



THE EVOLUTION OF THE NORTHERNMOST APENNINE FRONT (PIEDMONT, ITALY): PLIO-PLEISTOCENE SEDIMENTATION AND DEFORMATION IN THE PO BASIN AND MONFERRATO HILLS

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ABSTRACT: The area under investigation includes the southern Vercelli plain and the lower Cerrina valley, in the northern central Monferrato hills. The comparison between the deformation of the sediments of the foredeep basin, north of the Monferrato thrust front, and of the Cerrina valley syncline, south of the front, enabled our understanding of the Pliocene and Pleistocene environmental and tectonic evolution to be improved. The study of the Plio-Pleistocene sedimentary successions allowed the phases of subsidence and deformation produced by the compressive tectonic to be dated. The subsidence involved the Po foredeep basin and the Cerrina valley syncline during the same periods, but with different intensity. A first phase of subsidence occurred before the sub-chron Olduvai, while the second phase can be dated between about 1.5 and 0.5 MA ago, but the maximum subsidence rate occurred around 1.07 and 0.99 MA ago. Also the main deformation phases of the Cerrina valley syncline are coeval with the activity of the Lucedio and Cavourrina faults, that correspond to two different buried thrust fronts.

The Lucedio fault is linked to the Gaminella-Cerrina valley syncline through the NW-SE trending Crescentino fault (west) and the N-S trending Salera Line (east) acting as ramps, while the ramps linking the Cavourrina fault to the syncline are the NNE-SSW trending Fontanetto Po (west) and the N-S trending Trino (east) deformation zones. The tectonic frame indicates that the syncline corresponds to a trough behind the thrust front.

However, the asymmetry of the Cerrina valley in its stretch with a W-E orientation, and the presence of a sequence of terraces only on the northern side, suggest that the hills north of the valley were gently uplifted at least until the upper Pleistocene. It follows that the syncline may have acted, until very recent times, as a boundary between two hilly areas (north and south of the valley) subject to different tectonic evolution.

The results of the research suggest that the river, which entered the Cerrina valley during the Early and Middle Pleistocene, was probably fed by the Alpine valleys lying SW of the Aosta valley, or a collector of the streams that drained the Northern Monferrato.

Keywords: Vercelli plain, northern Monferrato Hills, Cerrina Valley, Po foredeep basin, Monferrato thrust front, Plio-Pleistocene marine and continental sediments, geological and tectonic evolution

1. INTRODUCTION

The Monferrato and Turin hills are extensions to the NW of the Northern Apennine (Fig. 1A). Behind the Monferrato thrust fronts, active also in Plio-Quaternary times (Fig. 1B), deep piggyback basins are present: the subsidence in the basins was contemporary with the compressional tectonic (Dela Pierre et al., 1995; Irace et al., 2009).

The Monferrato-Turin Hills thrust front is formed by three stretches with different characteristics.

The eastern Monferrato thrust front (Fig. 1B) was active until, at least, the late Middle Pleistocene (Giraudi, 2015a) and in the hills south of the front, according to Livio et al. (2015), some tectonic deformations occurred also during the Holocene. South of the eastern Monferrato lies the Alessandria basin, which seems to be subsiding also during the present time (Devoti et al., 2011).

South of the front of the Torino Hills and the western Monferrato (Fig. 1B), active in Plio-Pleistocene times (until Early or Middle Pleistocene, according to Pieri & Groppi, 1981; Cassano et al., 1986; Galadini et

al., 2012; Galli et al., 2012), lies the Saluzzo basin, which subsided during the same period.

The central Monferrato thrust front (Fig. 1B), buried under Quaternary sediments of the Po plain between Crescentino and Trino, was active in more recent times than the western one (Dela Pierre et al., 2003a;b). Near Trino, the compressive tectonic ended before 300 ka BP (probably around 400 ka BP) according to Giraudi (2014). According to Michetti et al. 2012 and Burrato et al. 2012) the compressive tectonic could still be active.

The boundary area between the Saluzzo and Alessandria basins, called the Asti basin in the present paper (Fig. 1B), lies south of the Central Monferrato front. The Asti basin was subsiding until the early Pliocene but from the middle Pliocene the area underwent a slow uplift (Dela Pierre et al. 2003a;b). It is clear that after the Early Pliocene the Asti basin ceased acting as a piggyback basin and no correlation with the later compressional tectonic of the central Monferrato thrust front can be assumed.

In the hilly area located south of the Trino front, however, there is an area where continental sediments, contemporary with the phases of thrust activity, are out-

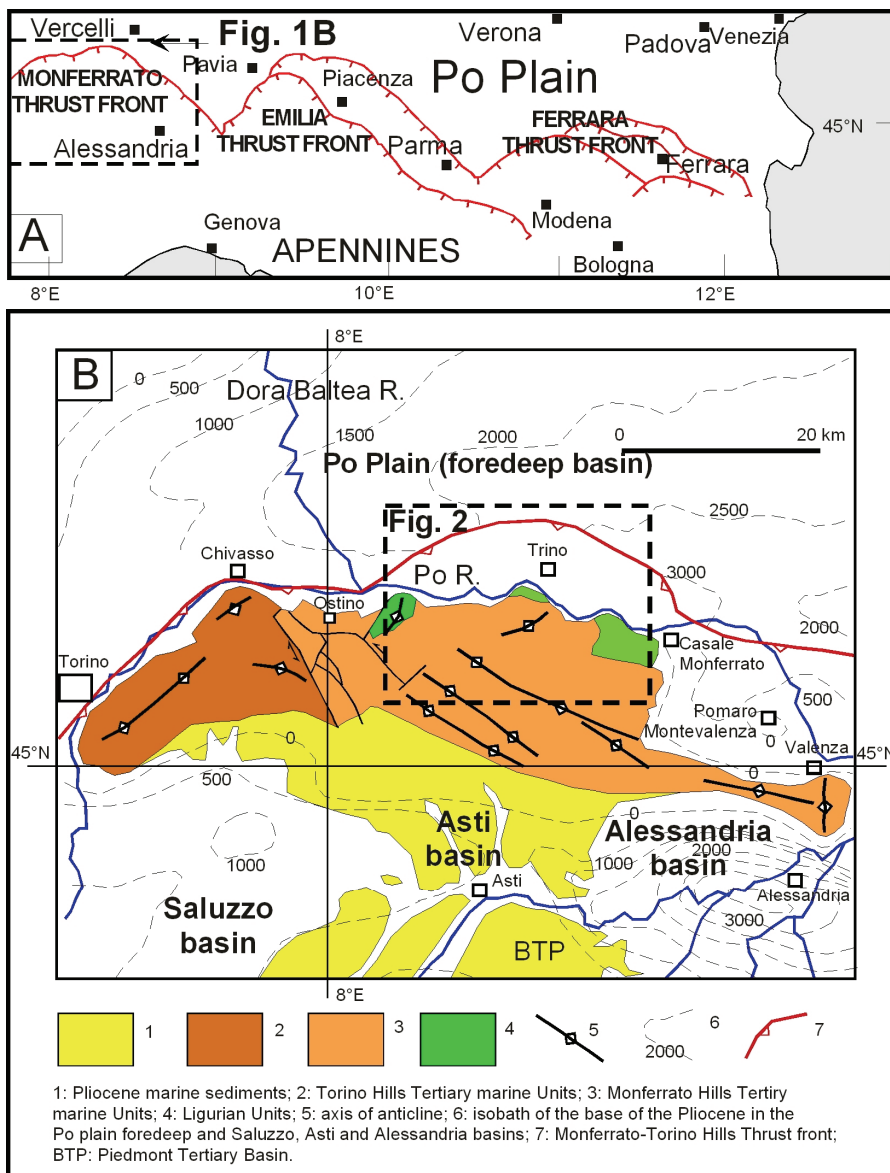


Fig. 1 - Geological sketch of the Monferrato and Turin Hills. 1A: main Northern Apennine thrust fronts. 1B: geological and tectonical outline of the Monferrato and Torino Hills with isobaths of the Pliocene Base in the Saluzzo, Asti and Alessandria basins (south of the hills) and in the Po foredeep basin (north of the hills). Modified from Dela Pierre et al. (2003a).

cropping: the lower Cerrina valley.

The preliminary comparison between the tectonic and sedimentary evolution of the basin north of the thrust front and of the lower Cerrina valley enabled it to be assumed that the valley, after the Lower Pliocene, became a tectonic trough produced by the migration of the front (Giraudi, 2015b).

The aim of the present paper is to discuss the tectonic evolution of the thrust front and to make a more detailed comparison between the evolution of the foredeep basin north of the thrust front and that of the Cerrina valley, in order to verify the reliability of some hypotheses reported above and to improve the understanding of the Pliocene-Pleistocene evolution of the Monferrato front and define its chronology.

The conclusions reached below are based mainly on data reported in literature supported by the stratigraphy of some boreholes drilled in the Cerrina Valley and on the presence of tectonic structures affecting Tertiary sediments outcropping in the Po riverbed.

The area under investigation includes the southern Vercelli plain and the lower Cerrina valley, that is the valley of the Stura di Monferrato stream (Fig. 2).

About the Vercelli plain, the present paper will present and discuss mainly the data for the Pliocene and Pleistocene marine sediments and Early Pleistocene continental sediments, because in a previous paper (Giraudi, 2014) the activity of the front during the past 870 ka was already discussed.

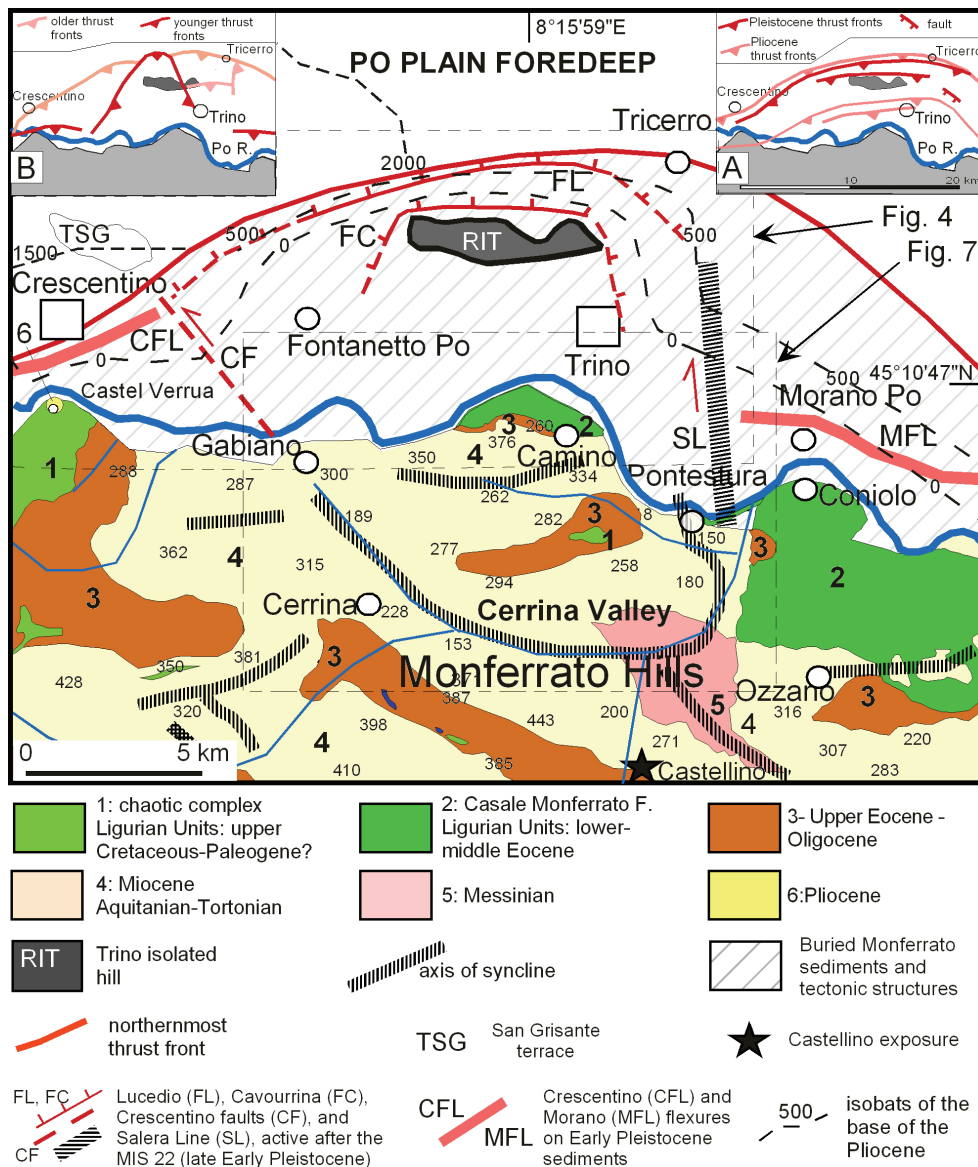


Fig. 2 - Geological map showing the main tectonic structures of the Central Monferrato hills and of the Buried Monferrato underlying a thin cover of Quaternary sediments. The figure shows only the thrust fronts, faults and flexures affecting the Buried Monferrato during the Pleistocene. In Fig. 2A and 2B, all the buried structures according to ENEL (1984) and Bigi et al. (1990) are drawn.

2. METHODS

In order to achieve the results necessary to improve knowledge of the Pliocene-Pleistocene evolution of the Monferrato front, in the present study is an analysis of the data available in the literature integrated by some new data from field surveys.

For the Cerrina valley, the bibliographic data are based on field surveys, studies on artificial outcrops and stratigraphies of cores taken in some boreholes, on the fossil content, and on dating with the method of the racemization of the amino acids on the remains of vertebrates (Giraudi, 1981; ENEL, 1984; Dela Pierre et al., 2003a,b; Giraudi et al., 2003; Siori & Sala, 2007). New field surveys have been carried out in the Stura river-

bed.

For the stratigraphy and tectonics of the Pliocene and Pleistocene sediments which form the Po Valley north of the Monferrato, the data derive from literature (Pieri & Groppi, 1981; ENEL, 1984; Cassano et al., 1986; Bigi et al., 1990; Giraudi, 2014) and from new surveys in the Po riverbed.

During the researches reported in ENEL (1977; 1984), in which the author of the present paper also collaborated, dozens of boreholes were drilled up to 200 m deep, trenches were dug and stratigraphic, micropaleontological and palynological analyses were carried out on the sediments.

The chronology of the Pliocene and Early Pleistocene sediments is also supported by palaeomagnetic

analysis on marine, transitional and continental sediments (ENEL, 1977).

Some tilted bedding plains recognized in cores, lacking any precise orientation, have been used for the only useful datum, that is the value of the dip.

The correlation between stratigraphic sequences in several drillings and the presence in marine and continental sedimentary units of less tilted deposits overlying more tilted ones, have been used in order to evidence some unconformities.

The difference between the stratigraphy of the sediments sampled in alignments of boreholes drilled for just a few tens of metres or, in one case, a few metres apart allowed the presence to be inferred of the Lucedio and Cavourrina faults up to a few metres below ground level (ENEL, 1977; 1984). Also, the direction and the slip of the two faults was evaluated thanks to the alignments of boreholes, without knowing, however, the true dip of the fault planes. Many fault planes have been observed in the cored sediments, but it should be noted that the real dip of the planes remains unknown: the only reliable datum is the value of their tilt.

It has been assumed that at least a part of the fault planes dipping $<30^\circ$ indicate the presence of thrust faults. As a matter of fact, among the various fault planes, those dipping $<30^\circ$ were lying exclusively in correspondence to, or in areas close to, the thrust fronts reported by geophysical surveys.

3. THE PLIOCENE-PLEISTOCENE SEDIMENTARY SEQUENCE OF THE PLAIN NORTH OF THE THRUST FRONT AND ITS PHASES OF DEFORMATION

The southernmost portion of the Vercelli plain is made up of Quaternary sediments, less than 20 m thick, covering Tertiary marine sediments. The latter, similar to those outcropping in the hills that limit the plain to the south, are defined as Buried Monferrato. Compared to the plain which extends north of the Turin Hills and Monferrato, the Vercelli plain is peculiar. In fact the southern Vercelli plain is formed by the isolated Trino hill (RIT) and by a series of terraces that are not present elsewhere (Giraudi, 2014) and the Buried Monferrato goes much further north than in the western and eastern plains. The Buried Monferrato ends at the thrust front.

The tectonic structures that displace the Buried Monferrato sediments are known thanks to geophysical and geological studies based on wells and boreholes drilled as part of oil exploration (Bonsignore et al., 1969; Pieri & Groppi, 1981; Cassano et al., 1986) and seismotectonic studies (ENEL, 1977; 1984). The later Structural Model of Italy (Bigi et al., 1990) suggested a new interpretation of the same structures.

All the papers related to the area of the Buried Monferrato show the presence of a series of thrust fronts, but with various and important differences. Bonsignore et al. (1969) and ENEL (1984) assume thrust fronts with characteristics that are quite similar. In ENEL (1984) a first, northernmost, front was highlighted (Fig. 2A), active until the initial portion of the Middle Pliocene, and a second front, very close to the first, dated to the Late Pliocene- Early Pleistocene. South of this there are three other smaller fronts, whose activity it is difficult to

assess. Also Bigi et al. (1990) indicate the presence of a large northernmost front (Fig. 2B) on which a second front partially overlaps restricted to the area north of Trino. Bigi et al. (1990) also show other thrust fronts that are less extensive and having different direction. The two interpretations of the tectonic structures of the Buried Monferrato appear quite different.

Overall, only the northernmost front and part of the second front located north of the isolated Trino hill (RIT) are accepted by all authors.

However, the data obtained from the boreholes (ENEL, 1977; 1984) show that the Pleistocene tectonic activity is certainly documented only along two stretches of the thrust fronts indicated by the geophysical research, which are known as the Lucedio and Cavourrina faults, which reach near ground level, being covered by only few metres of Middle Pleistocene fluvio-glacial sediments. Therefore in the present paper only the tectonic deformations along the Lucedio and Cavourrina faults and the northernmost thrust front will be discussed.

The interpretation of the geological and stratigraphic data have instead enabled Giraudi (2014) to assume that in the Crescentino and Morano Po areas, on the surface projection of the thrust front highlighted by geophysical studies, faults with any great throw may not be present, and the sediments would be deformed mostly by flexures, at least, to a depth of about 200 m below the ground level (Fig. 2; 3).

The sediments of some cores contain fault planes (ENEL, 1977; 1984). The dip of the planes is variable, from near-vertical to near horizontal. At times the striae suggest strike slip activity. Tertiary layers having cataclastic structures have sometimes been observed.

The fault planes are affecting both Tertiary and Quaternary (Early Pleistocene) sediments (Fig. 4A). Only in one case is a fault at the contact between sediments of different stratigraphic units.

As regards the tilt of the sediments cored in the boreholes, it is observed that the most tilted ones are located near the buried fronts (Fig. 4B). Near the thrust front also the stratigraphic unconformities are much more evident.

To the north of the thrust front is the Po (foredeep) basin consisting of thick fluvio-lacustrine, fluvial and fluvio-glacial sediments covering mainly slightly deformed Quaternary and Tertiary marine deposits (Fig. 3). In the Po basin, thanks to the subsidence, documented during the Pliocene and the Pleistocene (Pieri & Groppi, 1981; Cassano et al., 1986; Dela Pierre et al., 1994), sedimentation has prevailed over the erosion.

It follows that the sedimentary sequence filling the Po basin provides more continuous data and allows for a more reliable interpretation of the geological evolution.

3.1. The Po basin sediments

The Po basin corresponds to the northernmost part of the study area and is filled by continental Quaternary sediments overlapping gently folded Quaternary and Tertiary marine deposits (Pieri & Groppi, 1981; ENEL, 1984; Cassano et al., 1986).

Because the subsurface data discussed in the present paper were collected during the ENEL seismotectonic studies, the chronology of the sediments is the

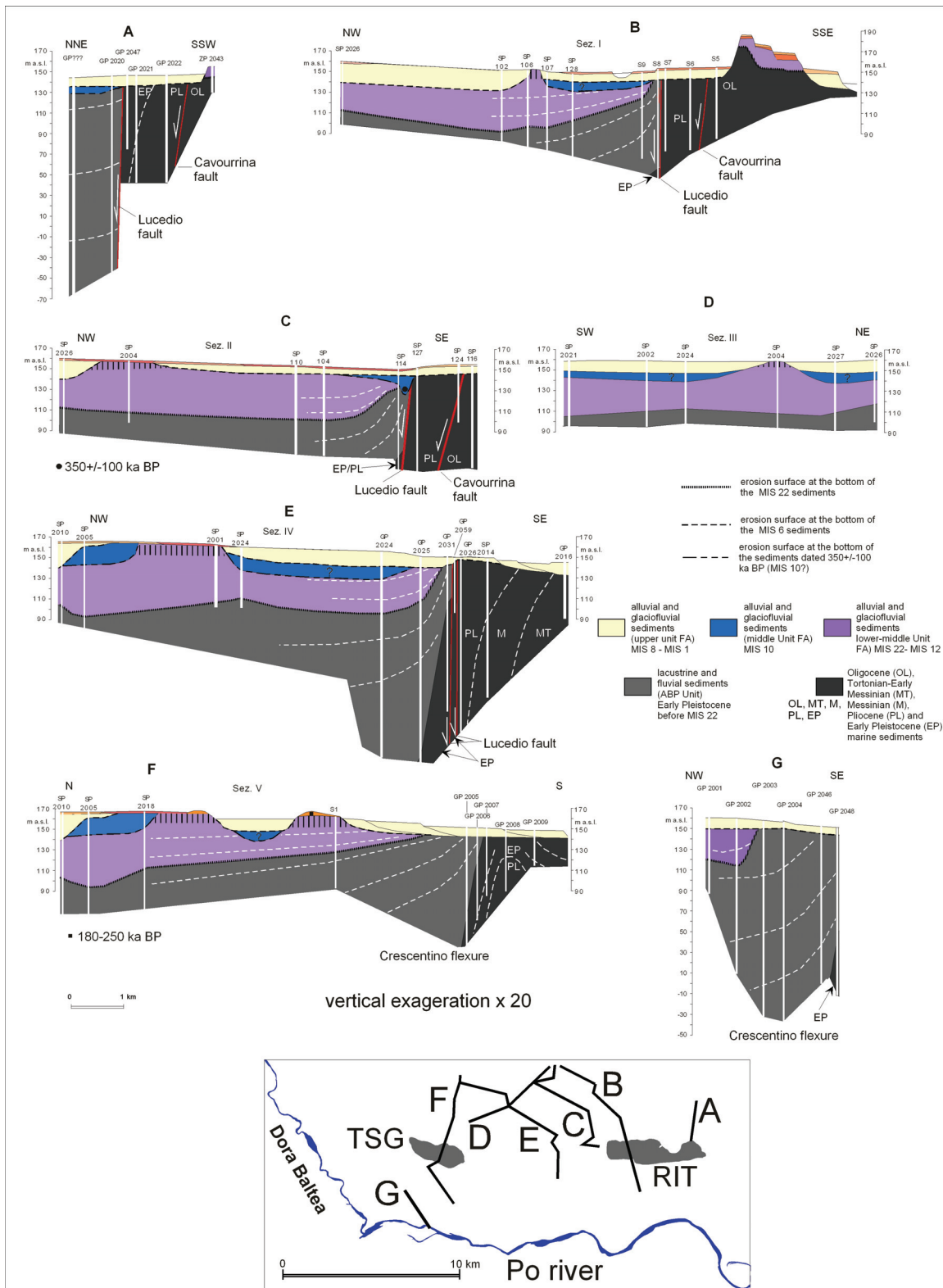


Fig. 3 - Stratigraphic sections through the Buried Monferrato and the Po plain foredeep basin in the southern Vercelli plain.

same as that adopted in ENEL (1984), based on micropalaeontological, pollen and palaeomagnetic analyses. The geological sections shown in Fig. 3 were obtained using the stratigraphies of the ENEL boreholes.

Pliocene and Pleistocene marine sediments, sampled with boreholes in the area of the Po basin north of the front lying between Crescentino and Trino, are represented by the following stratigraphic units (Fig. 3 and 5):

- **Unit M1.** This consists of a monotone sequence of silt locally interbedded with thin sandy layers. According to the malacofauna content, the Unit has been dated from Lower to Middle-Upper Pliocene (ENEL, 1977; 1984). The sedimentary environment varies from lower neritic, at the bottom of the unit, to upper neritic, at the top. The palaeomagnetic analyses (ENEL, 1977) have revealed that the top of the unit presents a reverse polarity, and is therefore attributable to the chron Matuyama with a consequent age of less than 2.58 MA. While at the time of the studies published in ENEL (1977; 1984) the bottom of the chron Matuyama was considered Late Pliocene, currently the same period is considered the base of the Pleistocene (Gibbard et al., 2010), and it follows that the Pliocene-Pleistocene boundary lies in the middle-upper unit M1.
- **Unit M2.** This consists mainly of sands with interbedded silt horizons and, sporadically, gravelly sand, showing a littoral environment (ENEL, 1977; 1984). At the top of the unit, some horizons with reworked fauna may indicate the presence of continental facies. The unit M2 appears in continuity of sedimentation on the M1.
- **Unit M3.** This is formed mainly of sand, generally in centimetres thick laminae which, at their bottom are coarser and interbedded with fine beds of gravelly sand, while upwards they are interbedded with sandy-silt. The facies of the sediments and the fossil content indicate a gradual shift from a littoral marine environment to a brackish water environment (ENEL, 1977; 1984). The unit M3 is transgressive on the units M1 and M2.

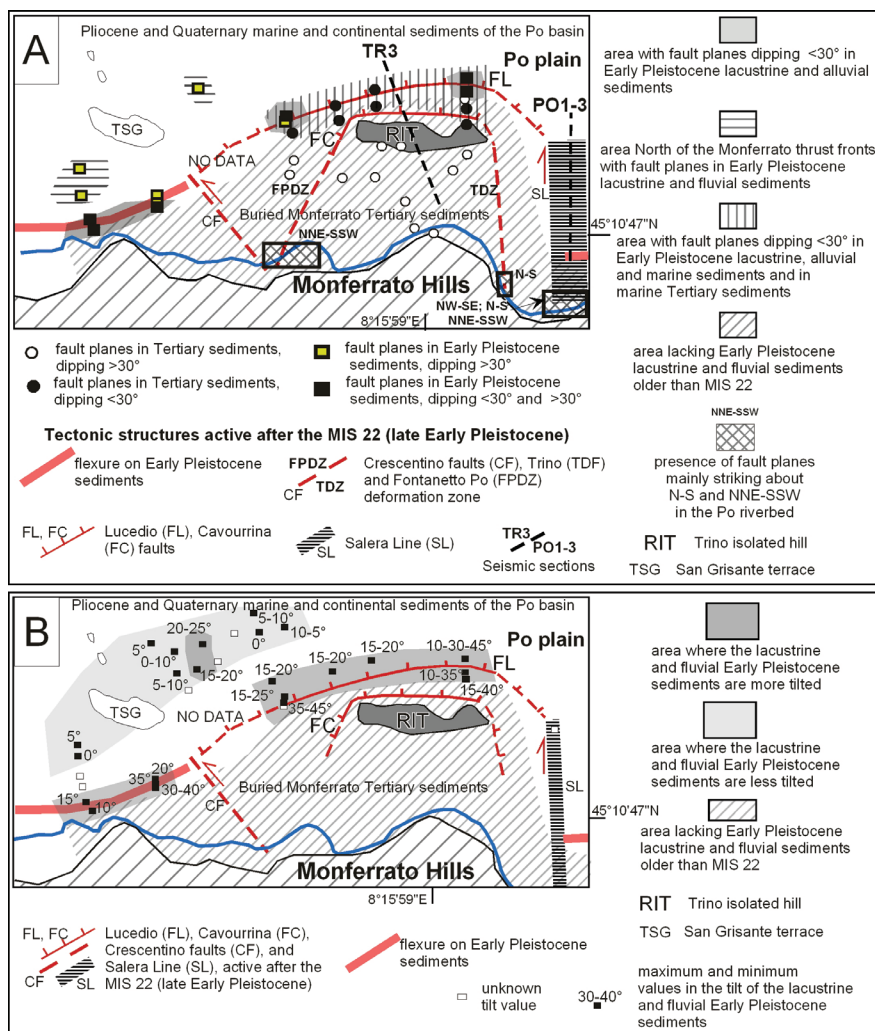


Fig. 4 - Tectonic structures and sediment's deformations below the Vercelli plain. 4A- fault and flexures. 4B- tilt of the sediments.

The stratigraphic units evidenced by the continental sediments of the Po basin are the following (Fig. 3, 4):

- **Unit ABP.** This is made up mainly of silt, containing plant remains and wood, and rarely of sand and gravelly sand. Peat horizons are common among silt and sand layers. The thickness ranges from a few metres to more than 200 m in areas far from the Monferrato thrust front. The palaeomagnetic analysis of the sedimentary sequence indicated that a reverse polarity prevails although there are intervals with normal polarity (ENEL, 1977). Since the unit overlies sediments dated to the chron Matuyama (ENEL, 1984), and older than about 870 ka BP (Giraudi, 2014), the sedimentation of the unit ABP occurred during the Early Pleistocene. Along a belt lying near the thrust fronts, the sediments of this unit are tilted up to 35-40°, but the tilt value becomes lower north of the fronts (Fig. 4B). The only excep-

tion is a small area NE of the San Grisante terrace (TSG in Fig. 4B), at a distance of a few kilometres from the thrust front. In this area the sediments show an anomalous tilt even though there are no known Quaternary tectonic structure that could have produced the tilting.

In some areas, the presence of a greater number of boreholes showed that the unit ABP includes sediments of two sedimentary facies separated by an unconformity:

- **The lower part (IABP)** is made up of clayey silt and sandy silt, with some sandy and, less frequently, sandy gravelly horizons. The sedimentary facies is mainly lacustrine and alluvial. At the top of the IABP sediments, the pollen content suggests that the sedimentation occurred during a cold period (ENEL, 1977). The magnetization of the sediments shows a mainly reverse polarity, with two short periods of normal polarity (possibly corresponding to the sub-chron Reunion I and II). According to ENEL (1977) the sediments of the lower ABP unit should be dated to about 2 MA, and therefore to the Gelasian.
- **The top of the unit ABP (uABP in Fig. 5)** differs from the bottom by the greater abundance of sandy and gravelly horizons of fluvial environment. The pollen content suggests that the climate was cooler than before. The magnetization of the sediments shows mainly reverse polarity. According to ENEL (1977), the sediments of the upper ABP unit are less than 1.8 MA old. The top of the ABP unit, therefore is Calabrian in age. The less tilted uABP sediments lie unconformably on the more tilted IABP ones (Fig. 4B).
In the area of Crescentino, some sandy-gravel levels found towards the top of the ABP unit, at about 40-60 m below ground level, contain brown flint and violet jasper pebbles with a diameter of 7-8 cm. The pebbles of flint and violet jasper were never found in the other boreholes but were present in alluvial gravelly sands of the Cerrina valley, described in Giraudi (1981) and Giraudi et al. (2003), sedimented by a stream, probably Alpine in origin, during the Early Pleistocene (see below).
The whole sedimentary sequence that forms the Unit ABP is displaced by the Lucedio and Cavourrina faults (Fig. 3). Moreover, both near such faults and south and south-east of Crescentino (Fig. 4A), the cored sediments are cut by several fault planes dipping even less than 30°. North of the Lucedio fault, the amount of fault planes is inversely proportional to the distance from the thrust fronts. Therefore, the presence of several fault planes both SW and NE of the St. Grisante terrace (TSG of Fig. 4A) is surprising at a distance of some kilometres from the thrust front, to which the faults do not seem connected.
- **Unit FA** consists mainly of sandy gravel much coarser than the older sediments, fluvio-glacial and alluvial in origin, that form a succession of sedimentary bodies and terraces dated from MIS 22 to the present (Giraudi, 2014). North of the thrust fronts, the base of the FA unit appears deformed by subsidence,

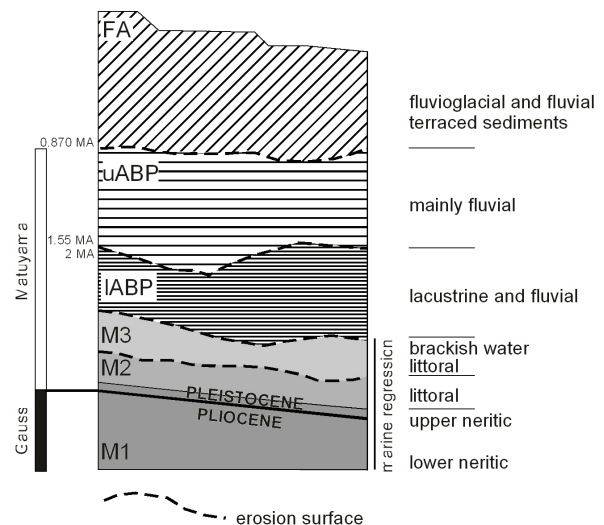


Fig. 5 - Stratigraphic sketch of the Plio-Pleistocene marine and continental sediments drilled in the Po foredeep basin just north of the Monferrato thrust front.

while south of the front the sediments are displaced by the Lucedio and Cavourrina faults.

3.2. Sediment deformation and thrust front activity

The geological sections, drawn up on the basis of the stratigraphic data (Fig. 3), indicate that the area of the basin north of the main thrust fronts was subsiding during the sedimentation of the ABP unit and of the older part of the FA unit.

The Pleistocene sediments (including the oldest part of those in the FA unit) are strongly displaced by the Lucedio and Cavourrina faults (Giraudi, 2014). The faults were certainly active during or after the sedimentation of the lower part of the ABP unit (phase F1), and then in the course of sedimentation of the upper part of the same unit (phase F2).

In the area between the thrust front and the RIT, also the Early Pleistocene tilted continental sediments of the unit ABP have undergone two phases of deformation. The first one (D1), acted before the sedimentation of the upper ABP unit, and in fact the sediments of the lower ABP unit are more tilted than the top of the same unit. The second deformation phase (D2) was simultaneous with and/or subsequent to the sedimentation of the upper ABP unit and caused the tilting of the sediments, the displacements along the Lucedio and Cavourrina faults and the development of low-angle faults.

Along the Lucedio fault tectonic contact took place between Gelasian marine sediments and Calabrian continental ones.

According to the sedimentary facies, the phases of deformation affecting the upper ABP unit in the period before 0.87 MA, certainly related to compressive tectonic, produced no significant changes in the landscape of the Po basin. In the period following 0.87 MA, while the compression phase was still in progress, the area north of the Monferrato front was subsiding and filled by fluvio-glacial and fluvial sediments, but south of the front alternating phases of sedimentation and erosion oc-

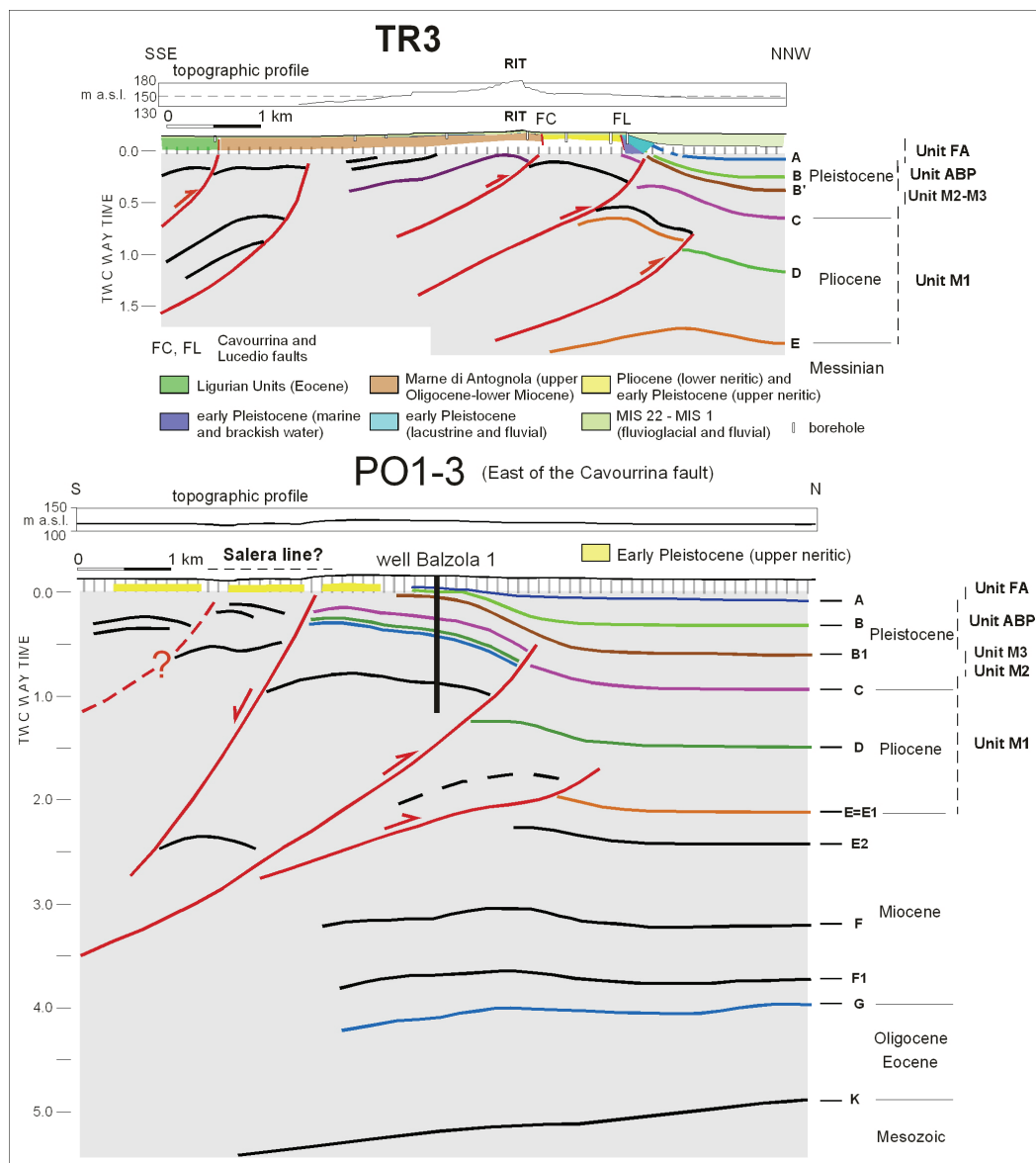


Fig. 6 - Seismic sections through the Monferrato thrust front of the Trino isolated hill and east of Trino. The sections, modified from ENEL (1984), reports also the stratigraphy and chronology of the sedimentary units discussed in the text, and atop of the sections are reported stratigraphic and tectonic data obtained studying cores taken from boreholes.

currered and the oldest terraces of the RIT were shaped. Depending on the age of the sediments that seal the faults of Lucedio and Cavourrina, the thrust fronts would have been active up to about 400 ka BP or, in any case, in a period not more recent than about 280 ka BP (Giraudi, 2014).

4. THE FAULTS DISPLACING THE TERTIARY SEDIMENTS OUTCROPPING IN THE PO RIVERBED

The Tertiary marine sediments that form the Monferrato hills and the Buried Monferrato outcrop extensively in the Po riverbed, and in particular in the stretch north of the Cerrina valley, but have never been adequately studied in terms of stratigraphy and structural

setting. Some brief remarks on the outcrops of the Tertiary substrate in the river are found in Sacco (1889), Lovari (1912), Lupano (1912), Beatrizzotti et al. (1964), and in Dela Pierre et al. (2003 a;b). A small-scale map indicating the Tertiary sediments outcropping in the Po riverbed and their presence in the Buried Monferrato, below a thin Quaternary cover, is also reported in Giraudi (2014) together with the presence of the Crescentino fault and the Salera Line.

A description of the outcropping bedrock is outside the scope of this paper; however, during the field surveys faults were observed that may have played a role in linking the Cerrina valley syncline with the thrust fronts. The field surveys were carried out mostly N and NW of the head of the valley Gaminella-Cerrina basin

and in the area of the confluence of the Cerrina valley in the Po plain.

The fault planes identified affect layers deformed by folds, which could prove greater tectonic complexity than that hypothesized only on the basis of the few exposures in the adjacent hills. From the area east of the Crescentino fault (Fig. 4A) to the area north of Gabiano, there are several faults that displace the Tertiary sediments, oriented approximately NS, NNE-SSW and NE-SW. The faults lie on the theoretical southern extension of the branch of the NNE-SSW Cavourrina fault. Even in the bed of the Po, east of Camino, on the theoretical southern prosecution of the eastern branch of the same fault, running approximately N-S, there are fault planes that are approximately N-S, along with others from ENE to WSW, that do not correspond with the fault observed by Dela Pierre et al. (2003) in the hills.

The above reported new data allow some interpretations that can complete the tectonic framework. The presence of N-S striking faults east of Camino and NNE-SSW faults north of Gabiano suggests that the Cavourrina fault is formed by the short thrust front immediately to the N of the Trino isolated hill and by two ramps (Fig. 4A) reaching, at least, the edge of the hills. Because in the Po bed there is a series of parallel faults, lying in areas hundreds of metres wide, probably the ramps correspond to deformation zones (Fontanetto Po Deformation Zone, to the West, and Trino Deformation Zone, to the east).

The new data on the presence of deformation zones, located in the theoretical prosecution of the two branches of the Cavourrina fault, suggest that the fault is a complex tectonic structure, active for a long period, which could have played a role in the post-Messinian uplift of the Cerrina valley and of the Buried Monferrato, where there are no Pliocene marine sediments.

5. THE SEISMIC SECTIONS: THE CAVOURRINA AND LUCEDIO FAULTS AND THE BURIED THRUST FRONTS

The comparison between the data from boreholes and two seismic sections reported in ENEL (1984) helps to understand the relationships between the Cavourrina and Lucedio faults and the buried thrust fronts, and corroborates the hypothesis of the presence of the Trino deformation zone and of the Salera Line.

The seismic section TR3 (Fig. 4A) and its comparison with data from the boreholes (Fig. 6) suggests that the Cavourrina Fault lies exactly on a buried thrust front. The Lucedio fault lies a few hundred metres from a northernmost buried thrust front. The two faults dip towards the north while the thrust fronts dip south.

The section PO1-3, interesting the area east of the Cavourrina Fault-Trino Deformation Zone, shows quite different tectonic features, with the thrust fronts covered by thick marine and continental sediments, and absence of faults reaching nearly the ground level. Moreover, back of the thrust fronts, a fault produced the subsidence of the southernmost area, and the throw of another fault is uncertain.

The comparison between the two sections allows for some interpretations.

The difference among the structures evidenced in the sections PO1-3 and TR3 may be due to the presence of the Cavourrina Fault-Trino Deformation Zone, and the faults lying behind the thrust front in the PO1-3 section, could be linked to the Salera Line, assuming that one of the faults forming the Line was trending NNE-SSW, like some faults observed in the Po riverbed (Fig. 4A).

The Cavourrina fault corresponds to a thrust front and it is expected that the front is bounded by ramps. The Fontanetto and Trino deformation zones could be the ramps.

In the sections TR3 the Cavourrina and Lucedio faults dipping towards the North seem in contradiction with the thrust fronts dipping South. The resolution of the seismic sections does not indicate the trend of the structures in the interval between the ground level and a deep well below that reached by the boreholes and therefore the connection between the surface and deep faults is not known. The different dip of the faults could be due to the overturning of the thrust fault planes that show a "normal" sense of displacement towards the surface. A similar case is shown in Michetti et al. (2012) in a scheme based on the Novazzano structure, in the Central Po Plain.

6. THE LOWER CERRINA VALLEY

The lower Cerrina valley (the terminal portion of the Stura stream basin) and the Gaminella stream valley (Fig. 2), its north-western tributary, are situated in the Monferrato hills, south of the thrust fronts corresponding to the Lucedio and Cavourrina faults. The lower Cerrina valley shows a number of geological and morphological peculiarities. Among the geological peculiarities we can note the following.

- A part of the hills inside the lower Cerrina valley consists of Messinian sediments that are isolated among older Tertiary ones and are not covered by Pliocene marine deposits (Montrasio et al., 1969; Dela Pierre et al., 2003a;b). This is a unique case in the Monferrato and Turin hills, where Messinian sediments outcrop only at the edge of the hills and are always covered by Pliocene deposits.
- In the Cerrina valley, the only case in the northern Monferrato, there are lake and river sediments dated at the Early and Middle Pleistocene, reaching approximately 30 m in thickness (Fig. 7), isolated among Tertiary sediments. The river sediments are formed by sandy gravel composed also of pebbles of Alpine origin, deposited by a river (NW River) that reached the Gaminella-Cerrina valley through the Gabiano threshold (Giraudi, 1981; Carraro et al., 1995; Giraudi et al., 2003; Dela Pierre et al., 2003a;b).

The morphological peculiarities are the following (Fig. 7):

- The Gaminella-Cerrina valley is abnormally shaped compared with the surrounding valleys, running from NW to SE, then W-E, and finally approximately N-S.
- The valley from Gabiano to Pontestura appears too broad compared with the streams running through it.

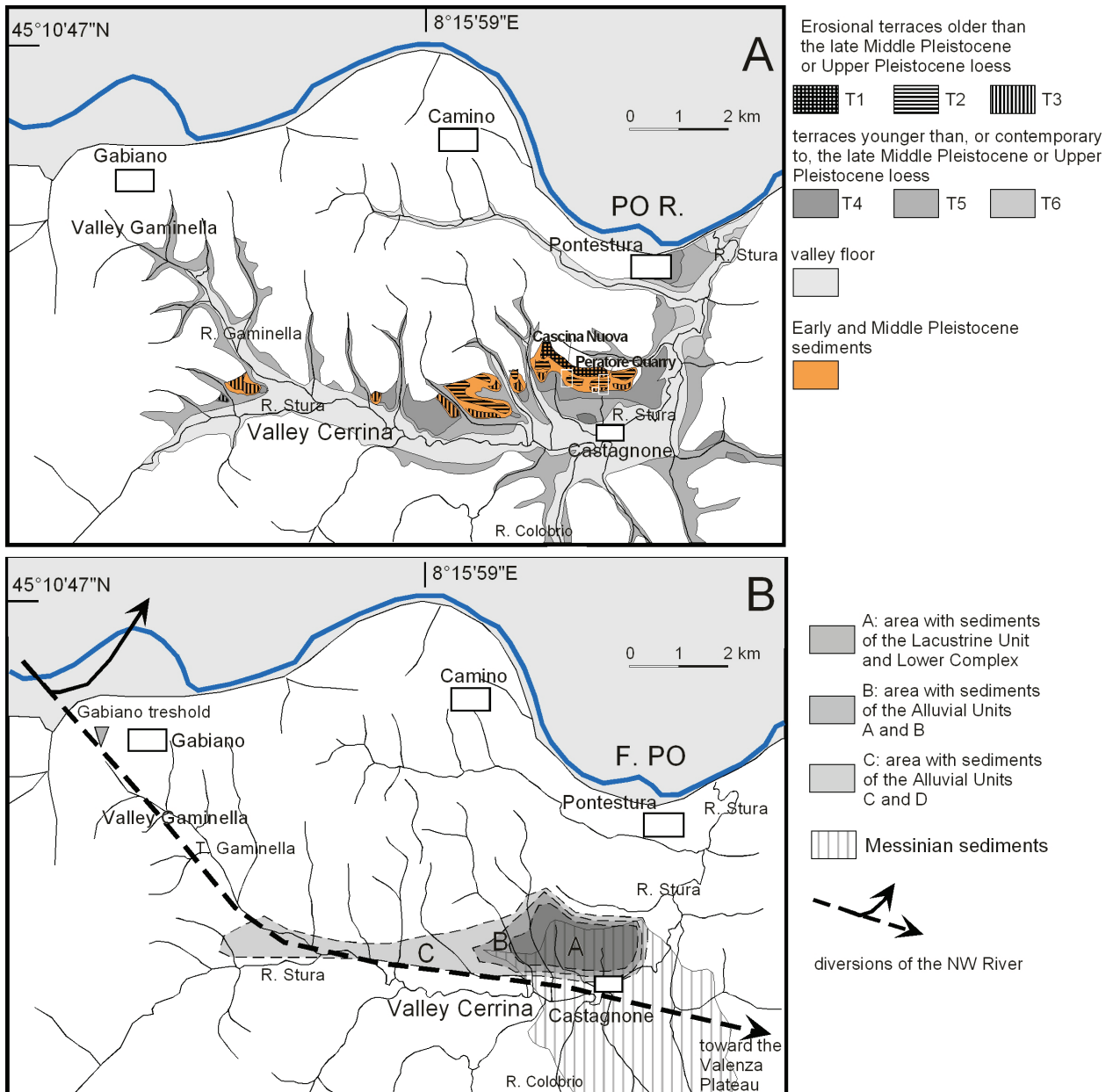


Fig. 7 - Quaternary sediments outcropping in the Gaminella/low Cerrina valley, alluvial terraces and location of the quarries studied (7A). 7B: scheme of the distribution of the Alluvial Units A, B, C, the possible bed of the NW River, and area of diversion of the River northwest of the Gabiano threshold.

- In the stretch oriented W-E, the valley shows a clear morphological asymmetry: the northern slope dips gently and in some places is formed by a series of five terraces, while the southern slope is very steep and there is only a discontinuous low terrace.

The differences between the geological and geomorphological features of the lower Cerrina valley and the surrounding hills and those of the other Monferrato hills must have been produced by geological evolution. The hypothesis that the valley is very broad because it was shaped by the NW River, which had more energy

than the streams currently present, does not appear able to explain all the peculiar characteristics of the Cerrina valley.

6.1 - Considerations on the peculiarity of the marine succession

The peculiarity of the Tertiary marine succession of the Cerrina valley, described above, has never been taken into account. No Author has discussed the causes of the presence of Messinian sediments isolated among older ones and not covered by Pliocene marine deposits.

A discussion on this point is beyond the scope of this paper, but the presence of Messinian sediments suggests that the area, open to the sea until the Messinian, emerged during the Pliocene, like other areas of the Monferrato (Bonsignore et al., 1969; Dela Pierre et al., 2003a;b).

Probably the connection with the sea occurred in the area near the south-eastern end of the syncline oriented NW-SE, located SW of Ozzano (Fig. 2). The syncline continues outside the area represented in Fig. 2. At the Cerrina valley divide, the axial zone is made up of Tortonian sediments, but, just to the east, the Messinian sediments outcrop again, although covered by Pliocene marine deposits, as in the whole area of the Monferrato and Turin hills.

6.2. The lower Cerrina valley: site setting and stratigraphy

The Gaminella-Cerrina valley (from now on called the lower Cerrina valley), in the stretch between Gabiano and Pontestura, was carved between hills reaching altitudes of up to just over 400 m asl, and ends up in the Po valley at an altitude of about 120 m asl. Its catchment basin extends outside the study area towards the southwest (the Stura stream) and south (the Colobrio stream, a tributary of the Stura).

The lower Cerrina valley mainly corresponds to the axis of a syncline having a peculiar direction. The axis is directed first from NW to SE, then W-E, and finally approximately N-S (Figure 2): to the west, it crosses tectonic structures having axes mainly oriented from WSW to ENE, while to the east it crosses also NW-SE structures.

Just SE of Pontestura, the axis of the valley continues in a S-N direction, while the axis of the syncline bends sharply towards NW.

Near the confluence of the Stura stream in the Po river, the valley floor is carved in the sediments of the Casale Monferrato Formation (Eocene) (Fig. 2), as shown by the sediment outcrops observed in the bed of the Po and the Stura rivers during the field surveys.

With regard to the Quaternary deposits, the presence of fluvial sediments deposited by the NW River (Giraudi, 1981; ENEL, 1984; Carraro et al., 1995; Giraudi et al., 2003; Dela Pierre et al., 2003a;b) indicates that the valley was, for a certain period, open towards NW.

According to the literature, east of the village of Castagnone (Fig. 7), the river probably continued to the east or SE (ENEL, 1984; Carraro et al., 1995; Dela Pierre et al. 2003a;b; Giraudi, 2015a) following roughly along the axis of a post-Messinian syncline located SW of Ozzano, and finally reaching the lower Rotondo valley. According to Giraudi et al (2003) the hilly area of Gabiano and Camino, north of the left side of the Cerrina valley, was uplifted in the Lower and Middle Pleistocene and, according to Dela Pierre et al. (2003a;b), the uplift would have been related to the northward migration of the Monferrato thrust front.

The fluvial deposits, deformed by tectonics and syn-

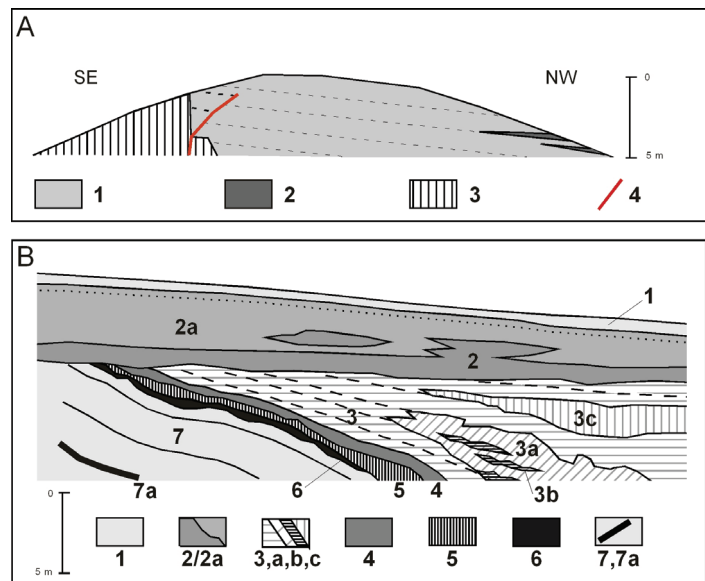


Fig. 8 - Stratigraphy of the Castellino (A) and Cascina Nuova (B) sites.

A) Legend: 1 - sand and fine gravel interbedded with clayey silt, 2 - reddish colluvial silt; 3 - Tertiary sandstones; 4 - syn-sedimentary fault.

B) Legend: 1 - Aeolian Unit; 2 - gravelly sand of Alluvial Unit C; 2a - sandy silt and silt of Alluvial Unit C; 3 - sandy gravel and silty sand of Alluvial Unit A; 3a - unconsolidated sand of Alluvial Unit A; 3b - calcareous crust of Alluvial Unit A; 3c - dark clay of the Alluvial Unit A; 4 - calcareous crust of the Lower Complex; 5 - gravelly sand and silty clay with patches of a colluviated soil of the Lower Complex; 6 - partially cemented clayey silt of the Lower Complex; 7 - Lacustrine Unit; 7a - calcareous crust interbedded with the Lacustrine Unit.

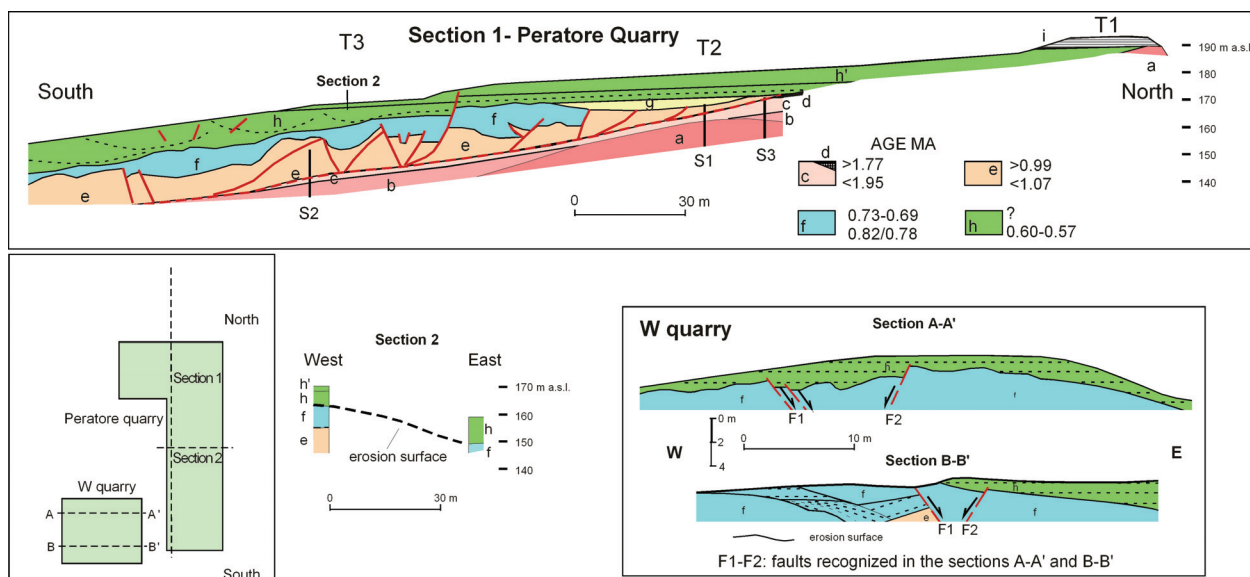
-sedimentary landslides, occur only on the left side of the valley and are dated at the Early and Middle Pleistocene (Giraudi, 1981; Dela Pierre et al., 2003a;b; Giraudi et al., 2003).

Also on the left side (Giraudi et al., 2003), the slope of the valley is shaped by a series of terraces (Fig. 7A) while in the rest of the Stura stream catchment only in some places there are remnants of a low terrace at the base of the slopes and the valley bottom is made up of thin layers of recent alluvial sediments.

In the literature, the anomalous width of the Gaminella-Cerrina valley has been attributed to the erosional activity of the high energy NW River, potentially stronger than that produced by the small hill streams. However, the anomalous size of the valley continues also in the stretch heading north, up to Pontestura, where there is no evidence of the presence of a high energy river.

It is therefore necessary to review and discuss the stratigraphic data and the phases of tectonic deformation of the sediments in order to characterize the tectonic-sedimentary evolution in the detail needed to identify any elements of correlation with events recorded near the Buried Monferrato front.

In this chapter the stratigraphic data collected (Fig. 2; 7; 8) at a place near Castellino and in two quarries, now abandoned (Cascina Nuova quarry: Giraudi et al., 2003; Peratore quarry: Giraudi, 1981) will be examined in detail, discussed and compared.



a=Unit AVC; b=Unit BVC; c=Lacustrine Unit; d=Lower Complex; e=Caotic Complex; f=Alluvial Unit B; g=palustrine sediments at the top of the Alluvial Unit B; h, h'=Alluvial Unit C; i= Alluvial Unit D. T1, T2, T3: higher terraces of the northern slope of the Cerrina Valley

Fig. 9 - Stratigraphic sections through the Peratore and W quarries

6.2.1. The Castellino alluvial sediments

North of Castellino (Fig. 2) on the right side of the valley of the Colobrio stream, about 250 m asl, a small exposure (a few hundred m²) of continental uncedmented sediments was present. The deposit was discovered by the writer in the early 80's thanks to an ephemeral outcrop (Fig. 8A) and is described in ENEL (1984). It is formed of sand and fine gravel interbedded with grey, compact clayey silt. In the north-west, reddish silt is interfingering. Gravelly sands are fluvial in origin and their lithological composition (the pebbles are mainly of marl, greenstone and cemented diatomite) clearly indicates that the clasts derive from Tertiary sediments forming the bedrock. The reddish silt is colluvial. The pebbles of diatomite most likely derive from the "Diatomitic Member" of the "Marne a Pteropodi" formation (Aquitanian PP- Burdigalian PP, according to Dela Pierre et al., 2003a;b) outcropping a few km west of the site. The sediments, observed only for a thickness of approximately 5 m, are tilted about 10° towards the NW, and lie unconformably on Tertiary marine sediments, having a clear-cut contact with sub-vertical strata of sandstones. The base of the fluvial sediment was not exposed but must have been at an altitude of at least 50 m above the base of the Cerrina valley Gelasian sediments (see below).

The sediments are also displaced by a small syn-sedimentary fault, whose plane dips about 60° towards the SE, sealed by the gravelly sands that form the top of the exposure. The NE-SW direction of the fault plane coincides with that of a fault hypothesized by Dela Pierre et al. (2003a;b) in the adjacent valley bottom of the Colobrio stream. The palaeontological study of the sediments indicated the presence of an abundant reworked

fauna of marine origin (ENEL, 1984).

There are no data about the age of the sediments, but the presence of alluvial deposits at an altitude next to those of the highest hills of the area lying on the right slope of the Colobrio valley allows us to assume that sedimentation took place in a period during which the drainage network was not yet very well developed.

According to Carraro et al. (1980) and Dela Pierre et al. (2003a;b) some parts of the Monferrato emerged from the sea during the phase of intense tectonic deformations contemporary with the sedimentation of the marine Pliocene succession. The syn-sedimentary fault and the tilt of the sediments suggest that the sedimentation occurred during a period characterized by tectonic activity. It is possible, therefore, that the alluvial sediments of Castellino date back to the Pliocene.

6.2.2. Stratigraphy and deformations of the Cascina Nuova and Peratore quarry sediments

The sequence described below refers to the Cascina Nuova (Fig. 7A; 8B) and Peratore quarries (Fig. 7A, 9) and to an ephemeral small quarry, called W quarry (Fig. 9). The sediments on which the studies have been based were outcropping or were exposed digging trenches. Some boreholes were drilled in order to reach the bottom of the continental sediments and the bedrock. Only the stratigraphic data obtained from boreholes drilled in the Peratore quarry and surveying the exposures in the W quarry, were not reported in literature.

The sediments of the Cascina Nuova and Peratore quarries contained vertebrate remnants and microtine teeth (Giraudi, 1981; Giraudi, 1983; ENEL, 1984; Giraudi et al., 2003; Siori & Sala, 2007) and have been

analyzed in order to detect their magnetic polarity (ENEL, 1984; Giraudi et al., 2003).

Some fossil teeth found in the Peratore quarry were dated with the method of amino acids racemization (ENEL, 1984) and some of these datings were also reported in Dela Pierre et al. (2003a;b).

The stratigraphy of the Cascina Nuova quarry was discussed in Giraudi et al. (2003) while that of Cava Peratore (drawn in Fig. 9) was obtained by updating the section reported by Giraudi (1981), which also included the deepest part of the stratigraphic succession, no longer visible after the year 1980, with the data obtained through special excavations during the ENEL (1984) studies.

The bedrock

The bedrock underlying the continental sediments of the Cascina Nuova and Peratore quarries, according to Dela Pierre et al. (2003a;b), consists of marine sediments (Sant'Agata Fossil Marls) Tortonian in age. However, some boreholes drilled inside the Peratore quarry, never discussed before, and some ephemeral exposures observed in the 1980s made it possible to detect the presence of other Upper Miocene sediments.

- **Unit AVC** - grey-green compact silt, drilled for 8 m in the Peratore quarry. The microscopic observation of the sediments revealed concretions of white clay and gypsum, rounded fragments of gypsum covered with a patina of alteration, and concretions of pyrite. Depending on the fauna content (studied by M. Sampò in the year 1984), the sedimentary environment is a marine external platform (intermittent anaerobic); the age of the sediments is Lower Messinian.
- **Unit BVC** - grey to dark grey compact silt, up to 3 m thick, sampled by means of boreholes in the Peratore quarry, but observed also in ephemeral exposures at Cascina Nuova and east of Peratore quarry. The sediments lie unconformably on the Early Messinian AVC Unit. Observation under the microscope showed clasts of gypsum, transparent and otherwise, pyrite concretions and rare glauconite grains. The microfauna, mostly reworked (studied by M. Sampò in the year 1984), suggests that the sediments pertain to the Upper Messinian post-evaporitic "Strati a Congerie" (Conglomerati di Cassano Spinola formation, in Bonsignore et al., 1969).

Neither of the two units (ABC; BVC) corresponds to the Valle Versa Chaotic Complex, Upper Messinian in age, outcropping about 1 km to the west and south of the described area: at the base of the BVC unit, then, there is a hiatus, probably corresponding to the discontinuity surface D6 (younger than the Chaotic Complex), reported in the adjacent areas by Dela Pierre et al. (2003a;b). Even in the Tertiary Piedmont Basin the last Messinian discontinuity separates the Valle Versa Chaotic Complex from the "Conglomerati di Cassano Spinola" formation (Clari et al., 2008).

The lacustrine, alluvial and aeolian sediments

The post-Messinian sedimentary sequence is best preserved and thickest (20-30 m) between Cascina

Nuova and the area east of Peratore Quarry. West of Cascina Nuova, however, the sediments are discontinuous and only a few metres thick.

- **Lacustrine Unit:** this consists of clay and silt sedimented in a low energy environment, lake or marsh. The lowest levels exposed consist of homogeneous silty clay, little or poorly bedded, fissured, and with a patina of iron oxide, containing an intercalation of silt with whitish calcareous concretions. The sediments of the top of the unit are formed of silty clay, grey-whitish and yellowish, finely laminated, fissured and with Fe oxide patinas in the cracks. The sediments sometimes contain fragments of wood completely mineralized, and are interbedded with thin and discontinuous calcareous crusts and horizons containing calcareous concretions, and can be strongly cemented. About 2.5 m below the top of the unit, associated with strongly cemented silty clay, a fragment of wood was found, transformed into limonite by diagenetic processes. Since this is a fragment of considerable size (up to 60 cm long, 25 cm wide and 8-10 cm thick) and of considerable weight, intercalated between deposits of low energy with plane-parallel fine lamination, it is presumed that diagenesis of the wood took place after sedimentation.

Among the silty clays of the top of the unit there is a small angular unconformity of about 2°.

There are no direct data for the dating of the Lacustrine Units, but its stratigraphic position and the palaeomagnetic polarity of the sediments indicate a chronological framework. The palaeomagnetic analysis showed that the polarity of the sediments sampled in the upper half of the unit is normal (Giraudi et al., 2003).

The Cava Peratore boreholes show that the Lacustrine unit lies unconformably on the post-evaporitic Upper Messinian sediments. The unconformity excludes the chronological attribution of this unit to the Upper Messinian.

- **Lower Complex:** up to 70-85 cm thick, is exclusively colluvial and patchily preserved in the area and overlies the Lacustrine Unit. It consists of clayey, massive, light to dark-grey, consolidated silt, up to 40 cm thick, and grey sand, gravel and silty clay, with patches of colluviated soils coloured 2.5 YR of the Munsell Soil Color Chart (MSCC), up to 20-30 cm thick; a pedogenetic calcareous crust, more or less continuous, up to 10-15 cm thick, occurs on the top of the layer. The colluvial Lower Complex is unconformity-finished and most likely to be considered much older than the following alluvial unit. According to the palaeomagnetic analysis, the polarity of the sediments is normal (Giraudi et al., 2003).

The emplacement of the colluvium has not produced a clear erosion surface at the top of the Lacustrine Units, but the clear-cut contact between the two units suggests the presence of a paraconformity. In the Peratore quarry, the Lower Complex has been found only in the extreme northern portion of the quarry (Fig. 9). There are no direct date for the chronology of the unit, but the stratigraphic position and the magnetic polarity suggest that the Lower Complex was

formed still in the course of the same sub-chron during which the Lacustrine Unit was sedimented.

- **Alluvial Unit A and Chaotic Complex:** up to 10 m thick, lies unconformably on the Lacustrine Unit and Lower Complex. In the Cascina Nuova quarry; it consists of yellowish-grey sand and gravel, massive or poorly stratified yellowish-grey silt and sandy silt embedding carbonate concretions, and yellowish-grey unconsolidated sand with thin and discontinuous calcrete horizons. Unconsolidated sandy bodies are interbedded with silty and sandy silty layers. A heterotopic facies of gravelly sand and dark clay occurs near the top of the sandy silty sediments. For their lithological composition (discussed in Giraudi, 1981; Carraro et al., 1995; Giraudi et al., 2003; Dela Pierre et al., 2003 a;b) showing the presence of pebbles of rocks outcropping outside the T. Stura catchment, including violet jasper and flint with brown patina, the gravel must have been deposited by the NW River having its catchment NW of the Gaminella Valley. Alluvial Unit A contains the remains of Galerian macrofauna associated with early Biharian (Rodent age) microtine vole teeth.

The faunal content and the normal magnetic polarity enable these sediments to be dated in the sub-chron Jaramillo (Giraudi et al., 2003; Siori & Sala, 2007), dated 1.07-0.99 MA, namely in the Marine Isotope Stages (MIS) ranging from 31 to 28.

In the Peratore quarry, in the same stratigraphic position as Alluvial Unit A, a chaotic complex is present, formed by two members consisting of sediments strongly affected by plastic deformations and displaced by small faults and rotational surfaces.

The lower member is formed by silt interbedded with sandy-silt, and layers of sand, and more frequently gravelly sand. The latter are made up almost exclusively of clasts deposited by the NW River. The facies and lithology of the gravelly-sandy sediments are similar to those of the Alluvial Unit A of Cascina Nuova. Some silt layers are characterized by the presence of scattered pebbles from outside the valley and clayey-marl of local origin, showing a mud-supported structure.

The upper member consists of unstratified whitish clay that includes sets of strata formed by laminated silt and clay with horizons of calcareous concretions, clearly corresponding to the sediments of the Lacustrine Unit.

The Chaotic Complex contains fauna indicating (Giraudi et al., 2003) a generic Galerian (macro) mammal age (sensu Gliozzi et al., 1997) and re-worked marine fossils.

The sediments that form the Chaotic Complex have a normal magnetic polarity (ENEL, 1984), and are older than Alluvial Unit B, dated at the beginning of the Middle Pleistocene (see below). The sedimentation of the gravelly sand and most of the deformations thus occurred during the sub-chron Jaramillo.

- **Alluvial Unit B:** The sediments that form the unit are mostly sandy and gravelly, and have a facies similar to that of the alluvial sediments of Unit A. The lithology of the gravel indicates the prevalence of clasts from outside the valley. Among the alluvial sediments

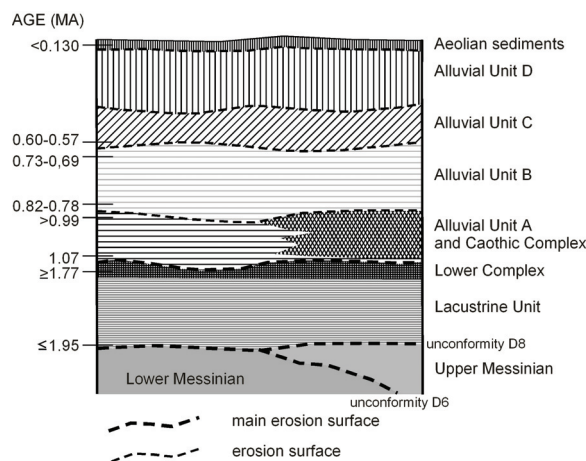


Fig. 10 - Stratigraphic sketch of the Upper Miocene – Middle (Upper) Pleistocene marine and continental sediments exposed in the Cerrina Valley.

some large blocks of clayey silts may be present similar to the Tertiary sediments forming the hills around the Peratore quarry. The presence of such blocks is due to the sliding of masses of bedrock into the sedimentation basin.

The alluvial sediments of Unit B lie on an erosion surface, dipping S and SE, cutting the top of Alluvial Unit A. In the sediments of Unit B some fossils remnant have been found (Giraudi, 1981; ENEL, 1984; Giraudi et al., 2003), indicating a generic Galerian (macro) mammal age (sensu Gliozzi et al., 1997).

Study of the racemization of the amino acids in three fragments of teeth found among the sediments indicated ages of 820-780, 750-706, 730-690 ka BP (ENEL, 1984; Dela Pierre et al., 2003 a;b) which are consistent with the stratigraphic position of the fossils analyzed. At the top of Alluvial Unit B are clayey silts, up 1.5-2 m thick, lying in a palaeo-channel. These sediments are palustrine in origin, and contained the remains of *elephas indet.* (Giraudi, 1983). Paleomagnetism (ENEL, 1984), indicating that Alluvial Unit B is of normal polarity. According to the fauna, the dating and the normal polarity of the sediments, Alluvial Unit B must have sedimented during the chon Brunhes, especially in the oldest part of the Middle Pleistocene, corresponding to MIS 20, 19, and 18. The erosion surface lying at the base of Alluvial Unit B might then have produced the erosion of sediments possible dated at MIS 27-21, corresponding to a chronological interval of about 200 ka. Some structures that displaced Alluvial Unit A and the Chaotic Complex also affect Alluvial Unit B.

- **Alluvial Unit C:** (4-5 m thick) has a sharp unconformity with the underlying one and starts with basal silty-gravelly sand with diffused clay chips deriving from the erosion of the Tertiary bedrock, followed upwards by sandy silt and silt with scant lenses of silty sand and clay. The gravel also contains pebbles from outside the Cerrina valley, but the sediments, compared with older units, contain a higher amount of clasts of marl from the marine Tertiary formations, and re-

worked marine fossils. The upper part of the Unit (h' in Fig. 9) shows a gradual decrease in grain size, from sandy silt, alluvial in origin, to clayey silt sedimented in a small lake or marsh. At the top of the unit is a reddish soil coloured 5YR 5/8 MSCC. The fossil content is poor, represented by fragmentary teeth of a herbivorous indet. and some arvicolid incisor teeth (Giraudi et al., 2003; Siori & Sala, 2007). A tooth fragment found among these sediments in the northern part of the Peratore quarry, dated by the method of racemization of amino acids, indicated an age of between 570 and 600 ka BP (ENEL, 1984; Dela Pierre et al., 2003 a;b), corresponding to the intermediate part of MIS 15. Palaeomagnetic analyses (ENEL, 1984; Giraudi et al., 2003) performed on the sediments at the bottom of Alluvial Unit C have indicated normal polarity.

Both in the Peratore and W Quarries, Alluvial Unit C overlies, via an erosion surface markedly dipping towards the SE (Section 2 in Fig. 9), the oldest sediments and is displaced to the top by limited movements along structures that have already affected the older Units or ones of new generation.

- **Alluvial Unit D:** this is a sequence of silts and sandy silts about 4 m thick (Fig. 9) deposited by a low energy stream: at their top lies a reddish yellow soil, coloured 7.5YR 5/8 MSCC. The sediments of this unit form the higher fluvial terrace observed in the Cerrina valley (T1).
- **Aeolian Unit:** Loess formed by aeolian silt, 70-80 cm thick. Mousterian scattered lithic artifacts lie inside the deposit and therefore the loess can be dated at the late Middle Pleistocene or the Upper Pleistocene (MIS 6 or MIS 4-3). The soil developed on the loess is coloured 10 YR MSCC.

The stratigraphy of the Tertiary and Quaternary Cerrina valley sediments described above is represented in Fig. 10.

The Lacustrine Unit and the chaotic complex of the Alluvial Unit A need to be discussed in order to reach a less approximate chronological framework or to establish their origin.

The dating of the unconformity lying at the base of the Lacustrine Unit can be used for a tighter chronological framework of the Unit. Based on the stratigraphy of the Monferrato sediments reported in Dela Pierre et al. (2003 a;b) the unconformity may correspond chronologically to the discontinuity surfaces D7 (Early Pliocene) or D8 (Early Pleistocene). However, it is unlikely that the unconformity corresponds to the discontinuity surface D7 because this discontinuity was observed only among Pliocene marine sediments and is covered by marine deposits of the final stages of the Foraminiferal Zone FPL3 (ending around 4 MA). Moreover, the bottom of the Lacustrine Unit lies at least 50 m below the bottom of the Castellino alluvial sediments, probably dating back to the Pliocene.

It is likely, therefore, that the unconformity at the bottom of the Lacustrine Unit corresponds to the Early Pleistocene D8 discontinuity surface. The lake sedi-

ments must have been sedimented in a sub-chron with normal polarity, older than Jaramillo (see below), during the chron Matuyama (Reunion, dated ca. 2140 ka BP; Olduvai, dated 1950-1770 ka BP; Gilsa, dated ca. 1680 ka BP; Cobb Mountains, dated 1220-1240 ka BP). The thickness of the sediments and their syn-sedimentary deformation suggest that sedimentation took place over a fairly long time interval and seem to exclude the assignment of the unit to a chron or sub-chron of short duration. The Lacustrine Unit, therefore, could be dated at the longer sub-chron, i.e. Olduvai.

About the Alluvial Unit A, the presence of blocks of older sediments intercalated chaotically between fluvial-lacustrine deposits, the abundance of plastic or brittle deformations, and the presence of rotational shear surfaces affecting all the sediments of this unit, suggest that the Chaotic Complex was produced by the collapse of a set of layers of the Lacustrine Unit that caused the syn-sedimentary deformation of the fluvial-lacustrine deposits related to the NW River. Also during the fluvial sedimentation even greater rotational movements occurred of the already deformed sediments, containing blocks, that had slipped earlier in the basin.

6.2.3. Sediment deformation and tectonics

The Pleistocene deformation phases have been deduced from the dip of the sediments and the age of the plastic and brittle structures observed in the sediments.

Near Cascina Nuova, the dip of the units (Fig. 8) progressively decreases from the bottom upwards but the inclinations are always southwards, that is towards the axis of the Cerrina valley syncline.

- The Lacustrine Unit sediments have a bedding inclination of between 14° and 12°. During the sedimentation of the Lacustrine Unit (Olduvai, 1,95-1,77 MA) a tilting of 2° occurred.
- The Lower Complex sediments dip about 12°. Therefore between the top of the Lacustrine Unit and the end of the emplacement of the Lower Complex there was no deformation.
- The Alluvial Unit A sediments dip between 10° and 4°. Therefore during the interval between the sedimentation of the Lower Complex ($\geq 1,77$ MA) and of the base of Alluvial Unit A (Jaramillo, about 1 MA; MIS 31-28) a tilting of 2° occurred, while during the sedimentation of Alluvial Unit A there was a tilting of 6°. During the sedimentation of Alluvial Unit A the emplacement also occurred of the Chaotic Complex exposed in the Peratore quarry.
- The Alluvial Unit C sediments are nearly horizontal. In the period between the sedimentation of the preserved top of Alluvial Unit A ($\geq 0,99$ MA) and the base of Alluvial Unit C (about 0.6 MA; MIS 15), namely during a period at least partially contemporaneous with an erosion phase and the sedimentation of Alluvial Unit B (about 0.78-0.7 MA), a tilting of 4° took place and, at the same time there was a less intense deformation of the Peratore quarry sediments.
- The latest small deformations also affect Alluvial Unit C in the Peratore quarry.

The different lithological composition of the sedi-

ments of Alluvial Units B and C suggests that the flow to the Cerrina valley of the NW River ended after 0.7 and before 0.6 MA, that is, when the sediment deformation had diminished significantly.

6.3. Tectonic interpretation

One of the peculiarities of the Cerrina valley listed above is the presence of the Messinian sediments isolated between older formations, and not covered by marine Pliocene, but by Early Pleistocene lake deposits. The late Miocene-Early Pleistocene stratigraphy implies a post-Messinian uplift of the area and then a post-Pliocene phase of subsidence (phase S1) which produced the depression that, at least during part of the Early Pleistocene (1.95-1.77 MA), hosted a lake. The syn-sedimentary tilting, towards south and SE, of the Pleistocene deposits forming the side of the Cerrina valley syncline implies the subsidence of the axial zone of the syncline. Tectonic deformation began during the sedimentation of the Lacustrine unit, but was more intense in the course of the sedimentation of Alluvial Unit A (Fig. 11).

It is possible that the subsidence of the syncline before the sedimentation of Alluvial Unit A (phase S2) created the topographical depression that triggered the diversion of the NW River into the Cerrina valley.

The strongest phase of subsidence in the syncline occurred during Jaramillo (ca 1 MA).

Also, the orientation of structures described in the Chaotic Complex (dated at Jaramillo) is compatible with a slip towards the south, that is, towards the axis of the syncline. The gravitational phenomena would have occurred, then, in correspondence of the strongest phase of subsidence of the Cerrina valley syncline indicated by the tilt of the sediments.

The deformation of the sediments continued, although less intense, at least up to about 730-690 ka BP, and then the syncline was active at least until that time.

The few deformations that affected Alluvial Unit C, more recent than 600-570 ka BP, and the dip of the erosion surfaces may indicate that the eastern part of the syncline was the part that subsided most or that only that part was still active. According to Giraudi (2014) in the final stretch of the Cerrina valley a complex structure was present, the Salera Line, oriented approximately N-S, crossing the Monferrato thrust front, active also during the phases of compressive tectonics. The tectonic activity along the Salera Line could have caused the subsidence of the eastern part of the Cerrina valley and, in the stretch where the valley bottom no longer coincides with the axis of the syncline, of the western portion of the Casale Monferrato Formation.

Later, but before the loess sedimentation, the area was uplifted, and the uplift triggered a phase of incision

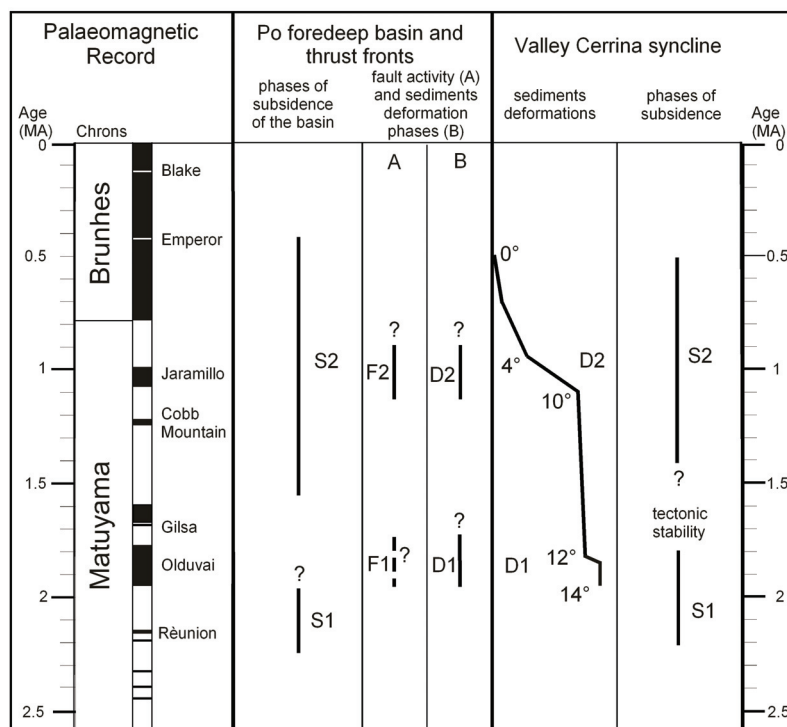


Fig. 11 - Correlation between the tectonic activity in the Monferrato thrust front and in the nearby foredeep basin, and in the Cerrina valley syncline.

of the valley (Dela Pierre et al., 2003 a;b; Giraudi et al., 2003). This uplift was already recognized south of the Cerrina valley by Carraro and Valpreda (1991).

Knowledge of the geological evolution can be completed by analyzing the main erosion surfaces observed between the Pleistocene alluvial sediments. A first erosion surface, that produced a gap of about 200 ka in the sedimentary sequence, is interposed between Alluvial Units A (MIS 31-28) and B (MIS 20 -18). The erosion of the sediments should therefore have ceased just before MIS 20. Since then, according to the displacements of the deposits, during the sedimentation of the two alluvial units the style of the deformation has not changed, it can be assumed that the erosion surface was formed mainly as a result of hydrological changes of the NW River related to the climate during the MIS 21 interglacial.

The second erosion surface lies at the base of Alluvial Unit C, and it can be dated between 0.73-0.69 and 0.6-0.57 MA. This erosion surface, sloping towards S and SE, developed during a period of tectonic change, which coincides with a phase of greater subsidence of the eastern part of the syncline. It is therefore likely that the erosion was triggered mainly by tectonics. In any case the erosion must have been active in a period, following MIS 18, probably corresponding to the early MIS 15. Overall, the only period of tectonic stability older than the sedimentation of Alluvial Unit C (age <0.6-0.57 MA) corresponds to the sedimentation of the top of the Lacustrine Unit and the Lower Complex (about 1.77 MA).

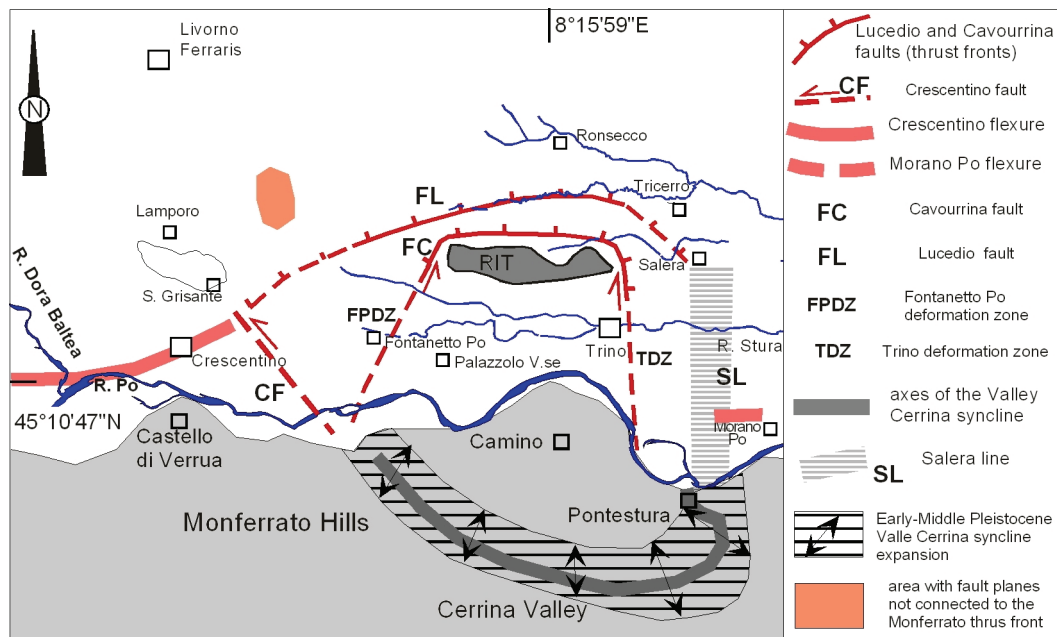


Fig. 12 - Surficial faults and flexures of the Monferrato thrust fronts and possible transpressive faults and deformation zones linking the Cerrina valley basin to the thrust fronts.

7. CORRELATIONS BETWEEN THE SUBSIDENCE OF THE CERRINA VALLEY AND THE DEFORMATION ALONG THE MONFERRATO THRUST FRONT

Behind the Torino Hills and the Monferrato arcs, deep piggyback troughs developed in Plio-Quaternary times near Saluzzo and Alessandria. (Dela Pierre et al., 1995; Irace et al., 2009) that is south-west and south-east of the arcs.

According to Giraudi (2015a) the subsidence of the northern Alessandria basin continued at least until the upper Middle Pleistocene or early Upper Pleistocene, in correspondence with the activities of the thrust front lying north of the Pomaro-Montevalenza isolated hill.

In the Pliocene basin north of Asti, exactly south of the Central Monferrato front and of the Cerrina Valley, the subsidence occurred only during the early Pliocene and later the area underwent an uplift (Dela Pierre et al., 2003 a;b).

The data reported in Dela Pierre et al. (1995) indicate that during the Pliocene-Pleistocene compressional phases there was subsidence both in the piggyback troughs and in the foredeep Po basin. During the Gelasian and Calabrian, while north and SW and SE of the front the subsidence continued, in the Asti trough it had already ceased.

According to Dela Pierre et al. (2003 a;b), the last stage of the evolution of the Monferrato, north of the Cerrina valley, would be connected to the northward migration of the thrust front on the Po basin. It is therefore necessary to assume that a possible trough behind the most advanced northern Monferrato thrust fronts active during the Early and Middle Pleistocene must be placed in an area south of the front, but north in the Asti basin: the only area that was subsiding during the same period was the Cerrina Valley syncline. The syncline

probably expanded and deepened gradually as a result of extensional tectonics that occurred behind the thrust front migrating towards north. So, the anomalous width of the valley may not be due to the NW River erosion, but be a consequence of the expansion of the tectonic depression.

If the hypothesis is correct, the deformation of the sediments and the unconformities related to the activity of the syncline can, then, be used to frame chronologically the migration towards the north of the Monferrato thrust front. It follows that the subsidence of the Cerrina valley must be synchronous with the deformation induced by the thrust front and with the phases of subsidence recorded by the sediments of the Po basin (Fig. 11).

The comparison between the sedimentary sequences of the Po basin and the Cerrina valley shows that, at least from the Pliocene to the beginning of the Gelasian, the area of the Cerrina Valley was emerged, while north of the thrust fronts and in the Asti basin there was marine sedimentation.

Pliocene marine sediments are also missing in the bedrock of the alluvial plain between the Monferrato hills and the thrust front corresponding to the Cavourina fault (Pieri & Groppi, 1981; Cassano et al., 1986; ENEL, 1977, 1984; Giraudi, 2014).

It is assumed that, at least from the late Messinian, the evolution of the area limited to the north by the Cavourina fault and to the south by the Cerrina Valley has begun to differentiate with respect to other areas located near the Monferrato-Turin Hill thrust front.

The following subsidence of the Cerrina Valley, which allowed the establishment of a lake basin between 1.95 to 1.77 MA, started, probably, contemporary to the early stages of deformation of the Gelasian sediments of the Po Basin, and continued until the time of

deformation of the base of the fluvial and lacustrine sediments of the Unit ABP.

The period of tectonic stability which took place in the Cerrina Valley during the sedimentation of the top of the Lacustrine Unit and the Lower Complex (≥ 1.77 MA) may correspond chronologically to the development of the erosion surface that, in the Po basin, occurred before the beginning of the sedimentation of the upper ABP unit, dated around 1.8 MA.

The stronger phase of subsidence of the Cerrina valley syncline happened mainly between 1 and 0.7 MA and therefore it is contemporary to the tectonic phase that caused the displacement along the Lucedio fault, the low-angle faults in the upper Unit ABP of the Po basin and the tilt of the sediments. Even the deformation of fluvial and fluvio-glacial sediments dated between 870 and 400 ka (discussed by Giraudi, 2014) is nearly contemporary with the displacements produced by syn-sedimentary landslide involving deposits of the Alluvial units B and C of the Cerrina Valley.

The interpretation of the data suggests that, during the Early Pleistocene and the middle Middle Pleistocene, the subsidence and deformation of the sediments in the Cerrina valley and in the Po basin were mostly contemporary.

The subsidence in the Cerrina valley and the activity of the Monferrato thrust front north of Trino, therefore, seem connected.

The hypothesis that the Cerrina valley syncline could correspond to a trough that developed behind the younger Central Monferrato thrust front, advanced by Giraudi (2015b) seems likely, and probably the tectonic depression expanded as the front migrated northwards.

The Cerrina valley syncline would be connected to the thrust front by two complex tectonic structures, called by Giraudi (2014) the Salera Line, to the east, and the Crescentino fault, to the west (Fig. 12). The two structures, covered by fluvial and fluvio-glacial sediments of the plain, could correspond to the two strike-slip or transpressive faults, assumed by Costa (2003), which would have acted as ramps for the movement of the Lucedio fault thrust front. However the continuity between the Cavourina fault and the Fontanetto Po and Trino Deformation Zones seems to suggest that also these tectonic structures were involved in the evolution of the Cerrina Valley syncline.

8. HYPOTHESES ON THE CATCHMENT BASIN OF THE NW RIVER

The tectonic evolution outlined above provides some elements in order to discuss the catchment basin of the NW River entering the Cerrina valley near Gabiano. It is unlikely that the NW River corresponds to the Dora Baltea river (flowing from the Aosta Valley).

In order to reach the Cerrina valley, the Dora Baltea would have to cross the area in subsidence, then to cut through the uplifting thrust front. The river, most likely, flowed eastwards along the axis of the depression lying north of the front.

In the plain north of the hills, the only alluvial sediments having a lithological composition fairly similar to

that of the NW River were sampled in a borehole near Crescentino (see above), 5 km west of the head of the Gaminella-Cerrina valley, and described near Ostino (between Monteu da Po and Brusasco), about 12 km west of the head of the valley, where sandy gravel (Bonsignore et al, 1969; Dela Pierre et al., 2003 a;b) is poorly exposed on a terrace at the foot of the hill. The lithology of the clasts forming the Ostino sandy gravel indicates (Dela Pierre et al., 2003 a;b) alpine (probably from the valleys of the Orco and Malone streams) and Monferrato hills catchment basins.

The first hypothesis, then, is that the NW River came from the alpine valleys lying SW of the Aosta Valley.

Some considerations on the evolution of the sedimentation in the Po plain suggest another hypothesis. In the plains north of the Monferrato hills (Giraudi, 2014), but also elsewhere (Muttoni et al., 2007), the sediments of the Alpine rivers are coarser starting from MIS 22 as a result of the stronger erosion caused by the expansion of the Alpine glaciers.

In contrast, among the alluvial sediments of the Cerrina valley, older (Alluvial Unit A) and younger (Alluvial Unit B) than MIS 22, there is no significant change in grain size. It can be assumed, therefore, that glaciers were absent in the NW River basin, which means that its catchment was outside the Alps. The river basin could, therefore, be represented mainly by the northern Monferrato. The NW River, lying mainly south of the thrust front, could have been the collector of the waters of the streams currently flowing into the Po river between Chivasso and Crescentino. In this case, in the plain, the boundary between its basin and that of the alpine rivers, was uncertain and/or variable. The northern boundary of the NW River basin could therefore be located, probably, near the Torino Hills-Monferrato thrust front.

The clasts of alpine origin, observed in the NW River deposits, could result from the reworking of older alluvial sediments deposited by alpine rivers and from the erosion of conglomerates outcropping between the sediments of the Monferrato "Ligurian Units".

The hypothesis of a catchment basin of the NW River mainly limited to the northern Monferrato does not exclude, however, the possibility that sometimes an alpine river could have flowed in the southern basin due to the uncertainty of the watershed boundaries.

9. CONCLUSIONS

The study of the Plio-Pleistocene sedimentary successions and Pleistocene deformation phases of the Cerrina valley and the southern Vercelli plain has enabled the sedimentary and tectonic evolution to be recognized of an area that extended both south and north of the Monferrato thrust front, and has also shown that the peculiar geological features of the two areas are not random but due to the correlation between events that have characterized their evolution.

In the area north of the thrust fronts, despite the presence of erosion surfaces, sedimentation has prevailed and the sediments are preserved over very wide areas, while south of the fronts, sediments are present

only in a small part of the Cerrina valley, their thickness is much smaller and the sedimentary sequence show significant gaps.

Subsidence, linked to thrust front activity, involved both areas, during the same periods, but with different intensity.

A first phase of subsidence (S1) occurred in the period before the sub-chron Olduvai. For the period immediately following, the lacunae present in the stratigraphy of the Po basin do not allow any reliable correlation to be made.

The second subsidence phase, subsequent to an erosion phase in the Po basin and to a phase of tectonic stability in the Cerrina valley, appears chronologically well correlated in the two areas and can be dated between about 1.5 and 0.5 MA BP. As for the main phases of deformation, the tilting of the top of the Lacustrine Unit (sedimented during the sub-chron Olduvai) in the Cerrina valley syncline appears to be related to the phase of deformation D1 of the Po Basin, and to the possible phase of activity of the Lucedio and Cavourrina faults, while the intense phase of deformation of the sediments of the Alluvial Units A and B (about 1.07-0.7 MA old) of the Cerrina valley syncline is well correlated chronologically with the deformation D2 of the sediments of the Po Basin and with the phase of activity (F2) of the faults.

The interpretation of the data therefore enables it to be assumed that the Cerrina valley syncline corresponds to a trough behind the thrust fronts corresponding to the Lucedio and Cavourrina faults.

The set of tectonic deformations that took place during the Early Pleistocene, due to the evolution of the thrust front and to the subsidence of the Cerrina valley syncline, favoured the flow of the NW River to the Cerrina valley. Between 0.7 and 0.6 MA ago, when the subsidence of the Cerrina valley was limited to the eastern part, the flow of the NW River to the valley ended.

Overall, then, the Cerrina valley syncline and the Lucedio and Cavourrina thrust fronts make the geological situation rather unique within the front that extends from Turin to Casale Monferrato.

It follows that, in the area studied, the compressive tectonics not only ceased in a more recent period than in the surrounding area (as suggested also by Dela Pierre et al., 2003 a;b) but that above the thrust fronts evidenced by seismic lines the faults reach almost ground level, while to the east and west the sediments appear deformed by flexures, at least to a depth of 150-200 m below ground level (Giraudi, 2014).

Morphological evidence suggests that, even after the end of the compressive tectonics, the hills north of the Cerrina valley underwent an uplift similar to those already reported by Carraro and Valpreda (1991) in other areas of the Monferrato hills and by Giraudi (2014) in the Vercelli plain, south of the fronts. The uplift probably continued during the Late Pleistocene and perhaps during the Holocene.

However, the asymmetry of the Cerrina valley in the stretch, orientated W-E, and the presence of a sequence of terraces only on the northern side, suggest that the syncline may have acted, at least until the Upper Pleistocene, as a boundary between two hilly areas

(north and south of the valley) subject to different tectonic evolution.

The results of the research suggest that the NW River that entered the Cerrina valley probably was a river fed by the alpine valleys lying SW of the Aosta valley, or a collector of the streams that drained the Northern Monferrato.

The second hypothesis does not exclude, however, the possibility that, sometimes an alpine river could have flowed in the NW River basin due to the uncertain watershed boundaries.

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Ms. received: March 16, 2016
Final text received: July 18, 2016

