted in order to hypothesize the presence of other buried structures. As reported above, the contour lines evidence the thrust fronts, the trends of the Villabella Syncline and of the Giarole Fault. It follows that the contour lines showing a depression of the Pliocene base indicate the presence of synclines or tectonic troughs, while the contour lines crossing the Monferrato Front could suggest the presence of faults.

Near Casale Monferrato and NE of the RIP, the contour lines of the depth of the Pliocene base are

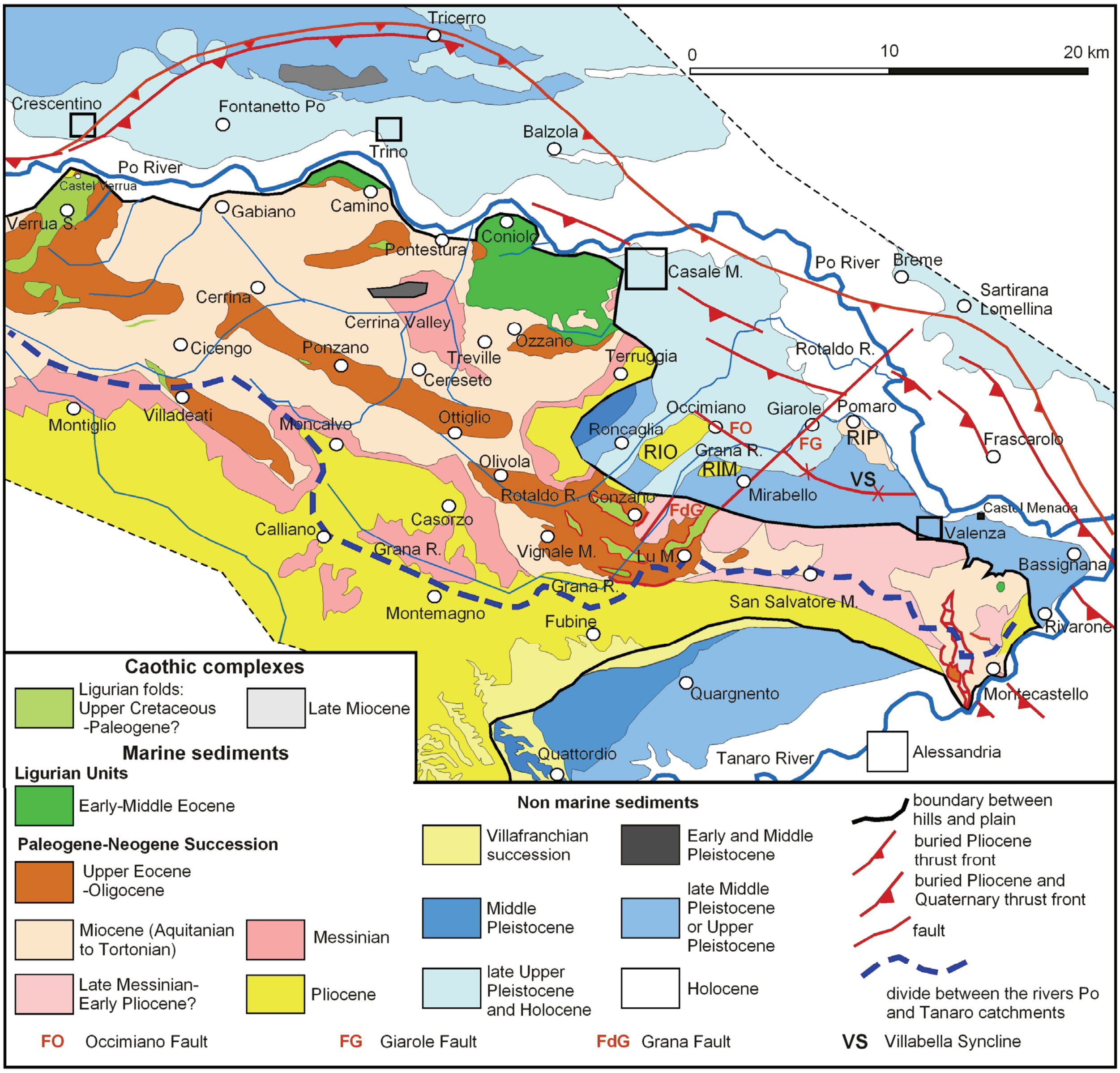

Fig. 2 - Geological map of the Central-Eastern Monferrato and surrounding plains (modified from: Montrasio et al.,1969; Corsi et al.,1969). The fronts drawn in the figure are reported in Montrasio et al. (1969), Corsi et al. (1969), Pieri and Groppi (1981), ENEL (1984), Cassano et al. (1986).

roughly parallel to the hillside and to the thrust front, while in the intermediate area they assume a transversal direction (Fig. 3) and indicate the presence of a depression, a syncline (Borgo San Martino syncline, SBSM in Fig. 3) with the axis oriented from SW to NE. The Borgo San Martino Syncline is transversal to the Villabella Syncline (Fig. 3). The eastern edge of the Borgo San Martino Syncline, in position and direction, coincides with the SW-NE trending Giarole Fault. The western edge of the syncline, which is parallel to the eastern one, could suggest the presence of another fault (Roncaglia Fault, FR in Fig. 3). It cannot be excluded that the tectonic depression called Borgo San Martino Syncline was a trough bounded by the faults trending SW - NE. The Giarole Fault acts as a boundary between the synclines trending SW-NE and NW-SE. The change in the direction of the tectonic structures occurring in correspondence with the Giarole Fault confirms the importance of the fault for the tectonic evolution of the area.

The NW-SE trend of the isobaths in correspondence with the Occimiano Fault suggests that south of the (thrust?) fault the base of the Pliocene is uplifted. The features of the Pliocene base near the Occimiano Fault are quite similar to those observed near the northernmost thrust fronts (Fig. 3) and suggest that the fault is a stretch of a buried front.

East of the RIP (Fig. 3), the contour lines of the depth of the Pliocene base assume a direction transversal to the thrust fronts, as in correspondence to the Giarole Fault: therefore the N-S contour lines may evidence a fault trending N-S (Valenza Fault).

2.1.2. The "*platea*" below the Po Plain fluvial sediments

In the plain between Casale Monferrato and Valenza, as in all the whole plain surrounding the northern Monferrato, there are areas where the Tertiary sediments lie less than 20 m below the ground surface (Fig. 3). In those areas, the top of the Tertiary bedrock, erosional in origin and shaped by rivers, is represented by a nearly flat surface, or by different surfaces located at altitudes slightly different, known in the Italian literature as "*platea*" (ENEL, 1984b; Carraro et al., 1995; Dela Pierre et al., 2003a,b; Festa et al., 2009). Quaternary fluvial sediments of various ages overlie the *platea*.

The stratigraphic data from boreholes indicate the extent of the *platea*, already partly represented in ENEL (1984), Dela Pierre at al. (2003a,b), ARPA Piemonte (2014) and Giraudi (2014). Figure 3 shows that north of the Monferrato, but also around the Turin Hills (Festa et al., 2009), the limits of the *platea* are always next to the thrust fronts or structures crossing them.

Outside the *platea*, the Quaternary fluvial and fluvioglacial sediments become thicker, indicating that the *platea* edge is a boundary between areas that have undergone a different evolution. Hence, during the Quaternary, the area outside the *platea* was mainly in subsidence, as demonstrated by studies on the westernmost plain (ENEL, 1984a; Dela Pierre at al., 2003a,b; Giraudi,

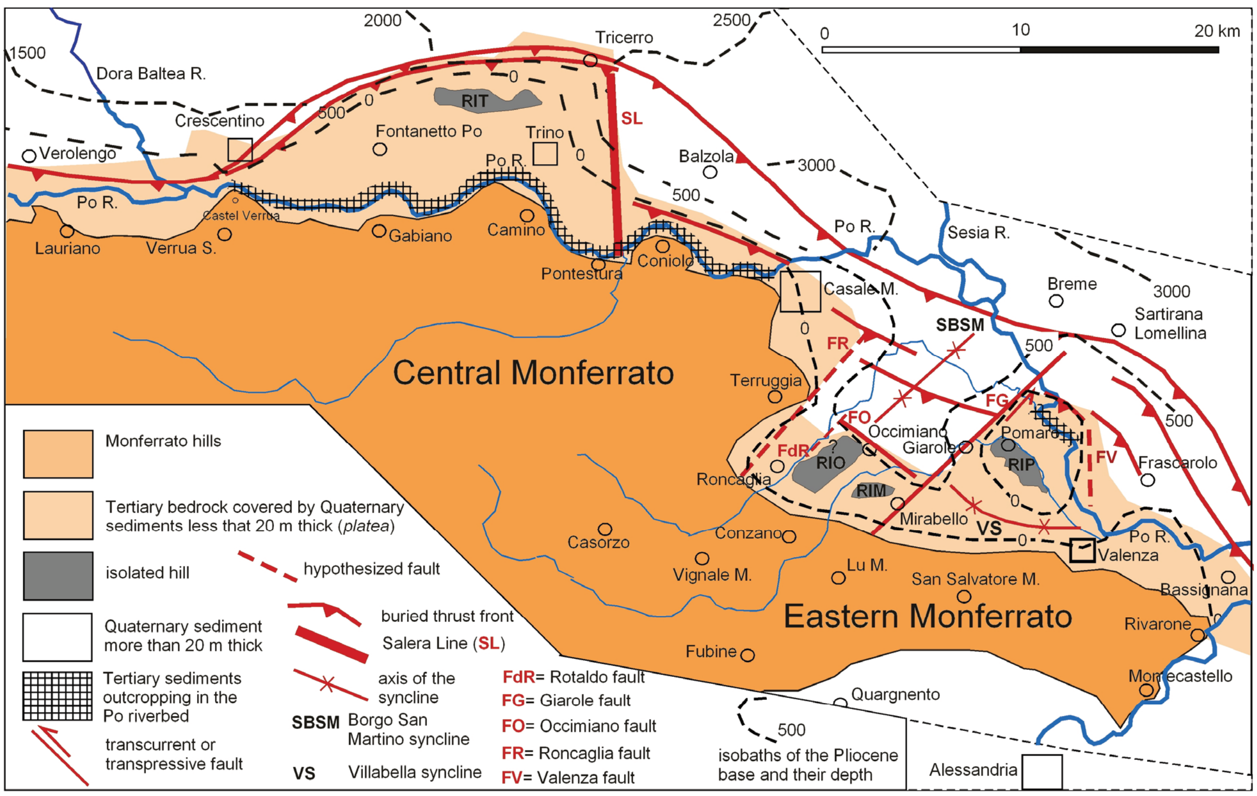

Fig. 3 - Tertiary bedrock covered by Quaternary fluvial sediments less than 20 m thick (*platea*), contour lines of the base of the Pliocene, and tectonic structures north of the Central and Eastern Monferrato Hills.

2014).

Fig. 3 shows that in the west, from Crescentino to Tricerro, the *platea* ends near the thrust front, reaching a distance of 10 km from the northern Monferrato hillslope. The eastern margin of the *platea* lies on the Salera Line, a complex N-S striking tectonic structure, according to Giraudi (2014).

In the area of Casale Monferrato and south of Balzola, the *platea* ends almost in coincidence with a trust front very close to the Monferrato hillslope.

In the Occimiano-Giarole area the northern margin of the *platea* lies on the Occimiano Fault, while, from Giarole to Bassignana, the *platea* ends near the thrust front north of the RIP, narrowing toward Bassignana.

In the area SE of Casale Monferrato, Occimiano and Giarole, the margins of the *platea* are also oriented SW-NE, transversal to the direction of the fronts. Near Giarole, the position of the margin of the *platea* almost coincides with the NE part of the SW-NE trending Giarole Fault.

2.1.3. Hyphotheses regarding the tectonic origin of the *platea* boundaries

The data reported above show that the platea edge is a boundary between areas that have undergone a different evolution, and that the area outside the platea is mainly in subsidence. Moreover, some stretches of the platea edge lie near some buried thrust fronts and correspond to the Occimiano and Giarole faults.

SE of Casale Monferrato, the margin of the platea is parallel to that corresponding to the Giarole Fault, and lies on the SW-NE striking Roncaglia Fault, hypothesized using the contour lines of the base of the Pliocene. The coincidence between two different data allows us to consider the presence of the Roncaglia Fault to be very likely.

The distance between the outer edge of the *platea* and the hillslope (Fig. 3) indicates a great difference between the areas separated by the Giarole Fault: to the east of the fault the *platea* expands strongly northwards beyond the Po river, seven kilometres further than in the western area. The activity of the fault, therefore, had an important role in determining the *platea* boundary. The position of the boundary may have been produced by left-slip displacements along the Giarole Fault or by the uplift of the area east of the fault. Transcurrent or oblique movements may indicate a continuation, even in the Quaternary, of the faults activity linked to the northward migration of the front of the Monferrato suggested by Costa (2003).

West of the Roncaglia Fault, the *platea* expands and its limit is about 5 km further north than in the area of the isolated hills RIO and RIM. The position of the edge of the *platea* is opposite to that produced by the Giarole Fault. The Roncaglia Fault could have been characterized by a right-slip activity (Fig. 3) and have been involved in the northward migration of the thrust front or could have produced the uplift of the area lying NW of the fault.

The Giarole and Roncaglia faults, thus, coincide with margins of the *platea* transversal to the direction of the fronts. Based on this datum, the correspondence between some stretches of the margin and other buried tectonic structures can be hypothesized.

Also near the NW margin of the RIO, the edge of the *platea*, west of the Rotaldo Stream, is about 1 km further south. This suggest the possible presence of a fault directed SW-NE near the streambed corresponding to the Rotaldo Fault (FdR in Fig. 3). Given the limited shift, it could be a fault with a left-slip component or a normal fault.

Overall, the subsurface data indicate that the structures which affect the margins of the *platea* were active during the Quaternary and that the whole area external to the *platea* has undergone a certain degree of subsidence.

2.2. Morphology, stratigraphy and tectonics of the Eastern Monferrato Hills

Some observations useful to understand and confirm the hypothesized geological structures buried below the Quaternary sediments derive from the interpretation of the morphology and the known geological structure of the adjacent hills (Fig. 2).

The divide between the Po and Tanaro river basins is arcuate in shape, first running from WSW to ENE, then approximately W-E and finally NW-SE, and is subparallel to the trend of the boundary between the Alessandria Plain and the southern slope of the hills.

However, the general trend of the divide undergoes noticeable local variations (Fig. 2): there are in fact stretches with a SW-NE direction in the west, and a NNW-SSE direction in the east.

The directions of the valleys of the Rotaldo and Grana streams are quite peculiar (Fig. 2). The high valleys are directed NW-SE and WNW-ESE, but the Rotaldo Valley, north of Vignale, changes direction toward NE, the same occurs at the Grana Valley SW of Vignale and west of Lu.

The geological features of the Eastern Monferrato Hills are reported in Bonsignore et al. (1969), Braga & Ragni (1969), Corsi et al. (1969) and Montrasio et al. (1969). The sediments that form the hills ranging from SSW to W of Mirabello (Fig. 2) include almost all the formations recognized in the Monferrato Hills and their age is between Upper Cretaceous and Pliocene. The oldest sediments are attributed to the Ligurian Units. It should be noted that the scarcity of outcrops in the hills allowed the Authors to recognize the general geological features but hardly to analyze in detail the characteristics of the structures.

According to Braga & Ragni (1969) in the lower Grana Valley there is a fault (the Grana Fault in the present paper, FdG in Fig. 2) having the same direction as the valley (SW-NE), and therefore transversal to the main structures of the Monferrato area.

On the northern hillslope, between Terruggia and the Rotaldo stream, the Pliocene sediments always overlie the Messinian ones, and are folded by synclines having axes trending SW-NE (Castello di Lignano Syncline- SCL in Fig. 4) and NW-SE (Ponara and Terruggia Synclines, SRP and ST in Fig. 4).

Between the Rotaldo and Grana Valleys the Pliocene sediments overlap on pre-Messinian sediments (Fig. 4), their eastern boundary lies near the Grana Fault and the western one close to the possible southern pro-

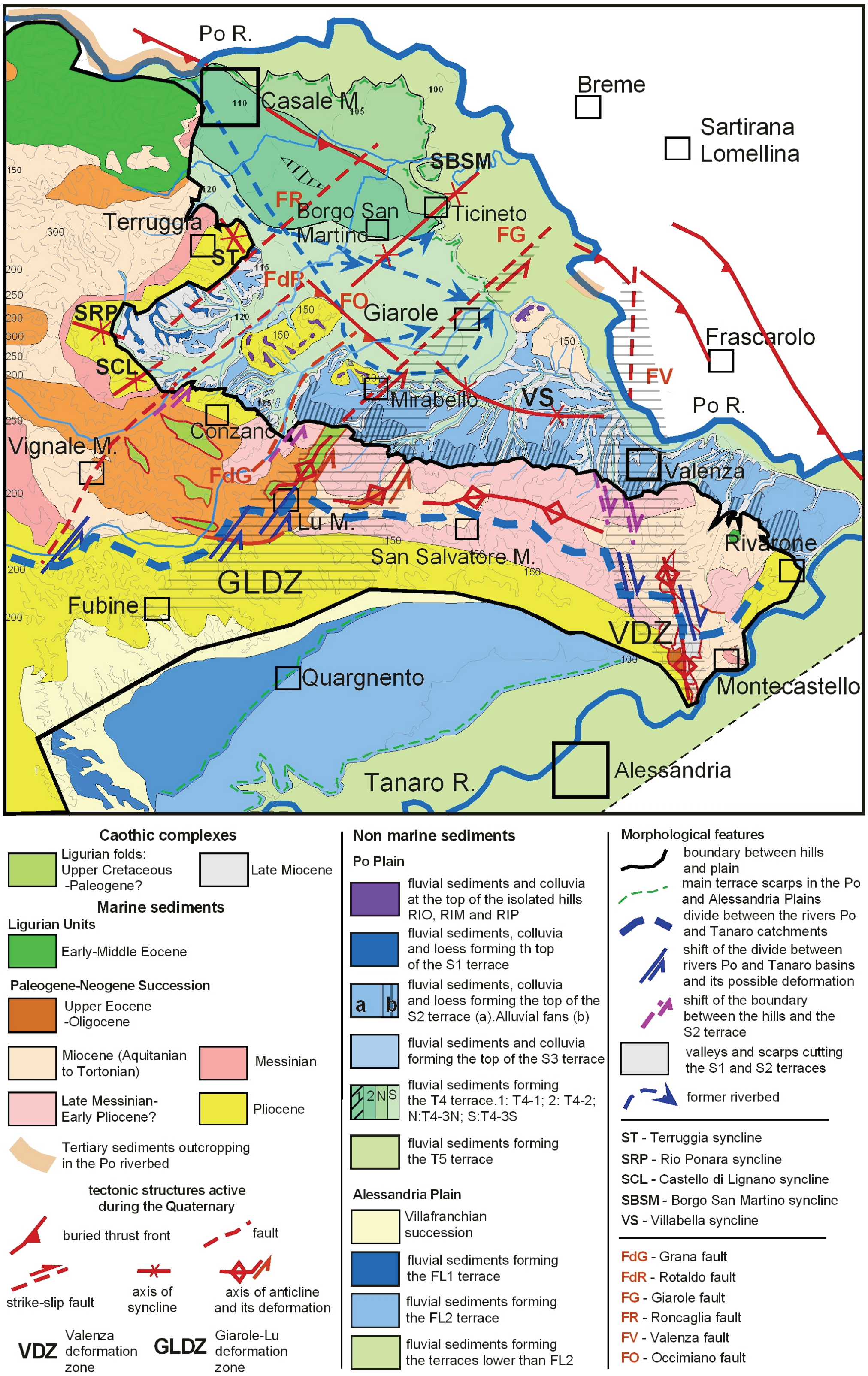

Fig. 4 - Geological map of the Po Plain, Monferrato Hills and northern Alessandria Basin. The geological structures active during the Quaternary lie from the Po Plain to the southern boundary of the Monferrato Hills, probably reaching the northern Alessandria Basin.

longation of the Rotaldo Fault (Fig. 4).

The hills to the east of the Grana Valley (south of Mirabello) and as far as the area of Valenza are composed mostly of Miocene sediments (mainly Tortonian and Messinian) and there are no outcropping Pliocene marine sediments on the northern slopes.

In addition, a seismic section through the area, reported in Cassano et al. (1986), highlights the lack, even in the subsoil, of the Ligurian Units outcropping a few kilometres to the west (Fig. 4). Starting from south of Valenza, the hills are formed by Eocene to Miocene sediments affected by diapirs and by Messinian and Pliocene marine sediments. The Pliocene sediments are lacking on the northern hillslope.

According to ENEL (1984b), NW of Rivarone lie also calcareous marls pertaining to the Ligurian Units.

Overall, there is a clear difference in the stratigraphy of the areas located SW and W of Mirabello, those located from SE of Mirabello and Valenza, and from Valenza to Rivarone, and the boundaries lie on the possible south-western prolongation of the Giarole Fault, and southern prolongation of the Valenza Fault.

It can be observed that the stratigraphy of the sediments forming the easternmost hills appears similar to that of the western hills, while the stratigraphic anomaly is restricted to the area between the southern prolongation of the Giarole and Valenza faults.

West of the possible prolongation of the Giarole Fault a stratigraphic anomaly can be observed also in the southern slope of the Monferrato hills, between the area south of Vignale and Lu. The Pliocene sediments outcropping on this stretch of hills overlie pre-Messinian sediments (Fig. 4), a case almost unique in the whole southern slope of the Monferrato and Turin Hills. Only near Castelnuovo Don Bosco and Passerano-Marmorito, at the southern boundary of Rio Freddo Deformation Zone (Dela Pierre et al., 2003a; Festa et al., 2009) a similar contact was observed. The eastern limit of the area of anomalous contact between Pliocene and pre-Messinian sediments lies on the possible prolongation of the Giarole Fault while the western one is on the possible southern prolongation of the Rotaldo Fault. A deviation of the divide of the Rotaldo and the change in the direction of the Grana and Rotaldo Valleys, occur in the possible southern prolongation of the Rotaldo Fault, north and south of Vignale.

Between Conzano and Lu, according to Corsi et al. (1969) and Montrasio et al. (1969) the axes of the anticlines, oriented WNW-ESE, are folded, assuming a SW-NE direction in correspondence with the possible SW prolongation of the (left transcurrent) Giarole Fault (Fig. 4).

To the west of the possible southern prolongation of the Giarole Fault, the Tortonian and Messinian sediments surround to the south the oldest sediments that form the Monferrato and dip towards the Alessandria basin, but east of the possible prolongation of the fault they advance considerably northwards forming also the northern slope of the hills and the southern slope of the RIP (Fig. 4).

East of the possible prolongation of the Giarole Fault until the area south of Valenza, the Tortonian and Messinian sediments form an anticline with an axis corresponding to the highest part of the hills. In no other sector of the Monferrato or the Turin Hills do late Miocene sediments form the highest hills. The anticline has a WSW-ENE trend, but to the east it is oriented WNW-ESE. The anticline lying north of Montecastello is formed by diapiric structures aligned NNW-SSE. This anticline therefore forms a nearly symmetrical structure with respect to the anticlines lying near Lu (Fig. 4). Near the Montecastello anticline, the divide between the Po and Tanaro basins undergoes some noticeable local variations assuming NNW-SSE directions.

On the northern prolongation of this anticline lies the hypothesized Valenza Fault having a similar direction.

2.2.1. Tectonic interpretation of the geological and morphological features

The joint interpretation of the morphological and geological features of the Eastern Monferrato Hills suggests that the hills are interested by the same kind of deformations affecting also the bedrock of the Po Plain.

As a matter of fact the anomalous contacts between Pliocene and pre-Messinian sediments, the distribution of the Tortonian and Messinian sediments, the presence or absence of the Ligurian Units, the folded anticlines, the sudden deviations in the divide and the change in the direction of the Grana Valley, are consistent with a left-slip displacement produced by tectonic deformations lying on the southern prolongation of the Rotaldo and Giarole faults and with one or more right-slip faults or plastic deformations lying on the southern prolongation of the Valenza Fault. But, according to Corsi et al. (1969) and Montrasio et al. (1969) there are not important surficial faults that produce the tectonic deformations and therefore we can assume the presence in the hills of plastic deformations induced by deep tectonic structures.

The Giarole Fault, and the tectonic deformations lying on its SW prolongation, stretches from the Monferrato Thrust Front NE of the RIP to the boundary between the hills and the Alessandria Basin: acting as a boundary between geologically different areas both below the plain and on the hills it can be considered the most important tectonic structure affecting the area. The complexity of the tectonic deformations observed in this area suggests the presence of a deformation zone (Giarole-Lu Deformation Zone, GLDF in Fig. 4).

Also the tectonic structure formed by the Valenza Fault and the associated tectonic deformations lying south of it reaches the boundary between the hills and the Alessandria Plain and suggests the presence of a deformation zone (Valenza Deformation Zone, VDZ in Fig. 4).

The Rotaldo Fault probably is a normal fault that starts near the Occimiano (thrust) Fault, continues toward SW, and reaches the southern slope of the Monferrato Hills.

Changes in the axes of the synclines similar to those occurring in correspondence to the Giarole Fault occur also on a possible southern prolongation of the SW-NE trending Roncaglia Fault (Fig. 4). In fact, the axis of the Ponara Syncline (lying west of the fault) is oriented WNW-ESE, while the axis of the Castello di Lignana Syncline (east of the fault) is SW-NE.

The Eastern Monferrato is not the only place in the Monferrato-Turin Hills where the southern slope is affected by deformation zones transverse to the hills: also the T. Traversola Deformation Zone, shows a strike slip nature (Forno et al., 2015; Gattiglio et al., 2015).

3. MORPHOLOGICAL FRAMEWORK AND QUATERNARY STRATIGRAPHY OF THE PLAIN BETWEEN CASALE MONFERRATO AND VALENZA

General indications on the Quaternary cover of the study area are shown by Anfossi et al. (1969), Bonsignore et al. (1969), Braga & Ragni (1969) and Montrasio et al. (1969). During the 80's of the twentieth century (ENEL, 1984), the area was also included in a morphostratigrafic study conducted during the research for the seismotectonic characterization of nuclear sites, and the results are partly discussed in Carraro (2012).

The main streams flowing in the area investigated are the Rotaldo and its tributary the Ponara, and the Grana, which flow into the Po river.

In the Rotaldo and Grana Valleys, clear remains of fluvial deposits different than those that form the valley floor have not been found. Outside the valleys, the streams cut into terraces lying at different altitudes.

The presence of some large terraces makes the plain north of the Eastern Monferrato Hills markedly different from the plain lying at the northern slope of the westernmost Monferrato-Turin Hills system (Fig. 2). Moreover in the area covered by this study, the Po lies at some distance from the hills while from Turin to Casale Monferrato it always flows near the foot of the hills.

The presence of the isolated hills at the boundary between the belt of high terraces and the Po Plain is also exceptional. The only other isolated hill to the north of the Monferrato area is located further west, near Trino.

These features thus make the plain to the north of the Eastern Monferrato peculiar compared with the westernmost plain. The same conclusion was reached observing the stratigraphy and the tectonics of the bedrock.

The morphology of the plain makes it possible to identify three areas with different characteristics: the isolated hills, the high terraces, and the lower terraces of the Po river.

3.1. The isolated hills

The isolated hills of Pomaro-Montevalenza (RIP), Mirabello (RIM) and Occimiano (RIO) are small hilly areas, consisting mainly of Tertiary sediments, isolated among the fluvial terraces (Fig. 2; 4).

The isolated Pomaro-Montevalenza hill (RIP)

The RIP is a hill, elongated in a NW-SE direction for about 3.5 km having a width of 1.5 km, reaching an altitude of 165-170 m a.s.l., that is ca. 60-70 m above the surrounding terraced plain. It is located on the northern edge of the Villabella Syncline (Fig. 4) and consists mainly of Late Miocene marls and clay, of marine origin (Casnedi, 1975). The RIP is divided into two parts by a valley that separates the hill of Pomaro from that of Montevalenza (Fig. 5 B).

The NW area (Pomaro) has steep slopes having a NW, SW, SE and NE orientation, and a nearly flat top, located at altitudes between 150 and 155 m, and is eroded by small valleys. The valleys are present only in the SE and southern slopes. In the summit area some patches of very weathered silty colluvial sediments were found (colour index up to 2.5 YR of the Munsell Soil Colour Chart-MSCC). In the colluvia, sand and small pebbles have also been observed, and their lithology suggests an Alpine origin. In particular the pebbles are lithologically similar to the gravel outcropping in the Cerrina Valley (ENEL, 1984), outside of the study area, described by Giraudi (1981), Carraro et al. (1995), Giraudi et al. (2003), Dela Pierre et al. (2003a,b).

The heterogeneous lithology of the deposits, their variable grain size and the presence of a fraction of gravel of Alpine origin, indicate that the colluvia derive from sediment of fluvial origin. The nearly flat summit is, therefore, the remnant of a terraced surface, originally shaped by a stream, for which there are no homologous terraces either to the north or on the Monferrato Hill slope.

The part of the RIP on which Montevalenza lies reaches 165-170 m, and is extremely asymmetrical since it is limited by very steep slopes to the NW, NE and east, while it slopes gently towards the south. The stream network is developed only on the southern slope. The Quaternary deposits identified are colluvia consisting of weathered silt, with a colour index reaching 2.5 YR MSCC. The silts are present however only at altitudes below 155-150 m, corresponding to the altitude of the top of the Pomaro hill.

It is possible that at the time of the shaping of the flat top of the Pomaro hill the highest part of the Montevalenza area was already a small isolated hill.

The isolated Mirabello hill (RIM)

The RIM, formed by Pliocene sediments (Corsi et al., 1969), is elongated for about 1.5 km in a W-E direction, about 0.6 km wide, and divided into two parts by a small valley. The largest slopes run W-E, and are exposed to the south and north (Fig. 5 A).

The western part of the RIM reaches a height of 161 m while the eastern one reaches 155 m. Some thin patches of weathered fluvial and colluvial silt, whose colour index reaches 2.5 YR MSCC, lie on top of the hill.

Also the surface of the RIM could correspond to the remains of a terrace which has no homologous terrace on the Monferrato hillslope. According to Corsi et al. (1969), the surface of the RIM corresponds to the top of the oldest terrace in this area (see below) dated at the Mindel.

The isolated Occimiano hill (RIO)

The RIO is an approximately rectangular hilly area, consisting of Pliocene marine sediments, elongated for about 3.5 km in a NE-SW direction, about 1.5 km wide, which reaches a maximum height of 166 m, ca. 25-40 m above the surrounding terraced plain (Fig. 5 A).

The slopes shaped by the Rotaldo and Grana

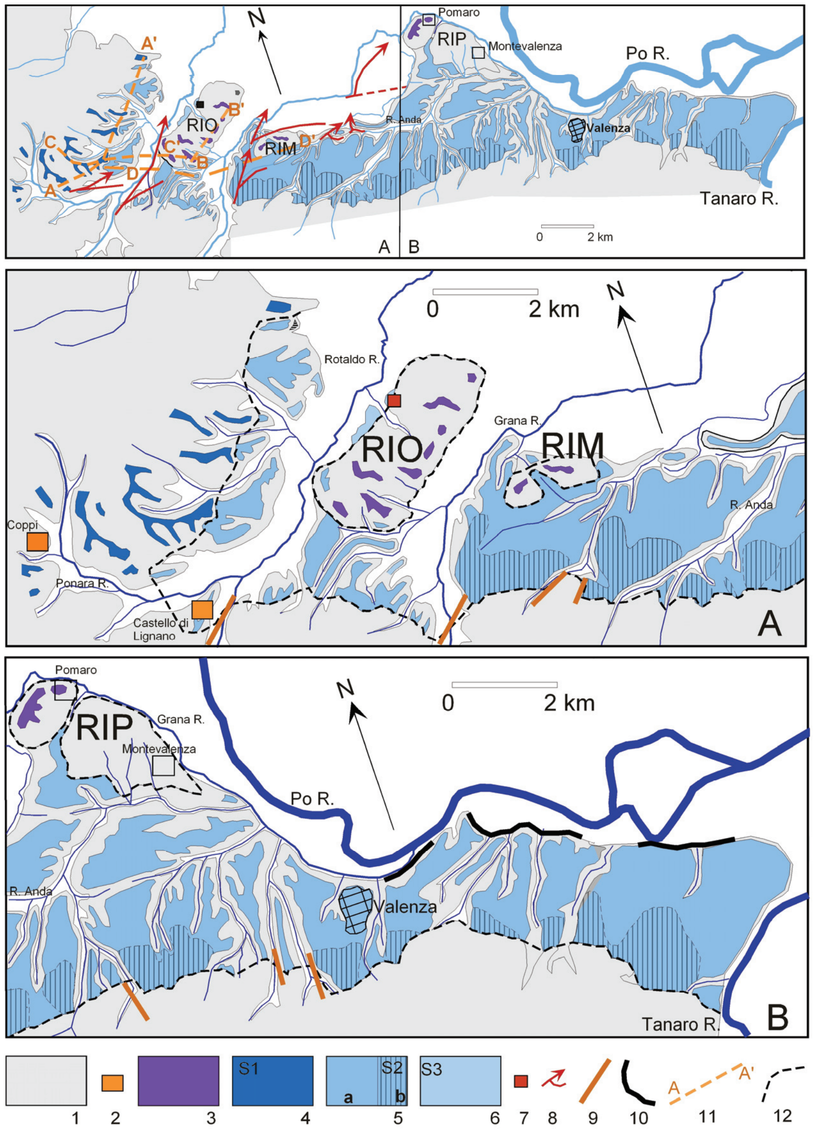

Fig. 5 - Map of the terraces lying north of the Eastern Monferrato Hills. 1 - Monferrato Hills; 2 - Fluvial and Lacustrine Unit exposures; 3 - summits of the RIO, RIM and RIP isolated hills; 4 - S1 terrace; 5 - S2 terrace (a: covered by aeolian sediments; b: covered by flat fluvial fans); 6 - terrace S3; 7 - studied colluvial series; 8 - river diversion; 9 - anomaly in the hillslope-terrace S2 boundary; 10 - Villafranchian succession outcropping in the S2 terrace scarp; 11 - A-A', B-B', C-C', D-D' cross sections through the terraces S1 and S2, and the top of the RIO reported in Fig. 8; 12 - boundary between hills and terraces.

streams corresponding to the longer sides of the rectangle, are oriented SW-NE like the axis of the Castello di Lignano and Borgo San Martino synclines, and the NW slope is parallel and lies near the Rotaldo Fault (Fig. 4); the eastern one is parallel to the Grana Fault and the NE one is parallel to the Occimiano Fault.

The hill is eroded by small valleys directed mostly towards NW and SE, but also to the S and NNE, due to a centrifugal drainage pattern. Near the summit of the hill discontinuous outcrops of very weathered silty sediments have been observed (colour index up to 2.5 YR MSCC). The silt sometimes contains a gravel component and the lithology of the gravel is similar to that of the fluvial sediments of the Cerrina Valley, Alpine in origin (ENEL, 1984). Artefacts from the Lower Paleolithic were collected towards the base of one of these silty deposits (Giraudi & Venturino, 1983).

Some colluvial patches with a different degree of weathering and colour index between 2.5 YR and 10 YR MSCC have been observed on the slopes of the RIO. The redder colluvia have the same grain size as the summit colluvia having the same degree of weathering.

The altitude of the various ridges is fairly constant (between about 160 and 165 m) and indicates that the top of the RIO was originally almost flat. If we consider also the fluvial origin of the gravel we can agree with Corsi et al. (1969) and Braga & Ragni (1969) that the summit of the RIO is a remnant of a mainly erosional fluvial terrace. Depending on the summit altitude, the terrace could have no homologous terrace either north or south.

The survey of some artificial exposures has also shown a sequence of colluvial phases (Fig. 6). The oldest colluvia, up to 3.5-4 m thick, overlying a nearly flat erosion surface lying at an altitude of approximately 130 m, are very weathered, with a colour index of 2.5-5 YR MSCC. An intermediate colluvial layer, with a colour index of 7.5 YR MSCC, rests on the older sediments. Some colluvial sediments that are little weathered (colour index 10 YR MSCC) overlie the intermediate layer. At the foot of the slope another sequence of colluvia was exposed. The oldest colluvia, about 3 m thick, with a colour index of 5YR MSCC, lie on an erosional surface about 6 m below the valley floor: they are covered by a second colluvial deposit with a colour index of 7.5 YR MSCC, on which lie the last, poorly weathered colluvia.

The sequence of erosions and sedimentation of the colluvia, enables us to recognize the evolution of the slope. The stratigraphy indicates that, after the sedimentation of the fluvial deposits preserved at the top of the hill, when the weathering was already very strong (2.5YR MSCC), a phase of erosion began which carved up the slope to an altitude of about 130 m a.s.l.. The erosion was followed by the emplacement of the colluvium.

Later, at the top of the RIP, a new paedogenesis took place which produced a soil with a colour index of 5 YR MSCC. The soil in turn was colluviated after the erosion of the slope, produced by the presence of a small stream at its foot. Later a soil with a colour index of 7.5 YR MSCC evolved; this was eroded and colluviated, and the new colluvium covered the older one. Finally the last soil, with a colour index of 10 YR MSCC, developed and was later eroded producing the colluvia of the same colour.

It is evident that the phase of erosion of the base of the slope (Fig. 6) decreased or ceased after the sedimentation of colluvium with a colour index of 5 YR MSCC and that the later phases of erosion and aggradation were weaker.

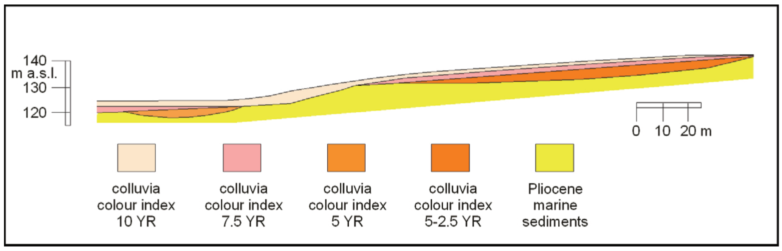

Fig. 6 - Colluvial deposits on the RIO NW slope.

3.2. The Quaternary sediments between the Eastern Monferrato hills and the Po river

The sequence of Quaternary sediments lying between the northern edge of the Eastern Monferrato area and the Po river, in spite of the information derived from water wells, is rather difficult to study and date mainly because of the scarcity of exposures and sections that can provide adequate stratigraphic and chronological data. The sediments will be described starting from the oldest.

Fluvial-lacustrine Unit

The poorly exposed sediments that form this unit have been identified in two places: near the Castello di Lignano and in the area of Coppi (the Ponara Valley- Fig. 5A).

Near the Castello di Lignano, about 140 m a.s.l., clay, silt and sand of fluvial-lacustrine origin, 5-6 m thick, have been identified, surrounded by Pliocene marine sediments (Sabbie di Valleandona, according to Montrasio et al.,1969).

Given the poor quality of the exposure, the nature of the basal surface is not clear but, since the Pliocene sediments lie at higher altitudes, it is likely that the base of the fluvial-lacustrine sediments was carved in the underlying marine deposits.

The mineralogical composition of the sands is similar to that of the fluvial deposits of the Lower and Middle Pleistocene of the Cerrina Valley (quartzites of various colours, gneiss and mica schist, fine-grained metabasites) studied by Giraudi (1981), ENEL (1984), Giraudi et al. (2001) and Dela Pierre et al. (2003b).

The sediments described above are covered, with a clear erosional contact, by weathered sandy silt, coloured 5 YR MSCC, about 1-1.5 m thick.

In the area of Coppi, at an altitude of about 160-170 m, in the ploughed ground gravelly sand is exposed, whose lithology is very similar to that of the sand found near the Castello di Lignano. Also in this area the bedrock is formed of Pliocene marine sediments.

The fluvial-lacustrine and fluvial sediments of the two areas are isolated and there is no direct dating. However, the lithological composition (quartzites of various colours, gneiss and micaschist, limestone, medium-fine grained calcarenite) shows similarities to fluvial sediments of Alpine origin observed in the Cerrina Valley, whose sedimentation began about 1 MA ago (Giraudi et al., 2003).

We can therefore assume (in accordance with ENEL, 1984; Carraro et al., 1995) that the sediments were deposited by the same river that flowed through the Cerrina Valley and continued eastwards reaching the area under consideration. Sedimentation would have ceased at the time of the deviation to the north of the river, which occurred in the Cerrina Valley, around 600 ka BP (Dela Pierre et al., 2003b). It follows that the sediments of the fluvial unit may be between about 1 and 0.6 MA old.

The terrace S1 and its sedimentary succession

The terrace S1, recognized in the Ponara Valley and on the left side of the Rotaldo Valley (Fig. 4; 5A), is the oldest (Corsi et al., 1969), heavily eroded and formed by relict surfaces preserved as narrow and elongated ridges covered by strongly weathered sediments.

In the Ponara Valley the surface of the terrace S1 dips from north to south and from NW to SE, that is towards the axis of the Rio Ponara Syncline, while on the left side of the Rotaldo Valley it dips from W to E and from SW to NE, that is, towards the axis of the Castello di Lignano and Borgo San Martino Synclines. The remnants of the terrace lie at altitudes between about 190 and 135 -140 m a.s.l., ca. 30- 40 m above the valley floor of the Rotaldo and Ponara Streams.

The sediments that form the surface of the terrace S1 consist mostly of weathered silt, with a colour index up to 2.5 YR MSCC. Horizons of fine gravel are sometimes interbedded in the silt, their lithology being similar to that forming the Fluvial-Lacustrine Unit but mixed with clasts of local origin. The sediments are fluvial and linked to a non-local river, according to Corsi et al. (1969). It can be assumed, therefore, that the clasts of Alpine origin derive from the erosion of the deposits of the older sedimentary unit.

The estimated thickness of the sediments is always less than 2-3 m. Colluvia with the same lithology as the fluvial sediments are also present on the terrace scarps.

According to Corsi et al. (1969) and Braga & Ragni (1969), fluvial sediments, weathered into a typical "*ferretto*", are covered by brick-red coloured loess a few metres thick. This results from outcrops no longer visible and indicates the presence of aeolian sediments much more weathered than those recognized further east (see below) described by Sacco (1889), ENEL (1984) and Corsi et al. (1969). The heavily weathered loess may be correlated to that found on the higher surfaces of the Isolated Trino hill (RIT in Fig. 3), reported by the Gruppo di Studio del Quaternario Padano- GSQP (1976) and ENEL (1984), assigned to the MIS 8 by Giraudi (2014) on the basis of the stratigraphy.

Therefore, sediments and soils similar to those found on the summit of the isolated hills RIO, RIM and RIP lie on the top of the terrace S1. The altitude of the eastern remnants of the S1 surface is slightly less than that of the RIO summit. According to Corsi et al. (1969), the sediments of S1 correspond to those found at the top of the isolated hills RIO and RIM. The age of the fluvial sediments, that date back to the Mindel according to Corsi et al. (1969), must therefore be more recent than the Fluvial-Lacustrine Unit, dated between about 1000 and 600 ka BP, and older than the weathered loess (MIS 8, dated between about 300 and 270 ka BP). According to Arduino et al. (1984), soils with a colour index corresponding to 2.5 YR MSCC may have developed from the early Middle Pleistocene.

The terrace S2 and its sedimentary succession

The terrace S2 is significantly lower than S1 and is divided into three parts (Fig. 4; 5), being cut crosswise by the Rotaldo and Grana Streams.

The first area where S2 is present (Fig. 4; 5A) corresponds to the left side of the Ponara and Rotaldo Valleys. The surface of the terrace dips from SW to NE, from about 160 to 140 m a.s.l., and must have been shaped by rivers that flowed in that direction. On the surface of the S2 terrace some quite extensive patches of weathered fluvial silts are preserved, with a colour index of 5YR MSCC, less than 1.5 m in thickness. According to Arduino et al. (1994) soils with a colour index of 5 YR MSCC would have developed during the Middle Pleistocene.

The second area is between the RIO and the hillside, limited to NW and SE by the Rotaldo and Grana streams (Fig. 4; 5A). The position and dip of the surface of the terrace suggest that S2 has been shaped by the Rotaldo and by smaller hill streams. The altitude of the S2 surface is between 150 and 135 m a.s.l.

The surface of the terrace S2 in this area is mainly eroded by streams that drain towards the NE and then, after forming an elbow, flow towards ESE. There is also a remnant of the S2 terrace on the western side of the RIO indicating that, in the course of the shaping of S2, the Rotaldo Stream changed direction and began to flow N.

The third area where the terrace S2 is present, the largest one, is located east of the Grana stream, and corresponds to the area known as the Valenza Plateau. The plateau is strongly dismembered as a result of the incisions of streams active after its shaping. About the streams, we can distinguish the longitudinal ones (with a bed extending in the direction of elongation of the terrace S2) and the transversal ones. The longitudinal streams form the collectors into which flow the transversal streams. They have approximately a WSW-ENE direction in the area south of RIM, W-E in the area south of the RIP, and then WSW-ENE from the RIP to Valenza. South of the RIP some stretches of longitudinal streams overlap almost exactly the axis of the Villabella Syncline (Fig. 4).

The transversal streams that cut the terrace from the area south of the RIM to the area to the SW of the RIP, flow NNE and NE, while from the area south of the RIP to Valenza, they flow N and NNW. The streams on the RIP slopes, flow from NNW to SSE.

East of Valenza the small valleys are generally directed NE and NNE.

Among the streams cutting the Valenza plateau, the longest one is the Rio Anda (Fig. 4; 5). It flows in a small valley which, SW of the RIP, has a flat bottom formed by sandy silty sediments, while starting from S of the RIP, it becomes very narrow and deep, as all the streams in the area.

Overall, the surface of the terrace S2, between the altitudes of 145 and 90 m, indicates a general slope from west to east and towards the northern quadrants.

The greater height reached by the surface S2 at the foot of the hills is mainly due to the presence of a belt of flat fluvial fans and a layer of colluvial deposits that stretches from the Grana Valley to the eastern end of the plateau. One of the most extensive fluvial fans is located on the right bank at the mouth of the Grana valley, showing that this stream also took part in the shaping of S2 (Fig. 5).

However, the presence of S2 at the western and northern edges of the RIM and on the right side of the Grana stream indicates that, during the shaping of the terrace, the stream changed its bed, heading N, bypassing the RIM and flowing eastwards reaching the longitudinal collector, oriented WNW-ESE, lying south of the RIP.

Overall, the sector of S2 corresponding to the Valenza plateau was therefore shaped by the Grana and other smaller streams, but it is possible that, before a diversion, even the Rotaldo and its tributary Ponara flowed eastwards forming a much longer collector.

The boundary between the S2 terrace and the hillslope shows some peculiarity. At the mouth of the Rotaldo and Grana valleys and of the valley of a minor stream, south of the RIM (Fig. 5A), in the eastern side of the valleys the boundary between S2 and the hillslope is located 800, 1000 and 500 m, respectively, further north compared to the western side. Instead, starting from the area SE of the RIM till the eastern end of the Valenza plateau (Fig. 5B), in correspondence with some small valleys, the boundary between surface S2 and the hillside is located, west of the streams, 500 or 600 m further north if compared to the east. Hence the position of the boundary between the surface S2 and the hillslope does not seem random; the peculiarities of the boundary observed S and SE of the RIM, lie in the Giarole-Lu Deformation Zone (Fig. 4), while those lying near Valenza are located in the Valenza Deformation Zone.

The sediments that form the terrace S2 consist, from top to bottom, of:

- Coarse yellowish quartz sands of aeolian origin, described by Corsi et al. (1969) and ENEL (1984), which form some small dunes less than 2-3 m high, present at the NE margin of the terrace. The shape of the dunes is no longer visible, probably because of the fields having been levelled for agriculture. The sands lie on the underlying sediments by means of an erosional contact. Similar dunes have been reported lying on the fluvial sediments to the east of the Po river, a few kilometres from the Valenza plateau, and their age is considered as Upper Pleistocene

Corsi et al. (1969) although it could reach the Holocene (ENEL, 1984).

- Unstratified silt, close to 2 m thick, already recognized as loess by Sacco (1889), which can be divided into two horizons between which there is a fairly sharp boundary (ENEL, 1984). The more surficial horizon, characterized by porosity and vertical prismatic fissures, is weathered by a soil with an average colour index of 10 YR MSCC. In the darker lower horizon, the prismatic structure is lacking, and there are carbonate concretions towards the base. Although there are no elements for a direct dating of these sediments, the loess of the Valenza plateau can be correlated to that widespread in Piedmont in the following areas: the Turin Hills, the Poirino plateau, the Rivoli-Avigliana Moraine Amphitheatre, the isolated Trino hill, the area near Novi Ligure, and the Cerrina valley (Forno, 1979; Biancotti & Cortemiglia, 1981; Giraudi et al., 2003; Festa et al., 2009; Balestro et al., 2009). The loess is generally attributed to the late Pleistocene. On the isolated Trino hill (Giraudi, 2014) loess with the same features contains some Upper Paleolithic artifacts while, in the Cerrina Valley, it contains Mousterian artifacts that can be dated to the very late Middle Pleistocene or to the Upper Pleistocene. We can therefore assume an Upper Pleistocene age for the loess of the Valenza plateau.
- Silt and sandy silt, from 1.5 to 5 m thick, sometimes containing thin layers of fine gravel at the bottom, of fluvial origin; the lithological composition of the gravel shows that the pebbles have a mixed origin, Alpine and local, and that they probably derive also from the reworking of the oldest fluvial sediments. The deposits are weathered and the soil colour index is 7.5 YR MSCC. The sediments lie, through an erosion surface, on the Tertiary marine and Villafranchian succession. Having been weathered before the sedimentation of the loess, the fluvial sediments must be significantly older than the aeolian deposits. The greater pedogenesis (5YR MSCC colour index) of the sediment lying on S2 in the valley of the Ponara and Rotaldo streams, where the described loess are lacking, should be connected, according to Arduino et al. (1984), to a soil that developed before the end of the Middle Pleistocene.

The fluvial sedimentation in the Valenza plateau was followed by a phase of pedogenesis, an erosion phase and finally by the sedimentation of the loess. The evolution of the soil buried by the loess was therefore halted during the Upper Pleistocene. For this reason, the palaeosol is less evolved than the soil preserved on S2 near the Rotaldo Stream. It is therefore likely that the fluvial sediments lying on S2 date back to the latest Middle Pleistocene.

The terrace S3 and its sedimentary succession

The terrace S3, recognized at the mouth of the Rotaldo and Grana valleys, is poorly preserved and discontinuous, and its surface lies between 127 and 120 m a.s.l. (Fig. 4; 5). No exposures indicate the stratigraphy and facies of the sediments. Only observation of the ploughed sediments has allowed us to establish that the top of the terrace is formed of silt, sometimes sandy, weathered by soil with a colour index of 7.5 YR MSCC.

The sediments of the valley bottoms and the plain south of the Po River

Between the Po river and the northern edge of the terraces S1, S2 and isolated hills, is the floodplain to which are connected the valley bottoms of the streams with catchments in the hills. The plain consists, basically, of a main surface (terrace T4) and a set of surfaces located at altitudes very similar to each other (for simplicity grouped under the acronym T5) that correspond to the area shaped in recent times by the Po river, and in which abandoned meanders and river beds are clearly visible (Fig. 4).

The bottoms of the Rotaldo and Grana valleys are connected with the terrace T4 at the mouth of the valleys, but further downstream the streams cut this surface joining the terrace T5. All the streams that cut the Valenza plateau SE of the RIP are connected to the terrace T5.

The morphological and geological features of the terraces, based on a field survey, small artificial exposures, and stratigraphic data from quarries and boreholes, are the following.

Terrace T4: It forms the largest sector of the area between the Po river and the Valenza plateau and isolated hills but is not present SE of the RIP. Its altitude ranges from about 120-125 m in the area of Casale Monferrato, to less than 100 m in the area near the RIP.

The surface T4 is correlated, according to its altitude, with a terrace lying north of the Po river formed by fluvio-glacial deposits, linked to the morainic amphitheatre of Ivrea, dated to the late Upper Pleistocene (Montrasio et al., 1969; Corsi et al., 1969; Giraudi, 2014).

The morphology of the terrace and the grain size of the sediments indicate that it has been shaped by the Po river.

The surface consists of sandy gravel covered by sand and silty sand. It is possible that some of the silty sands that form the surface were deposited by the streams with catchments in the hills, and date back to the Holocene.

The thickness of gravelly sandy sediments in the subsurface of T4 ranges from less than 10 m in some areas (Fig. 4) up to 50-60 m in the area north of the edge of the *platea*.

In the subsurface, two fossil elephant teeth were found which unfortunately do not provide any significant chronological information. In a quarry on the outskirts SE of Casale Monferrato, under the groundwater level, a tooth (right second molar) of *E. antiquus* was found (determined by V. Borselli, pers. comm., 1983, in ENEL, 1984). The depth is not known, but in the area the thickness of the fluvial sediments is less than 20 m. On the western outskirts of the same town, a few metres below ground level, an upper left molar of *E. primigenius* (Negri, 1884) was instead found in the fluvial sediments.

The age of the base of the sediments forming T4 is unknown, but it is very likely that, at least in the area where the sediments are thicker, that is north of the edge of the *platea*, it is considerably older than that of the superficial deposits.

The top of the T4 terrace is partially eroded and it is formed by three different surfaces that can be hardly recognized being separated by discontinuous scarplets.

SE of Casale Monferrato (Fig. 4), there is a flat-topped ridge (T4-1), about 2 km long and 500-600 m wide, slightly higher than the T4-2 surface. The ridge is limited by discontinuous very gentle scarps that do not reach one metre in height.

In a temporary quarry (ENEL, 1984) it has been observed that the ridge is formed, at least to a depth of 4 m, by slightly weathered fluvial sandy gravels quite similar to those which form the other sectors of T4.

The best preserved portion of the T4 surface (T4-2) surround the T4-1, but north and south of T4-2 lie surfaces whose altitudes are slightly lower (T4-3N; T4-3S) (Fig. 4). T4-2 is between Casale Monferrato and Borgo San Martino-Ticineto; it has a NW-SE direction and its northern and southern limits, in places, coincide with or are parallel to the buried thrust fronts (Fig. 4). A section of the boundary between the T4-2 and T4-3N surfaces corresponds to the northern limit of the buried *platea* and the width of T4-2 decreases east of the eastern edge of the *platea*.

The boundary between T4-2 and T4-3N is not represented by a real scarp, but just by a hardly noticeable scarplet in the plain having a nearly straight direction. Although it is possible that the scarplets in the plain were connected with the erosion of the Po river, their morphology is totally different from that of the escarpment, certainly shaped by the Po river, that separates T4-3N from the most recent T5 terrace. The latter is, in fact, much more evident and, especially, has been clearly shaped by a meandering river (Fig. 4).

The erosion of T4-3S is certainly due to the Gattola, Rotaldo and Grana streams. The streams gently eroded T4-2 and deposited surface silty sediments. The southern edge of T4-3S, especially where it reaches the scarp of the terrace S2 (Fig. 7), has a curvilinear shape as a consequence of fluvial erosion (Fig. 4).

The direction of the beds of the Gattola and Rotaldo streams, now artificially diverted, was from SW to NE, but before they reached the southern edge of the T4-2 surface, they diverged sharply to the SE and ESE (Fig. 4).

The mainly silty-sandy deposits of the Rotaldo and Grana valley bottoms are connected with the T4-3S surface.

Terrace T5: as noted above, this is formed by a series of low river terraces shaped during the changes of the bed of the Po river (Fig. 4). In the contiguous Vercelli plain and just north of the Po river, the sediments that form these terraces contain Bronze Age, Roman and Middle Age artifacts and remains (Tropeano & Olive, 1989; Giraudi, 1998; Giraudi, 2014). Therefore, the shaping of T5 took place during the late Holocene.

From the area of Casale Monferrato to the RIP, the T5 surface develops closely parallel to the current bed of the Po river and lies between T4 and a terrace, equivalent to T4, sited N and NE of the Po river (Fig. 2). Only downstream of the RIP, where T4 is lacking, does

Fig. 7 - The scarp between the S2 and the T4-3S terraces viewed from the S2 top. The scarp is in the foreground, while in the background lies the Pomaro isolated hill (RIP).

T5 reach the base of the scarp of the Valenza plateau and the river flows in an asymmetric position, very close to the scarp.

4. DISCUSSION

The data presented above will be interpreted and discussed in order to highlight the sedimentary and tectonic evolution of the area during the Quaternary. The results will be compared with geodetic data, derived from topographic measurements of precision and GPS stations, in order to verify the compatibility between tectonic interpretations and data relating to the ongoing deformation. Finally, we will discuss the distribution of the epicentres of earthquakes recorded in the area and the correspondence between epicentres and areas affected by tectonic movements.

4.1. Sedimentary and erosive Quaternary evolution

The data and the interpretations of the succession of phases, erosional, depositional and pedogenetic, enable the evolution of the area between the Po and the Eastern Monferrato Hills to be outlined.

It should first be pointed out that, apart from the coarse fluvial sediments of the Po plain, on the whole the sediments found are quite scarce and lie on planar erosional surfaces shaped on the bedrock, and this suggests that the terraces were mainly erosional.

The terraces can be regarded as remnants of an uplifted and eroded *platea*.

The erosional terraces ranging from S1 to S3, therefore, show the different stages of erosion. Also the base of the fluvial sediments in the southern area of terrace T4 is erosional. The sediments allow us to assess that the shaping of the erosional terraces occurred during the period between the beginning of the Middle Pleistocene and the Upper Pleistocene.

The incision of the valleys during the Quaternary may be linked to the gradual deepening of the erosion surface north of the hills, while the infilling of the Rotaldo and Grana valley bottoms may be connected mainly with the aggradation of the fluvial sediments that form the surface of the terrace T4.

During the late Upper Pleistocene or the Holocene, the Po river, which flowed S and SE of Casale Monferrato (Fig. 4), eroded the S2 terrace scarp and captured some stretches of the streams that flowed across the Valenza plateau between the RIM and the RIO (Fig. 5).

During the late Upper Pleistocene or the Holocene, the river underwent a diversion to the east and began shaping the T5 surface. During the Holocene the river eroded the northern side of the RIP and the escarpment which limits the Valenza plateau to the N, and induced a deepening of the tributary valleys which cut into the plateau in that area.

4.2. Evidence of tectonic deformations

The existence of Quaternary tectonic deformations is proved by the Quaternary evolution and by the relations between some morphological features and the structures affecting the bedrock.

The Monferrato Thrust Front is the most important tectonic structure having a regional extension that affects the area. Since the limits of the buried *platea* mostly coincide with the younger thrust front or transversal structures (Fig. 3) and outside the *platea* the Quaternary sediments become thicker, it can be assumed that compressive tectonics were active during the Quaternary. In particular, the stretch of the fronts situated near Casale Monferrato and NE of Pomaro would be the ones most involved in the deformation of the base of the Quaternary fluvial sediments, while the Giarole and Roncaglia Faults acted as boundaries of the subsiding Borgo San Martino Syncline or tectonic trough.

Among other structures, the Giarole-Lu Deformation Zone is the one that produced the most evident effects because it separates stretches of plain and hills with different geological and geomorphological features.

The interaction between the fluvial and tectonic Quaternary evolution could have produced the clearest morphological anomalies that are essentially the hills made of Tertiary sediments isolated between Quaternary fluvial deposits.

The only other isolated hill present north of the arc formed by the Monferrato and Turin Hills is that of Trino (RIT in Fig. 3). It is located in the *platea* area just south of the Monferrato buried front, and it was definitely affected by movements related to compressive tectonics, at least, up to part of the Middle Pleistocene (GSQP, 1976, ENEL, 1984; Giraudi, 2014) and, according to Burrato et al. (2012) and Michetti et al. (2012), even in more recent times.

In correspondence to the RIT, the bedrock is shaped by a series of planar erosion surfaces, covered by fluvioglacial deposits, located at altitudes gradually lower, both to the north and to the south, separated by buried scarps. The topographically higher surfaces are those covered by the older deposits.

The isolated hills RIP, RIO, and RIM are also located to the south of thrust fronts (Fig. 2; 4) and their edges are sub-parallel to thrust fronts or lie in correspondence of faults transversal to the fronts. Also in the area studied, the bedrock is shaped by a series of nearly flat erosion surfaces (corresponding to the top of the isolated hills) lying at different altitudes and separated by scarps. The higher surfaces were most likely produced by the Alpine river flowing from the Cerrina Valley while, after the diversion of that river (see above) dated around 600 ka BP, the erosional terraces S1, S2, S3 were shaped by local streams.

There is little doubt, therefore, that the development of the isolated hills is also connected with the Quaternary tectonic evolution of the Monferrato, as already hypothesized in ENEL (1984) and Carraro (2012). The existence of Quaternary tectonic mobility makes it difficult to accept the hypothesis that near-flat surfaces forming the top of the RIO and RIM isolated hills and the S1 surface were shaped simultaneously as assumed by Corsi et al. (1969). The chronological framework of the sediments lying on such surfaces is too loose to support a clear correspondence between them.

In the presence of tectonic movements, the erosion surface that was evolving in the area between the thrust front and the hillslope was certainly subject to deformations and these deformations could have been different in areas bordered by the various buried structures.

Some sectors could have been uplifted and in these the remnants of the erosional surface, covered by thin layers of fluvial sediments, were raised to form terraces higher than the surrounding area. The uplift induced the streams to migrate to topographically lower places where they began to shape new portions of the erosional surface.

The interference between tectonics and fluvial erosion would have produced an almost continuous evolution of the erosional surface and the different altitudes at which the erosion terraces lies demonstrate this.

A possible confirmation of the continuous erosion is also given by the almost total absence of terraces in the inner portion of the Rotaldo and Grana valleys. If the modelling of S1, S2 and S3 had occurred during three phases of erosion interrupted by periods of stasis, the three terraces would have formed also within the valleys.

Thus the continuous down-cutting of the valley bottoms and of the erosion surfaces that formed the terraces allows us to hypothesize a nearly continuous tectonic uplift, common to the hills and to the adjacent terraced plain.

Figure 8 shows a SSW-NNE section (A - A') of S1 on the left of the Rotaldo stream and the projection on the same section of the top surface of the RIO (section B - B'). From the B - B' section we note that the top of the RIO, apart from being located at higher altitudes, does not dip towards NE as S1.

This situation does not allow for an unambiguous interpretation. One could speculate that tectonic movements have induced changes in the river network. After the shaping of the erosional surface that corresponds to the top of the RIO, tectonic deformation induced a diversion towards the NE of the Ponara and Rotaldo streams that started to shape S1. Equally acceptable is the assumption that both the top of the RIO and of S1 were shaped by a drainage network having the same direction and that the current slopes of the terraces were pro-

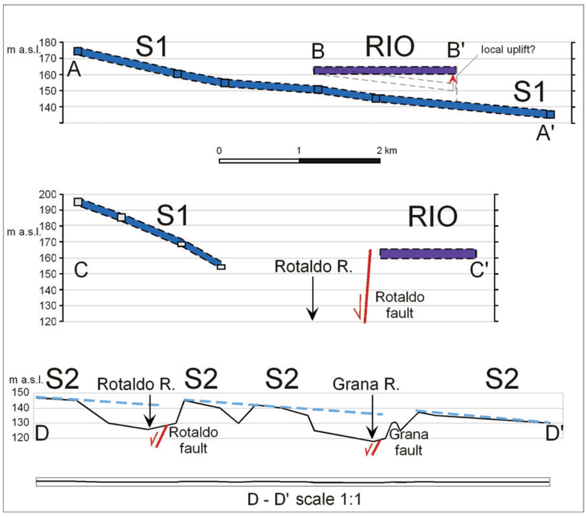

Fig. 8 - Cross sections through the terraces S1, S2 and the top of the RIO.

duced subsequently by differential tectonics. In any case, the evolution implies Quaternary tectonic deformations.

Because the RIO's north-western side lies near the Rotaldo Fault and is parallel to it and other major faults transverse to the Monferrato Front (Terruggia and Giarole faults) we can assume that the trend of that side was conditioned by the Quaternary activity of the Rotaldo Fault.

The lack of dip towards NE of the top of the RIO (Fig. 8) may be due to the activity of the Occimiano Thrust Fault, located at the base of the north-eastern slope of the RIO, which would have produced the uplift of the area.

After the shaping of the top of the isolated hills and of terrace S1, a stream fed at least by the Rotaldo and Grana valleys flowed to the ESE and east, in the area between the hills and the southern slopes of RIO, RIM and RIP, and started to form the S2 terrace. The S2 terrace lies, at least up to Valenza, on the axial zone of the Castello di Lignano and Villabella Synclines. It can therefore be assumed that the synclines were active and affected the drainage network at least until the late Middle Pleistocene.

The presence of several sectors of the S2 surface, separated by transverse river incisions and located at different altitudes, also suggests that the shaping of the terrace may have been complex, non-uniform and, in detail, not even contemporary in all its extension. In fact, a topographic profile oriented WNW to ESE (Fig. 8) shows that S2 is located at altitudes not compatible to the west and to the east of the Rotaldo and Grana faults.

The diversion towards the NE of the Rotaldo and Grana streams shown by the S2 terrace, could evidence that the differential tectonics started to prevail. After the diversions and the sedimentation of the fluvial deposits that form the surface S2, the streams started to down-cut the valleys. The colluvia observed on the RIO slope confirm the erosion and suggest that the main erosion phase ended with the aggradation of the present valley-bottom and the alluvial sediments that occurred during the late Upper Pleistocene-Holocene. The erosion was probably triggered by the uplift of all the area where S2 lies. In fact, if the shaping of S2 and of the older terraces was produced by the climatic cycles, a near continuous belt of terraces having the same age should surround the Northern Monferrato hillslope, from Casale Monferrato to Turin: as explained before, such terraces do not exist.

Therefore, the evolution of the drainage network suggests that the phase of deformation, due to structures connected to the thrust front, likely continued after the late Middle Pleistocene.

The Tertiary sediments outcropping in the Po riverbed (Fig. 4) near the thrust front north of the RIP (Fig. 9), and west of Casale Monferrato seem to confirm that an erosion surface on the bedrock is evolving even today and that the uplift near the front could still be active.

The plain east and south-east of Casale Monferrato deserves separate discussion because the evidence of tectonic deformation is more ambiguous.

The presence of an erosion surface (the *platea*) also under the sediments of the southernmost T4 terrace could suggest that the erosion, and then the uplift, acted up to the late Upper Pleistocene. However, since the shaping of this erosion surface is due to the Po river, it could be just lateral erosion of Tertiary sediments easy to erode.

For this area (Fig. 4) the coincidence between the

Fig. 9 - The Po river bed NE of the Pomaro-Montevalenza isolated hill. The small waterfalls in the river bed (right) evidence the plane-parallel layers of Tertiary sediments. In the background (left), the northern slope of the isolated hill can be observed.

almost straight trend of a stretch of the boundary between T4-2 and T4-3N, and the buried structures at the margins of the *platea,* have already been highlighted. It is possible that the boundary between T4-2 and T4-3N is the consequence of a tectonic deformation and that the higher surface (T4-1) derives from the tectonic deformation of the top of T4. In this case, one should assume a tectonic mobility more recent that the Upper Pleistocene.

Even though it is parallel and in part superimposed on thrust fronts, the possibly uplifted area crosses the Roncaglia Fault and extends also in an area of prevailing subsidence during the Quaternary. The uplift could have been produced by tectonic movements at least in part different from those linked to the Monferrato Front.

The diversion to the east and NE of the Po river at Casale Monferrato (abandoned bed in Fig. 4) is compatible with the hypothesis of tectonic deformation of T4. However, there are no clear morphological elements that can confirm the uplift of the area in periods before the Upper Pleistocene. The absence of traces of an older uplift may be due to river erosion, but it can also be explained by assuming that the tectonic deformation started or intensified during the Upper Pleistocene.

The location of T5 shows some elements worth being discussed. First, from Casale Monferrato to the area of the RIP, T5 is located between T4, to the south, and a terrace, equivalent to T4, to the north of the Po river (Fig. 2). From the RIP area to the SE, T4 is lacking and it may have been eroded or it was never formed as a result of the evolution of the hydrographic network. In this area T5 reaches the escarpment of the Valenza plateau (S2).

Precisely in the area where it crosses the Monferrato Front NE of the RIP, the Po river, which flowed into the central portion of T5, migrates to the SW following the scarp of the Valenza plateau to its end, and then flows to the east, again crossing the front.

The distribution of the terraces and the position of the Po river suggest that the Late Pleistocene and Holocene river migration could also be influenced by tectonics and that the migration of the river to the S and SW was triggered by the uplift of an area east of the RIP. This uplift concerns an area partially outside the buried Monferrato Front and it is not clear whether the assumed relative uplift is an indication of the ongoing compressive tectonics or if it is linked to other causes.

Overall, the Upper Pleistocene and Holocene morphological elements that may suggest tectonic mobility are open to more than one interpretation. If they were in fact produced by tectonics, they would not be fully compatible with some older morphological features clearly conditioned by tectonics.

The observations about the edge between the terrace S2 and the hillslope, mentioned earlier (Fig. 4; 5), can be used in order to prove the relations between the tectonic activity and the morphology. The different position of the boundary between the terrace and the hillslopes at the mouth of some valleys could be due to the displacement of the hillslope produced by transversal tectonics active before and, probably, also after the shaping of the T2 terrace.

In correspondence with the Giarole-Lu Deformation Zone, at least two of the changes in the position of the boundary between S2 and the hillslope (Fig.4) occur NE of two abrupt changes in direction of the divide between the Po and Tanaro basins and of the deformation of the axes of two anticlines (Fig. 4). All these morphological and geological features are compatible with the movements of the left-slip Giarole-Lu Deformation Zone (GLDZ in Fig. 4). The Deformation Zone runs from the thrust front to the hills south of the watershed and reaches at least 15 km in length.

The anomalies of the boundary between S2 and the hillslope in the area SSE of the RIP lie on the Valenza Deformation Zone (Fig. 4): the westernmost one lies north of a divide deviation and near the change of the direction of the anticline formed by Messinian and Tortonian sediments, while the easternmost one lies on the southern prolongation of the Valenza Fault, on the northwards prolongation of the NNW-SSE anticline and north of a noticeable deviation of the divide. These morphological and geological features are all compatible with dislocations produced by right-slip Valenza Deformation Zone (VDZ). The length of the deformation zone reaches, at least, 13-14 km.

One of the anomalies in the boundary between S2 and the hillslope is at the Rotaldo Valley mouth and lies on the Rotaldo Fault. South of this anomaly, on the possible prolongation of the same fault, there is a clear deviation of the divide and the western boundary of the area of anomalous contact between Pliocene and pre-Messinian sediments.

The joint activity of the Giarole-Lu (left-slip) and Valenza (right-slip) Deformation Zones would have produced the northward advance of the thrust front north of the RIP and of the area located between them.

The direction of many streams across the Valenza plateau, connected with the Holocene T5 terrace, is the same as the geological structures forming the Giarole-Lu and Valenza Deformation Zones. It follows that contractional tectonics may have been still active during the Upper Pleistocene and Holocene or, more likely, that the streams have retained the direction induced by tectonic structures that were active during the late Middle Pleistocene or early Upper Pleistocene.

In summary, the phase of deformation related to tectonic contraction of the Monferrato Front lasted, most likely, until the late Middle Pleistocene or early Upper Pleistocene. Only in the areas of Casale Monferrato and of Frascarolo did some tectonic movements, which may not be linked with certainty to the Monferrato Front, possibly occur during the Upper Pleistocene and Holocene.

Even in the adjacent Vercelli Plain, Upper Pleistocene and Holocene deformations have been observed, partially or totally independent from the Monferrato Front (Giraudi, 2014). In the Vercelli Plain, where the sedimentary units are much more abundant and better dated, the end of tectonic contraction took place mostly around or before 400 ka BP, and in any case could not be more recent than 280 ka BP, while the deformations independent from the thrust front were particularly intense during the last 140 ka BP.

The chronology of the Eastern Monferrato Front seems to indicate a significantly more recent age for the end of tectonic contraction. The morphological differences between the two zones confirm the different tectonic evolution, excluding the risk that the different chronology of the movements was caused by the approximation of the dating of the sediments and not by a really different evolution.

4.3. Tectonic zonation of the Po Plain and the Eastern Monferrato area

Overall, the area where the higher terraces and isolated hills lie could thus be divided into four parts with different Quaternary tectonic features (Fig. 10).

- The easternmost area, from the Valenza Deformation Zone to Rivarone, is formed only by the terrace S2 and was uplifted at least after the late Middle Pleistocene or early Upper Pleistocene.
- The eastern area, formed by the plain and the hills, situated between the Giarole-Lu and Valenza Deformation Zones and the thrust front north of the RIP, underwent a migration to the north, at least from the Lower Pleistocene to the end of the late Middle Pleistocene or early Upper Pleistocene and an uplift that lasted until the period following the shaping of S2. In this framework, the Villabella Syncline was able to influence the late Middle Pleistocene or Upper Pleistocene drainage network that developed on the S2 terrace.
- The central area, i.e. the plain located between the Giarole-Lu Deformation Zone and the Rotaldo valley and the adjacent hills, is affected by the Rotaldo, Grana and Occimiano faults and the Borgo San Martino Syncline, and is disjointed into various sectors. The tectonic activity lasted until the late Middle Pleistocene or early Upper Pleistocene. The Roncaldo Fault forms the western boundary of the area. The Grana Fault seems a normal fault, because it is not associated with morphological anomalies suggesting horizontal displacements. In this tectonic frame, the Occimiano Fault may correspond to the thrust front segment that seems to be lacking between the fronts lying near Casale Monferrato and NE of the RIP.
- The western area, i.e. the plain lying NW of the Roncaglia Fault and the adjacent hills, would have been subject to an uplift that started around 600 ka BP, after the sedimentation of the Fluvial-Lacustrine Unit dated between 1000 and 600 ka BP. Precisely that uplift could have halted the flow of the Alpine river that drained the Cerrina Valley. The uplift continued until the period subsequent to the shaping of S2. Even if the Roncaglia Fault could be of strike-slip or oblique type, in this area there are no morphological features suggesting the activity of strike slip or oblique-slip faults during the late Middle Pleistocene or later.

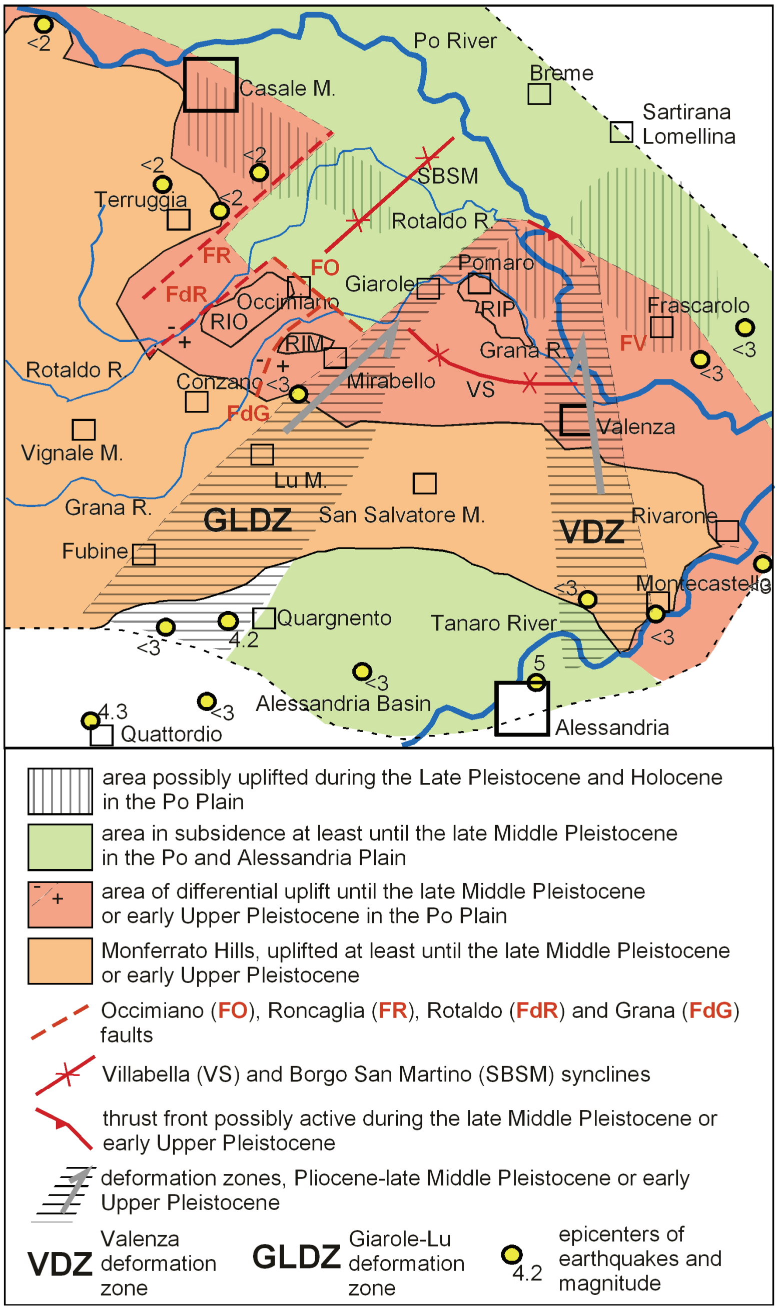

Fig. 10 - Tectonic movements affecting the area studied until the late Middle Pleistocene or early Upper Pleistocene.

The disarticulation in tectonic blocks of the area between the Giarole-Lu Deformation Zone and the Roncaglia Fault, and the subsidence of the Borgo San Martino syncline, may indicate that the central area represents a junction between the NW part, free of late Middle Pleistocene strike-slip movements and the eastern zone where such movements were active.

While the activity of strike-slip faults ended earlier in the western part (Roncaglia Fault) and did not occur east of the Valenza Deformation Zone, the uplift of the terraces and the hills seems mainly coeval from west to east.

However the presence of the older morphological features (isolated hills and S1 terrace) only in the area west of the Valenza Deformation Zone suggests that the uplift of the (now) terraced plain started in the west and that the deformation zone probably played a role as a boundary of the uplifting area.

The Po Plain, corresponding to the T4 and T5 terraces (Fig. 4), shows Quaternary subsidence north of the thrust fronts and on the Borgo San Martino syncline. The subsidence is known to have affected the Po basin foredeep during the advance of the thrust fronts (Dela Pierre et al.,1994). However some morphological features suggest the possibility of late Upper Pleistocene vertical movements near or outside of some stretches of the thrust fronts.

5. TESTING THE HYPOTHESIS OF LATE MIDDLE PLEISTOCENE OR EARLY UPPER PLEISTOCENE THRUST FRONT ACTIVITY: OUTLINES OF THE QUATERNARY EVOLUTION OF THE ALESSANDRIA BASIN

In order to test the hypothesis that compressive tectonics continued at least until the late Middle Pleistocene or early Upper Pleistocene, we can analyze the Quaternary evolution of the Alessandria Basin suggested by bibliographic data.

As noted before, the Alessandria piggyback basin subsided as a result of the northward migration of the Monferrato Thrust. If the migration northward had continued until at least the late Middle Pleistocene or Upper Pleistocene, south of the Eastern Monferrato hills the geological evolution of the basin is expected to show evidence of subsidence up to the same period.

The data for the interpretation of the evolution of the Alessandria Basin are reported in Anfossi et al. (1969).

Observing the terraces in the Alessandria Basin (Fig. 11), one can notice that they were formed by rivers that flowed towards the centre of the basin, that is, towards the area where the thickness of the Pliocene-Quaternary sediments is greater. Figure 11 shows that, generally, only the oldest terraces of the tributary rivers of the Tanaro (FL1, of undefined Pleistocene age, according to Anfossi et al., 1969) join the hillsides formed by marine Tertiary and Villafranchian sediments, and that the lower terraces (FL2, FL3-a1 a2-1; a3) are included between the older terraces and the centre of the basin. This means that the centre of the basin subsided more than its borders.

The contact zone between the northern margin of the Alessandria Basin and the southern slopes of the Eastern Monferrato, an area which is located just south of the hills lying between the Giarole-Lu and Valenza Deformation Zones, is an exception.

In this area the oldest terrace is lacking and it is the FL2 terrace, attributed to the "Middle Fluvial", Pleistocene in age, by Anfossi et al. (1969), that joins the hillslope. The anomaly can be explained by the subsidence of this part of the plain which lasted, at least, until the sedimentation of the fluvial deposits which form the FL2 terrace.

The subsidence of the area is also confirmed by the thickness of the Quaternary fluvial sediments. According to the maps shown in Irace et al. (2009), the thickness of the fluvial sediments forming FL2 south of the hills lying between the Giarole-Lu and Valenza Deformation Zones is greater than 20 m, while in the adjacent western area the thickness is 10 m or less.

The contour lines show that the base of the Pliocene reaches its maximum depth SE of Alessandria, exactly south of the hills lying between the Giarole-Lu and Valenza Deformation Zones.

If the subsidence is due to the northward migration of the Monferrato thrust front, we can assume that the thrust was active at least until the shaping of the FL2 terrace.

The dating of the terrace FL2, then, is the key to determining the age of the last phases of subsidence. However there is no direct dating of deposits that form the terraces and the chronological framework reported in Anfossi et al. (1969) is based on the relative position of the terraces and on the degree of pedogenesis.

In a study on the surroundings of Asti, just west of the area reported in the present paper, Carraro & Valpreda (1991) show that the terraces corresponding to FL2 of Anfossi et al. (1969) have, at their top, a yellowish soil with a colour index of 7.5 YR MSCC. In the area at the northern edge of the Alessandria Basin according to Ajassa et al. (1997), the thickness of the soil does not exceed one metre.

According to Arduino et al. (1984), this kind of soil can be compared to that which developed in the late Middle Pleistocene or early Upper Pleistocene. It follows that the aggradation of the sediments finished before that period. Cortemiglia (2012) assumes that the sediments forming the terrace FL2 were deposited between 220 and 128 ka BP and weathered in the period between 128 and 115 ka BP.

The age of the sediments FL2, therefore, is not very well determined, ranging from late Middle Pleistocene to early Upper Pleistocene, but it is similar to that of the fluvial deposits that form the surface S2 of the Valenza Plateau. The subsidence of the Alessandria piggyback basin in the area south of the Giarole-Lu and Valenza Deformation Zones continued at least until the late Middle Pleistocene or early Upper Pleistocene and seems to confirm the age of the northward compressive tectonics and of the uplift of the area just north of the hills.

6. DATA ON SEISMICITY AND ASEISMIC DEFORMATIONS

In some areas covered by this study, geodetic measurements have been carried out and stations of the GPS network are located. The seismic catalogues (Rovida et al., 2011; RSNI, 2014 a, b) report the earthquakes recorded in the area.

In the paper by Arca & Beretta (1985), the uplift rate of the Casale Monferrato area is reported. The uplift rate was obtained by means of a comparison of the data

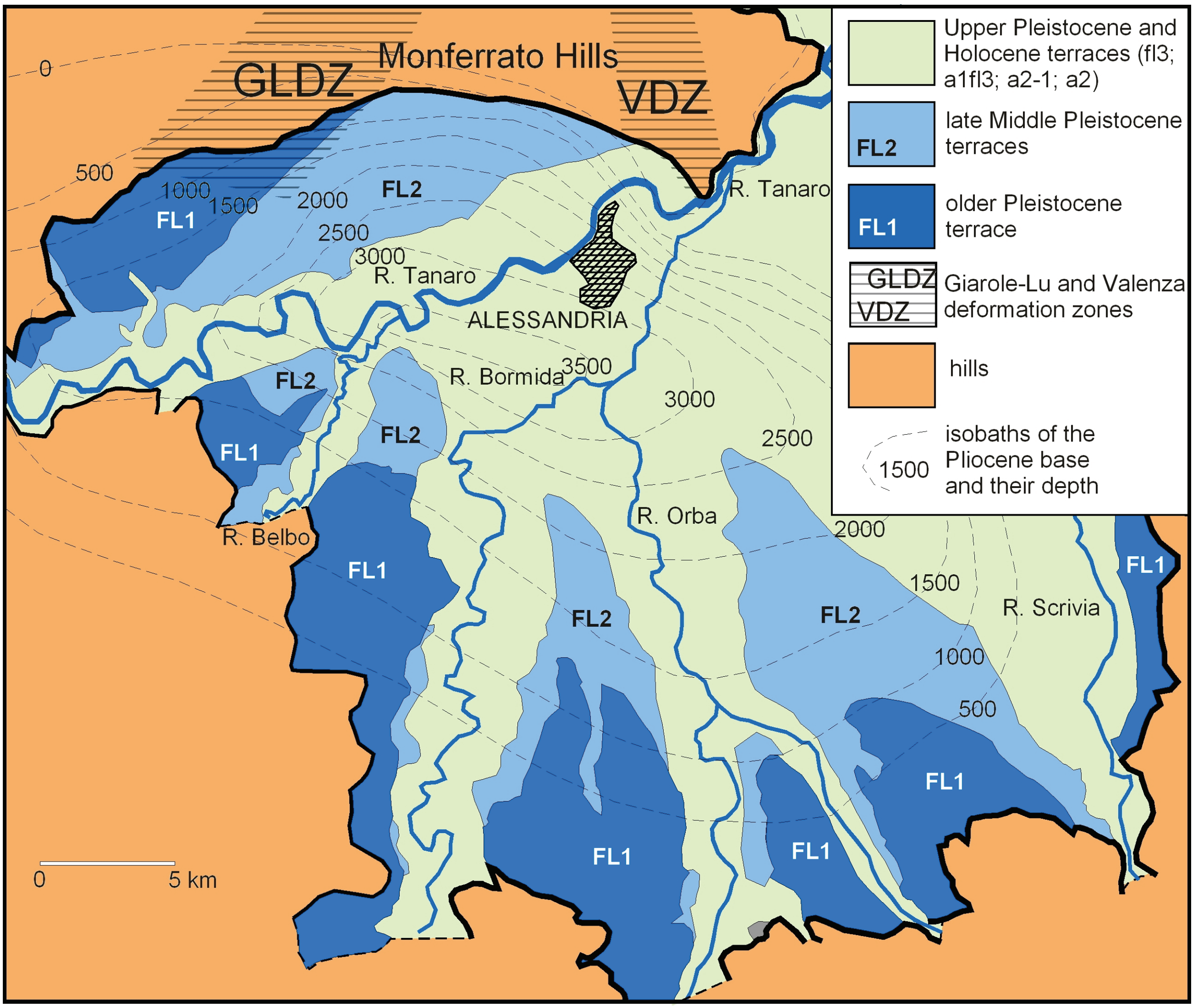

Fig. 11 - Terraces surrounding the Alessandria Basin (redrawn from Anfossi et al., 1969) and contour lines of the base of the Pliocene (redrawn from Bigi et al. (1990).

from detailed geodetic measures carried out in 1897 and in 1957 AD.

In particular, the points lying on a section from Casale Monferrato to Vercelli, crossing the Monferrato Thrust Front, indicate an uplift rate of 4.32 mm/yr^{-1} in the town of Casale Monferrato (south of the front) on the T4 surface, and of 1.37 mm/yr^{-1} at Villanova Monferrato, located north of the thrust front. The area south of the Monferrato Front has an uplift rate three times greater than the area north of it.

However, the section does not permit a three-dimensional interpretation and it is therefore not possible to determine whether the deformation took place exactly on the front, or along other structures transversal to the front.

In any case, between the two surveys no strong earthquakes occurred in the area and thus the deformation was completely aseismic or connected with non-recorded earthquakes of very low magnitude. The geodetic datum of Arca & Beretta (1985) would be consistent with the hypothesis of a recent uplift of the area corresponding to the T4 terrace provided by morphological evidence (Fig. 10).

The same paper also reports the uplift rate (1.2 mm/yr^{-1}) measured in Quattordio, on the boundary between the hills and the western edge of the Alessandria Plain (Fig. 10). Also in this area no earthquakes occurred between 1897 and 1957, although one of magnitude 4.2, with its epicentre in Quattordio, struck the area on July 18, 2001 (Rovida et al., 2011; RSNI, 2014 a, b).

The seismic hazard of the area under investigation is considered low because the earthquakes reported by the catalogues are scarce and of magnitude less than or equal to 5 (Rovida et al., 2011; RSNI, 2014 a, b). Some of the epicentres of earthquakes (Fig. 10) of magnitude between 2 and 4.3 are in the Giarole-Lu Deformation Zone or their prolongation to the SW, while only three epicentres, including that of the earthquake that struck Alessandria in 1369 AD (estimated magnitude around 5, the strongest that occurred in the area) are inside, or near, the Valenza Deformation Zone.

Some very low magnitude earthquakes occurred near the buried thrust fronts east of the Valenza Deformation Zone. Few other earthquakes with magnitude less than 3 occurred in the study area or the surroundings.

Studies on the data of the GPS network (Devoti et al., 2011) have shown that the Alessandria Basin has a negative vertical speed slightly greater than -1 mm/yr^{-1} and a horizontal speed towards the northern-western quadrant a little less than 2 mm/yr^{-1}. The movements seem compatible with the migration to the N of the area located between the Giarole-Lu and Valenza Deformation Zones and with the subsidence of the Alessandria Basin, and could support the hypothesis that tectonic activity still occurs in the Monferrato thrust.

7. CONCLUSIONS

The plain between the Po river and the Eastern Monferrato Hills consists of fluvial sediments lying on the Tertiary marine bedrock. The Tertiary sediments are displaced by thrusts and strike-slip or oblique faults produced by the compressive tectonics of the Monferrato Front, the westernmost of the Northern Apennine fronts.

The presence of a nearly continuous belt of terraces at the base of the northern hillslope, of isolated hills formed by tertiary sediments, and the distance between the Po river and the hills are peculiar characteristics of the Eastern Monferrato and immediately suggest some geological differences between the eastern and the westernmost Monferrato-Turin Hills system.

Study of the stratigraphy and morphology has enabled us to advance several hypotheses about tectonic mobility during the Quaternary. However, the absence of well dated morphological and stratigraphic features suitable for the correlation of the terraces affected by tectonic movements precludes any reliable estimates of the deformation rate. The assumptions regarding the type and age of tectonic deformations are summarized below.

- The areas located north of the youngest thrust fronts and the area corresponding to the Borgo San Martino Pliocene Syncline mainly subsided during the Quaternary. On the other hand, starting at about 600 ka BP, the area of the isolated hills RIO, RIM and RIP and S1, S2, S3 terraces suffered an almost continuous uplift until the late Middle Pleistocene or early Upper Pleistocene. The dataset makes it possible to assume that compressive tectonics were active at least until that time, and could still be active.
- The tectonic interpretation of the contour lines of the depth of the Pliocene base and the comparison of the altitudes of the top of isolated hills and terraces suggest that the areas where the uplift prevailed were affected by faults transverse to the thrust fronts, and subject to differential movements.
- The overall interpretation of the tectonic structures lying below the plains and affecting the hills allow us to assume (Fig. 4) that there are normal faults (Roncaglia, Rotaldo and Grana faults) and two deformation zones (Giarole-Lu and Valenza Deformation Zones) where strike-slip or oblique-slip faults that make up the thrust ramps were active until the late Middle Pleistocene or the early Upper Pleistocene. In the first deformation zone (Giarole-Lu Deformation Zone) ccurred some left-slip displacements, while in the second one (Valenza Deformation Zone) some right-slip deformations would be present. The tectonic movements along the two deformation zones would result in an advance towards the north of the thrust front near the RIP. The Villabella Syncline evolution and the subsidence of the northern Alessandria Basin between the two deformation zones would be connected with the northward shift of the thrust front.
- The age of the sediments affected by subsidence in the Alessandria piggyback basin corroborate the hypothesis that the activity of the Monferrato Front continued at least until the late Middle Pleistocene or the early Upper Pleistocene.
- The horizontal and vertical deformation rates obtained by the Alessandria GPS station seem compatible with the hypothesis of a shift to the north and with a subsidence still in progress.
- The morphology and distribution of the most recent terraces lying north of the hills suggest that some sectors of the Po Plain may have been affected by upper Pleistocene and Holocene tectonic movements. These areas include Casale Monferrato which underwent a remarkable aseismic uplift during the twentieth century. The possible tectonic mobility of these areas could have been independent from the main structures of the Monferrato Front.

The possible end of the compressive tectonics and the beginning of the deformations related to structures wholly or partly different from those that form the buried Monferrato Front seem to confirm the findings of the study of the Vercelli Plain (Giraudi, 2014). In the plains north of the Eastern Monferrato area, however, contractional tectonics would be more recent or still active.

It was already known (Pieri & Groppi, 1981; Cassano et al., 1986; Costa, 2003; Burrato et al., 2012; Galadini et al., 2012; Galli et al., 2012; Michetti et al.,2012) that tectonic activity on the three main fronts of the Northern Apennines increased from west (Monferrato Front) to east (Emilian and Ferrarese Fronts). The results of the present study indicate that also in the Monferrato Front the eastern portion shows greater mobility in a very recent period.

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