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THE MORPHOLOGY OF THE BASE OF THE ALLUVIAL SEDIMENTS OF THE VERCELLI PLAIN (PIEDMONT, NW ITALY): AN INTEGRATION OF THE KNOWLEDGE ON THE QUATERNARY GEOLOGICAL EVOLUTION

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ABSTRACT: The southern Vercelli Plain lies on the top of the westernmost Apennine thrust front (Monferrato thrust front). According to previous studies, it is interested by Quaternary tectonics and, despite the absence of historical earthquakes, could be affected by ML 6 earthquakes. However the lack of Middle Pleistocene river sediments and terraces in the southern part of the plain prevents any knowledge of the geological evolution for a period that lasted about 600-700 ka and limits the data useful to establish the seismo-tectonic characteristics of the Monferrato thrust front and to establish the seismic hazard.
Using the data derived from studies carried out in the 70s and 80s of the 20th century in order to localize a nuclear power plant, including field surveys, the drilling of dozens of boreholes, geophysical surveys, and hydrogeological studies of superficial waters and aquifers, and also data on the base of the unconfined aquifer, it has been possible to evidence the morphological features of the surface that lies at the base of the alluvial sediments.
The data indicate that in the southern Vercelli Plain there are small valleys and ridges covered by alluvial sediments, originated by erosion connected with the Alpine rivers and local streams, that do not show any evidence.
The pattern of the buried ridges and valleys appears to be influenced by tectonic movements along faults that, only in part, correspond to the Monferrato thrust front and transverse deformation zones active until the Middle Pleistocene.
Only for a small area, the buried drainage network flowed towards a karst system developed in Messinian gypsum.

Keywords: Quaternary, geological evolution, alluvial sediments, buried morphology, salt-karst in gypsum, Vercelli plain, Piedmont, Italy.

1. INTRODUCTION

The present work aims at a more complete definition of the geological evolution of the Vercelli plain. The succession and distribution of fluvial terraces in this area indicate the presence of Quaternary tectonics (GSQP, 1976; ENEL, 1984; Giraudi, 2014) and the relationship between the hydrographic network and the buried tectonic structures of the Apennines thrust front (Monferrato thrust front) are similar to those known in the easternmost Apennines front (Bonadeo et al., 2010; Burrato et al., 2012; Michetti et al. 2012; Livio et al., 2015). However, unlike the other sections of the front, the Vercelli Plain is characterized by extremely low seismicity, represented by very few earthquakes with local magnitude < 3 and also with their hypocentre located at depths exceeding 50 km (Rovida et al., 2011; RSNI, 2014a, b).

In the southeastern part of the plain, geodetic studies (Arca and Beretta, 1985) have also documented an uplift rate of more than 4 mm/year^{-1} between 1897 and 1957 AD, a period without earthquakes.

According to Michetti et al. (2012), the Vercelli Plain could be a seismic gap area, where the magnitude of the earthquakes could reach values close to ML6.

Published studies have provided information on the geological evolution of the area and on the shaping of the fluvial terraces since Marine Isotopic Stadium (MIS) 22, according to Giraudi (2014). While near the edge of the hills the terraces were formed only during the Late Pleistocene and Holocene, in the northernmost area there are six older terraces dated between the late Early Pleistocene and the late Middle Pleistocene. It follows that in the plain near the hills, the age of the terraces allows the evolution to be assessed only since the Late Pleistocene (Fig. 1A).

In fact, in the late Early Pleistocene and the early Middle Pleistocene, Alpine rivers that shaped the oldest terraces abandoned the area nearest to the hills and migrated north, and only in the Late Pleistocene returned to occupy the southern area (Giraudi, 2014).

The lack of glaciofluvial and fluvial sediments (from now on “alluvial sediments”) and terraces thus prevents any evaluation of the evolution of the southern plain for a period of about 600-700 ka.

The purpose of this study is to fill this knowledge gap and recognize at least some of the phases of the geological and morphological evolution that occurred before the Late Pleistocene and to outline the evolution of the area since the end of the Lower Pleistocene.

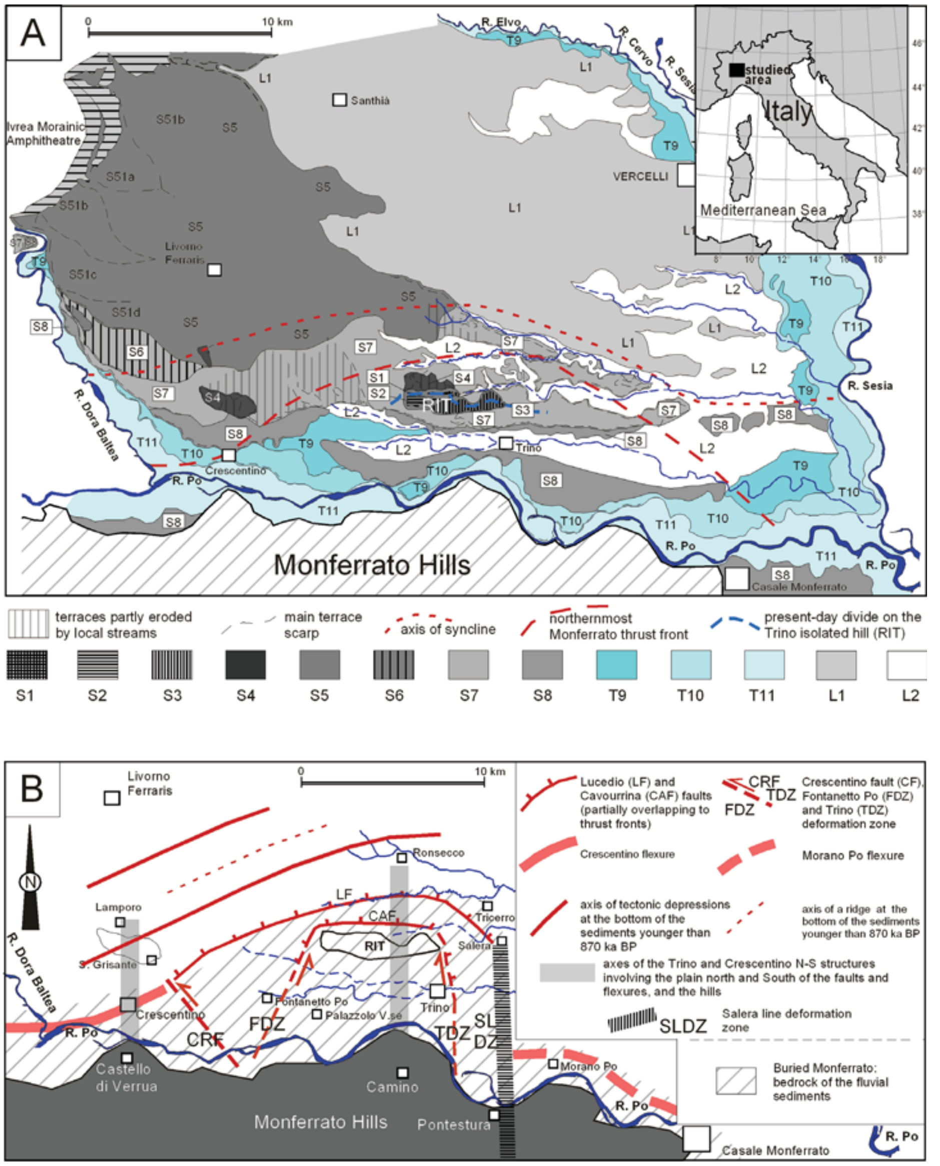

Fig. 1 - Morphological and tectonic sketch of the Vercelli Plain between the rivers Dora Baltea, Po, and Sesia. 1A - Fluvial and fluvioglacial terraces forming the Vercelli Plain. S1-S3: terraces forming the Trino isolated hill (RIT); S4-S8 terraces shaped by Alpine rivers when their beds were far from the present ones; T9-T11: terraces forming a belt near the present-day Alpine river beds; L1-L2: terraces shaped by local streams.

2. METHODS

To achieve the goal of outlining the geological evolution of the area since the end of the Lower Pleistocene some stratigraphic and morphological data were taken into account.

The strong variations in thickness of the sediments of alluvial origin have been evaluated over the Vercelli Plain lying near the northern edge of the Monferrato. The sediment thickness variations are derived from ENEL (1984) and from the stratigraphic data reported in the data-base of the Piedmont Region, and in particular from the map of the base of the unconfined aquifer (Regione Piemonte, 2004).

The shape of the surface lying at the base of the alluvial sediments, showing gentle ridges and depressions, was compared with the morphology of the valleys in the adjacent Monferrato hills, reported in the Carta Tecnica of the Piedmont Region at 1:10, 000 scale, in order to check any similarities, and with the direction of known tectonic structures, definitively active during the Early and Middle Pleistocene (Giraudi, 2014; 2016), in order to detect any tectonic constraints.

In particular, when the remnants of the depressions have similar directions to those of the main tectonic structures on which, or near which, they are located, or when significant changes occur in the buried drainage in correspondence with tectonic structures, it has been assumed that tectonics have influenced, directly or indirectly, the evolution of the drainage network that shaped

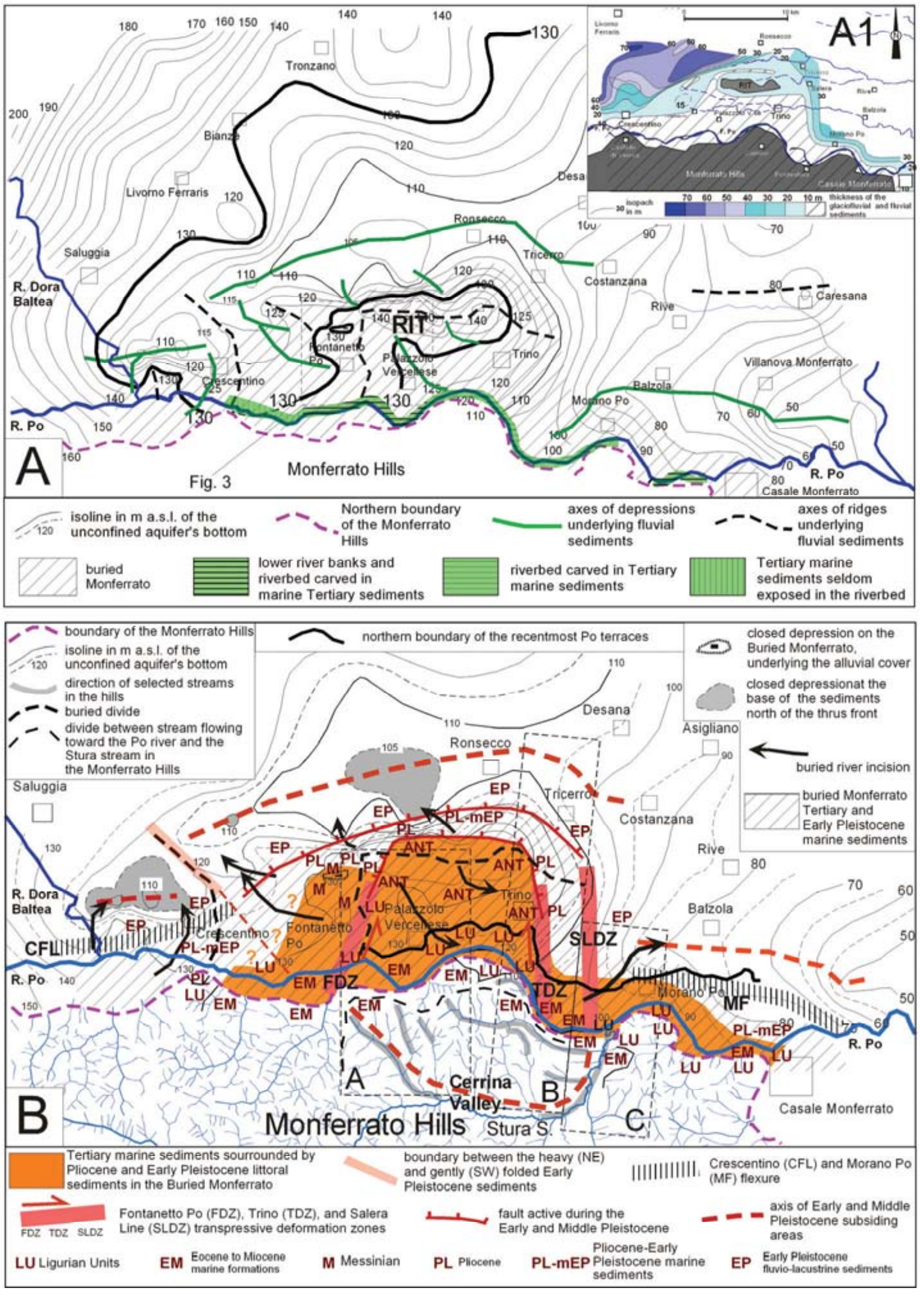

Fig. 2 - Isobaths of the base of the unconfined aquifer and morphological and geological features buried by the alluvial sediments. 2A- map of the isobaths of the unconfined aquifer (modified from Regione Piemonte, 2004) and morphological features buried by alluvial sediments. A1 - thickness of the alluvial sediments dated between ca 870 ka BP and the present (from Giraudi, 2014).
2B - Interpretation of the morphological features at the base of the unconfined aquifer, comparison between the direction of the valleys covered by alluvial deposits and of some valleys and streams in the nearby hills, correlations between morphological features and tectonic elements, and age of the sediments that form the Buried Monferrato.

the buried surface.

The position of the thrust front and of the structures connected with it, assumed in the present paper, have been discussed in Giraudi (2014; 2016). In those papers it was observed that the various models, inferred from the geophysical data, if considered in detail, overlap only partially the structures indicated by the field and borehole data: therefore in the present paper are reported only faults and deformation zones that have been evidenced by field researches and borehole data and that show a clear post-Pliocene activity.

The chronological framework of the erosion phases that shaped the surface on which the alluvial sediments lie is based on the age of the sediments on which the surface lies and of the sediments that seal it, and on a comparison with the shaping of the oldest terraces, for which we have dating elements. The age of the fluvio-lacustrine, fluvioglacial and fluvial sediments, discussed in Giraudi (2014; 2016), is based on palaeomagnetic data, on the presence of a tephra layer (reported in ENEL, 1977; 1984), on the correlation with the nearby Ivrea morainic amphitheatre, and on archaeological artefacts dating from the Lower Palaeolthic to the Roman age.

3. GEOLOGICAL OUTLINE OF THE SOUTHERN VERCELLI PLAIN

The Vercelli plain, mainly formed by sediments of the Dora Baltea, Po and Sesia rivers, extends southwards as far as the Monferrato hills (Fig. 1). In the 70s and 80s of the 20th century, the plain was the subject of thorough geological surveys in order to site a nuclear power plant (ENEL, 1977; 1984). The researches produced a wealth of data which, integrated with the most recent data, are subject to different interpretations.

Geological studies carried out between 1975 and 1984 (ENEL, 1977; 1984) were intended to improve knowledge of the tectonic evolution of the Monferrato thrust front, that is, the westernmost of the Apennine chain thrust fronts. The studies included geological and geomorphological field surveys, the drilling of dozens of boreholes up to 200 m deep, geophysical surveys using electric (Fig. 2A) and seismic methods, and finally, the hydrogeology and the geochemical characteristics of surficial waters and aquifers.

In more recent years, the review of the data has suggested some new interpretations that have increased our understanding of the Pliocene-Pleistocene geological evolution of the area enabling it also to confirm previous interpretations and to assume the presence of tectonic structures transverse to the front (Fig. 1B), which sometimes affect also the neighboring hills (Bigi et al. 1990; Costa, 2003; Giraudi, 2014; 2015; 2016).

The Vercelli Plain is made up of a series of terraced sedimentary units, whose origin is mainly glaciofluvial and fluvial, that can be dated between ca. 0.87 MA ago and the present time (Fig. 1A).

According to the data reported in ENEL (1976; 1984) and Giraudi (2014; 2016), in the southern plain the sediments are less than 20 m thick (Fig. 2A) and cover a complex erosional surface that shapes the top of strongly deformed Tertiary marine sediments, similar to those forming the Monferrato hills (Fig. 2B). The marine sedimentary units buried in the Vercelli Plain will be called, from now on, the Buried Monferrato.

The Buried Monferrato also includes Piacenzian marine sediments and Gelasian littoral ones (ENEL, 1984; Violanti and Sassone, 2008; Giraudi, 2016) that contour the oldest marine sediments and do not outcrop on the adjacent hills (Fig. 2B).

The sequence of Tertiary sediments sampled in boreholes drilled in the Buried Monferrato deserves special attention because it helps to recognize the displacement produced by some tectonic structures.

According to ENEL (1984), in the area north and south of the RIT, the pre-Pliocene sediments are represented by the Late Oligocene-Early Miocene Marne di Antognola Formation and by Late Cretaceous and Eocene Ligurian Units (Complesso Indifferenziato and Casale Monferrato Formation) outcropping also in the neighbouring hills. In the area near Fontanetto Po, the sediments are Messinian (post-evaporitic, evaporitic and pre-evaporitic) consisting also of layers of crystalline gypsum, both compact and laminated, and of conglomerates with pebbles of crystalline gypsum, which do not outcrop in the adjacent hills. The Messinian sediments then, although not studied in detail, show a succession similar to that of some stratigraphic sections studied by Clari et al. (2008) and Dela Pierre et al. (2016) in the Piedmont Tertiary basin, south of the Monferrato.

The marine sediments that form the Buried Monferrato (Fig. 1B, 2B) and the Early Pleistocene fluvio-lacustrine sediments, lying north of the thrust front but close to the tectonic structures, can dip strongly towards the north and be affected by both low-angle and sub-vertical fault plains, sometimes with striae (Giraudi, 2016).

The activity of the Monferrato thrust front lasted until the Lower or Middle Pleistocene (GSQP, 1976; ENEL, 1977; 1984; Cassano et al., 1986; Costa, 2003; Galadini et al., 2012; Giraudi, 2014). Instead, according to some Authors the thrust front would still be active (Bonadeo et al., 2010; Burrato et al., 2012; Michetti et al. 2012; Livio et al., 2015).

In Giraudi (2014) it is observed that two areas near Crescentino and Trino, having their axis oriented approximately N-S, seems affected by a weak Late Pleistocene and Holocene uplift, supporting the hypothesis, advanced by previous Authors, that tectonics are still active. The uplift, however, occurred also north of the thrust front, in places subsiding during the main phases of activity of the structure (Fig. 1B).

The deformation of the sediments is connected to the activity of faults, i.e. the Lucedio, Cavourrina, and Crescentino fault (LF, CAF, and CRF in Fig. 1B), the Fontanetto Po, Trino and Salera Line deformation zones (FDZ, TDZ and SLDZ of Fig. 1B), and the Crescentino and Morano flexures (Giraudi, 2014; 2016).

According to Costa (2003) a first fault, the position of which corresponds to the Crescentino fault of the present paper, and a second fault, corresponding to the Salera Line deformation zone, acted as transpressive structures that cut across the buried fronts.

The Lucedio and Cavourrina faults overlap only in part short stretches of two different thrust fronts evidenced by geophysical researches (ENEL, 1977; 1984; Cassano et al., 1986; Bigi et al. 1990), according to Giraudi (2014; 2016). The displacement of Tertiary and Quaternary sediments produced by the faults indicate that, near the surface, they acted as normal faults that moved downward the sediments lying north. In the Fontanetto Po and Trino deformation zones, the vertical component of the displacement produced the subsidence of the areas west of Fontanetto Po and east of Trino. Also the flexures lie only on some stretches of thrust fronts. Thus, not knowing the real connection between the superficial and deeper tectonic structures, in the present paper, the evolution of the erosion surfaces

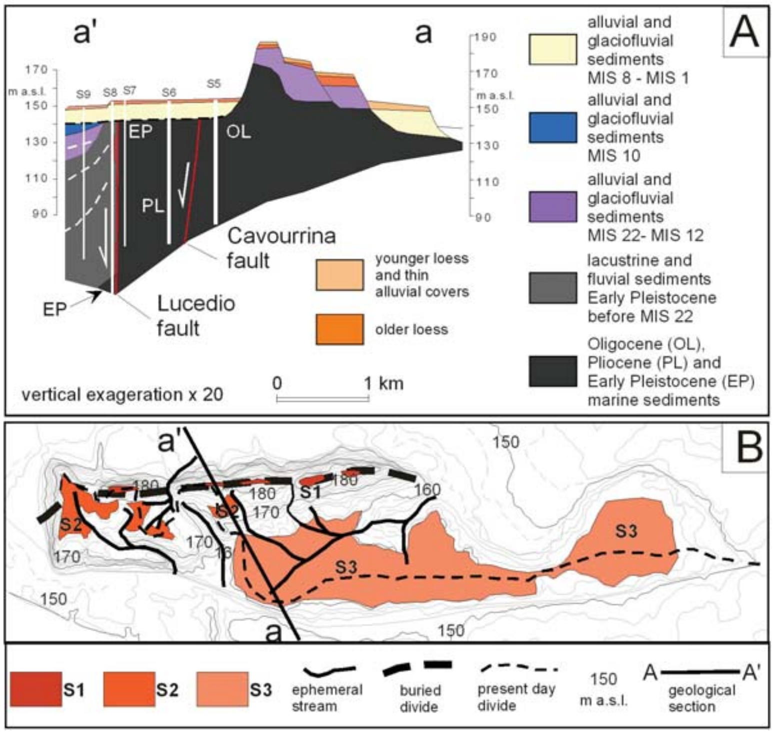

Fig. 3 - The Trino isolated hill (RIT). 3A: geological section through the hill and the surrounding terraces. 3B: Morphological features and buried and present-day divides (modified from Giraudi, 2016).

that shaped the Buried Monferrato will be compared only with the activity of faults, deformation zones and flexures, active during the Quaternary, that have been characterized using borehole data and field observations, without any reference to the activity of the Monferrato thrust front that could be more complex.

Some analysis of the deformation phases, of the age and sedimentary facies of the Early and Middle Pleistocene lacustrine, fluvio-lacustrine and alluvial units lying north of the Lucedio fault and in the Cerrina valley syncline, in the Monferrato Hills (Fig. 2B), have been discussed in Giraudi (2016). The data enabled it to be hypothesized that the hilly area north of the Cerrina Valley and the Buried Monferrato lying between the hills and the Lucedio and Cavourrina faults, were involved in the same phases of migration toward north of the Monferrato thrust front.

The review of the stratigraphy of the boreholes reported by ENEL (1984) has shown that in some cases, in correspondence with the Fontanetto Po deformation zone (FDZ - Fig. 2B), the tertiary sediments are affected by subvertical fault planes and that, in general, to the west of the deformation zone, the sediments (Messinian, Pliocene and Early Pleistocene littoral) are more recent than those located to the east (Ligurian Units, dated between the Upper Cretaceous and the Lower-Middle Eocene, and Marne di Antognola Formation, dated between the Upper Oligocene and the Lower Miocene).

In addition, to the west of the Fontanetto Po deformation zone, both the contact between the Pliocene and pre-Pliocene sediments and the northern limit reached by the Ligurian Units are considerably further south than in the eastern area. These data confirm the presence of that deformation zone, suggested by Giraudi (2016) on the basis of the correlation between the Cavourrina fault segment oriented NNE-SSW and a series of fault lines oriented approximately N-S and NNE-SSW identified in the bed of the Po, and also probably a left slip component.

Along the Trino Deformation Zone (TDZ in Fig. 2B), postulated by Giraudi (2016) on the basis of the correlation between the eastern branch of the Cavourrina fault segment oriented NNW-SSE and a series of fault lines oriented approximately N-S and NNW-SSE identified in the bed of the river Po, it can be observed that, to the west, the sediments (Ligurian Units, Marne di Antognola Formation) are older than those located to the east (marine Pliocene and Early Pleistocene). In addition, to the west of the Trino defomation zone, the northern limit reached by pre-Pliocene tertiary sediments, corresponding to the Cavourrina fault, lies considerably further north than in the eastern area, suggesting a possible right slip component.

To the north of the Lucedio fault (Fig. 3A), the oldest continental sediments lying in the area between the Crescentino fault and the Salera Line deformation zone are strongly deformed, while W and E of these structures, the sediments are gently tilted northward (ENEL, 1984; Giraudi, 2016).

During the phases of activity of the Lucedio fault, the Buried Monferrato was uplifted while in the subsiding northern basin a syncline evolved having its axis nearly parallel to the fault (Pieri and Groppi, 1981; ENEL, 1984; Cassano et al., 1986).

Based on the difference between the elevations of the base, the different thicknesses and the age of the alluvial sediments north and south of the Lucedio fault, said fault may have been active up to about 0.4 MA ago and the total deformation of the bottom of these sediments has been estimated as between 80 and 120 m (Giraudi, 2014; 2016).

The succession of Quaternary sediments lying on the Buried Monferrato is represented by alluvial deposits which chronologically refer from about 0.87 MA ago to the present (Giraudi, 2014).

These sediments form ten different terraces (S1, S2, S3, S4, S7, S8, T9, L2, T10, T11 - Fig. 1A). The oldest terraces (S1-S3) form the RIT, a ridge which rises 40-50 m above the surrounding plain (Fig. 3B). The lower terraces incline mainly from west to east, only those NE of the RIT inclining mainly from WNW to ESE.

North of the Lucedio fault, Early Pleistocene fluvio-lacustrine deposits lie below alluvial ones that started to sediment during the MIS 22 (Giraudi, 2014; 2016). In this area, where the terraces S1, S2 and S3 are lacking, rivers formed three terraces (S5, S6, L1), lacking south of the fault, and sloping mainly from NW to SE.

4. THE BURIED MORPHOLOGY AND THE BASE OF THE UNCONFINED AQUIFER

Since the ENEL (1984) studies, it is known that in the Buried Monferrato the base of the unconfined aquifer corresponds indisputably to the top of the marine sediments, mostly marl and clay, while in the area just north of the Lucedio fault it generally corresponds to the contact between alluvial and fluvio-lacustrine sediments.

The comparison of the thickness of river sediments reported in Giraudi (2014), based mostly on the ENEL (1984) data, and the shape of the base of the unconfined aquifer reported on the Piedmont Region map (Regione Piemonte, 2004) confirms the previous data.

The two maps (Fig. 2A), albeit at a different scale and resulting from the processing of data of different origin, show a substantial accordance for the Buried Monferrato and the area located immediately to the north. Also the data reported in Irace et al. (2009), on a less detailed map, show a similar trend.

In addition, the set of geophysical surveys and calibration boreholes carried out in the central area of the Buried Monferrato (ENEL, 1977; 1984) provided a reconstruction of the top of the marine sediments which confirms, with more detail (Fig. 4A), the trend shown by the map of the Regione Piemonte (2004).

The map of the base of the unconfined aquifer is thus taken as the basic document for discussion and interpretation of the main morphological features buried by the alluvial sediments in the southern portion of the Vercelli plain, while the more detailed map of the RIT and neighbouring areas (Fig. 4) is used to discuss some specific features.

It should first be noted that in Fig. 2 the continuity of the isobaths of the base of the aquifer is interrupted by the presence of the Po riverbed, which is eroding the Monferrato Hills and Buried Monferrato tertiary marine sediments, and acts as the southern boundary of the unconfined aquifer.

In any case, in Fig. 2A the stretches of the Po riverbed with different characteristics have been highlighted: in the less incised ones the tertiary sediments occasionally outcrop, in the more eroded ones the same marine sediments constitute most of the riverbed; and finally the deeply incised riverbed, where also the river banks consist of tertiary sediments.

The map of the depth of the base of the unconfined aquifer (Fig. 2A) shows some elements of direct interest such as ridges and depressions covered by alluvial sediments.

The most obvious buried ridge is oriented approximately west-east, and lies beneath the alluvial sediments of the RIT: towards the east, it becomes less noticeable and takes an approximately NW-SE direction, while to the west it takes a north-south direction. The southern edge of this ridge is cut by the Po riverbed which, precisely in this area, is more incised.

Ridges are less evident NW of Fontanetto Po and near Crescentino, but one of them, which lies NE of Crescentino, divides into two a buried depression described below.

Among the depressions covered by alluvial sediments, the most obvious one runs from the area west of Crescentino to Costanzana, east of the RIT, while a second one, the southernmost one, runs from Morano Po to the area north of Casale Monferrato.

The first of these depressions is complex, with the presence, west of Crescentino and north of the RIT, of deeper closed basins separated from the rest of the depression by means of some buried ridges.

Other minor depressions lie near Crescentino, Fontanetto Po, Palazzolo and north of the RIT.

North of Fontanetto Po there is a small closed depression with its bottom lying some metres below the top of the Buried Monferrato in the surrounding area.

The morphology of the top of the Buried Monferrato, corresponding to the base of the unconfined aquifer, in the Fontanetto Po area has been highlighted in detail by the use of a greater number of boreholes and geophysical surveys.

Fig. 4A, modified from ENEL (1984), shows that the morphology of the top of the marine sediment is very complex, being affected by gentle ridges and depressions. The more evident ridge is buried under the RIT. Two other major ridges are lying north of Palazzolo, running from NW to SE.

There are also elongated depressions in various directions and, especially, in the area north of Fontanetto Po, there is a complex closed depression, corresponding to that observed in Fig. 2A.

A special case concerns the RIT. The base of alluvial sediments which form the terraces S1 and S2, dating from the final stages of the Early Pleistocene (Giraudi, 2014), fills a depression running N-S and then NE-SW, while the sediments that form the S3 terrace fill a depression (only partially preserved due to erosion) that seems oriented from NNW to SSE. Said direction is not very different, therefore, from that of the southernmost depressions.

5. THE BURIED MORPHOLOGICAL FEATURES: INTERPRETATION AND DISCUSSION

The interpretation of the buried depressions and ridges (Fig. 2A), is based on the comparison with the direction of the valleys carved by the streams on the hills, and on the relationship between the identified morphological features and the lithology of the Tertiary sediments and the tectonic structures affecting the Buried Monferrato and the northernmost areas (Fig. 2B).

The comparison allows some immediate interpretations. The two stretches of the depression that extends from west of Crescentino to the Costanzana area (Fig. 2B) nearly overlap a syncline, evidenced by geophysical data and wells for oil research, that was formed in the subsiding basin north of the Lucedio fault during the Pliocene and Early Pleistocene (Montrasio et al., 1969; Pieri and Groppi, 1981; ENEL, 1984; Cassano et al., 1986). The westernmost depression is almost parallel to the Crescentino flexure, while the remaining stretch is almost parallel to the Lucedio fault. The depression west of Crescentino is a closed one, therefore it cannot have been produced only by river erosion but also by tectonic deformation. Also the depression extending towards

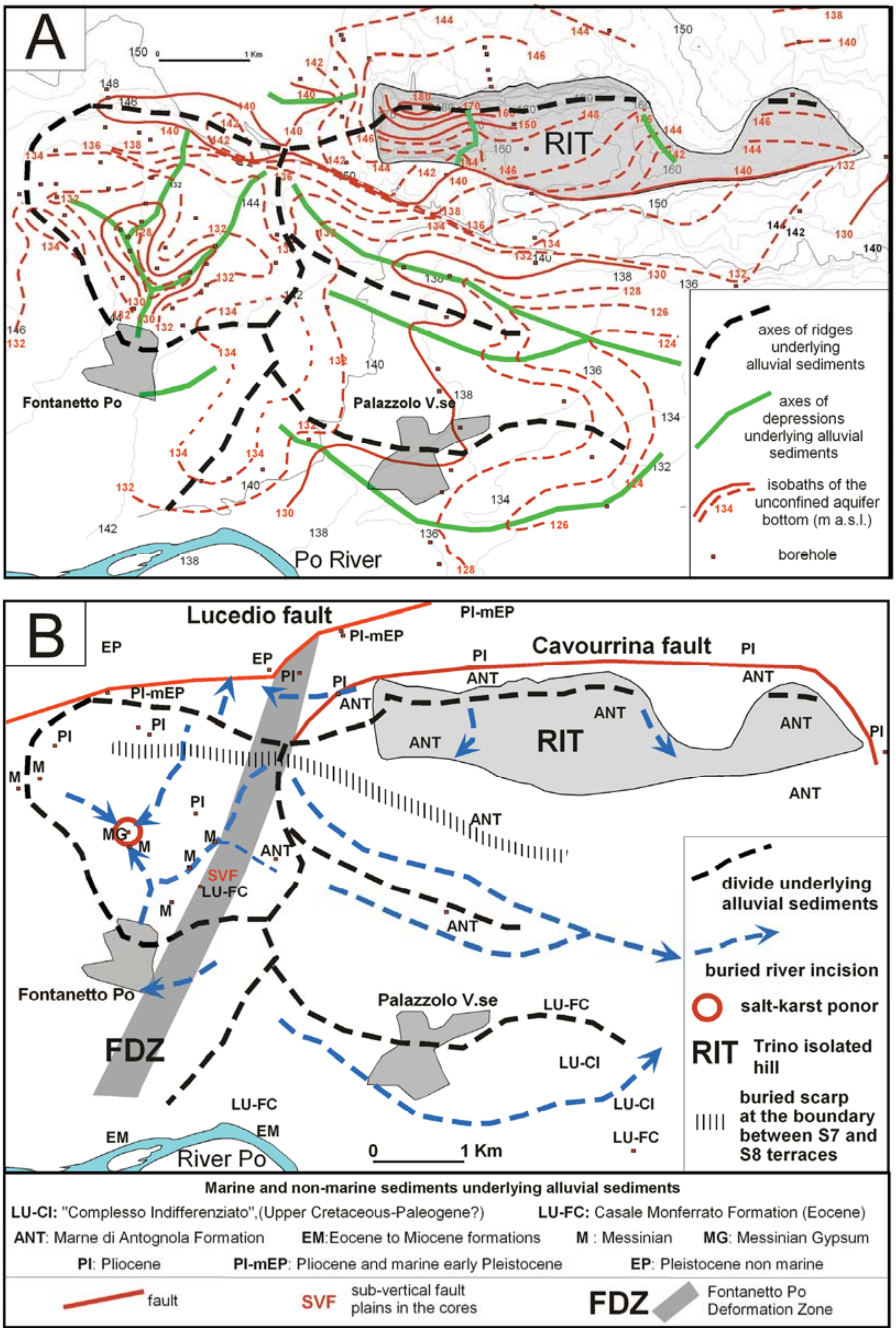

Fig. 4 - Detailed map of the isobaths of the base of the unconfined aquifer, and interpretation of the morphological features buried by alluvial sediments near the Trino isolated hill (RIT). 4A- Map of the isobaths of the base of the unconfined aquifer and buried morphological features. 4B- Interpretation of the buried morphological features, main tectonic structures active after 870 ka BP, Upper Cretaceous to Early Pleistocene marine sediments forming the Buried Monferrato.

Costanzana, that overlaps a long stretch of the Pliocene and Early Pleistocene syncline, does not correspond only to a river incision, subsequently filled by sediments, because it includes two smaller closed depressions that can be explained only by assuming a tectonic deformation.

Moreover, the western and eastern boundaries of the same depression lie in correspondence with the extension towards the northwest of the Crescentino fault and with the Salera Line deformation zone.

The subsidence of the area lying north of the Lucedio fault suggests that between the Early and Middle Pleistocene sedimentation prevailed over the erosion (Giraudi, 2016).

The second wide depression, which lies north and east of Morano Po, is almost parallel to the Morano flexure, and nearly overlaps a post-Pliocene syncline, evidenced by geophysical data and wells for oil research, that was formed in a basin north of the flexure (see geological sections in Montrasio et al., 1969). The depression, filled by sediments dated since the MIS 22 (Giraudi, 2014), ends abruptly to the west and, if it had been produced only by the erosion of a river, it would have to continued toward west or NW.

The depression north of the Morano flexure starts just east of the Salera Line deformation zone while, as reported before, the depression that lies north of the RIT ends in correspondence with the northern extension of the same deformation zone. Therefore, the Salera Line deformation zone could also have played a role in influencing the evolution of the buried morphologies at its western and eastern edges.

Other linear depressions, smaller in size and having various orientations, run from marginal areas towards the axis of the main depressions: it follows that the smaller depressions were probably palaeovalleys weakly carved by local streams.

In the area north of Palazzolo and NW of Trino the depressions run from NNW to SSE and then bend E. The trend of these depressions appears similar to that of the valleys in the adjacent hills (Fig. 2B). It is therefore likely that the shaping of the buried depressions observed in that area and of the valley in the Monferrato was conditioned by the same tectonic and morphological forcing factors.

The depressions lying between the Fontanetto Po deformation zone and the Crescentino fault, show a SE-NNW trend, while those observed west of the Crescentino fault run towards the north, like the valleys in the adjacent hills.

Figure 2B shows some interpretations of the buried ridges.

The main ridge present in the RIT area and towards the hills is almost parallel to the Cavourrina fault and the Fontanetto Po deformation zone. However, the ridge has an irregular shape, because it was affected by the erosion produced by the heads of catchment basins of small streams tributary to the main rivers.

The secondary ridge located east and north of Crescentino is aligned with the extension towards the northwest of the Crescentino fault, at the boundary between the sediments gently deformed by the Crescentino flexure and the sediments strongly deformed by the Lucedio fault (Giraudi, 2014; 2016).

The more detailed data shown in Fig. 4 confirm the presence of a main buried divide trending west-east in the RIT area, which is connected to the stretch of the divide running south. That ridge lies at the northern and western margins of the area uplifted by tectonics along the Cavourrina fault and the Fontanetto Po deformation zone, and is almost parallel to these structures.

South of the RIT, there are smaller buried divides trending NW to SE, and separate buried valleys elongated from NW to SE, then about west-east and, in some cases, WSW-ENE.

The valleys are the same already highlighted in the less detailed map of Fig. 2, and confirm a trend similar to that of the valleys in the adjacent Monferrato hills.

In Fig. 4 the differences in elevation between the various sections of the main divide can be observed: the divide reaches 180 m a.s.l. under terrace S1 of the RIT and 148-146 m a.s.l. under terrace S3, while below the upper Pleistocene and Holocene sediments, forming the S7, S8, T9, T10 and T11 terraces, its elevation is between 146 and 132 m a.s.l.

The buried divide, then, reaches the lower elevation near the margin of the hills, below the alluvial sediments of the most recent terraces, having been subject to fluvial erosion until the late Holocene.

The present summit elevation of the top of the divide may have been influenced not only by its original height and by the river erosion but also by sub-aerial erosion that occurred before the alluvial fill, and by tectonic uplift.

In the absence of any alluvial cover, the divide was subject to sub-aerial erosion, but when covered, it ceased to evolve and its height can only have been influenced by tectonics.

For a long time, while the main rivers flowed north of the RIT, south of the isolated hill the stretch of the divide running N-S was not covered by river sediments, and thus underwent sub-aerial erosion. Only in the initial phase of the Late Pleistocene, when diversion of the Alpine rivers to the south of the RIT occurred (Giraudi, 2014), this stretch of divide began to be affected by more intense fluvial erosion and was then covered by alluvial deposits.

The Tertiary sediments that form the buried divide southwest of the RIT are clearly cut into by a scarp elongated about W-E located exactly in correspondence with the escarpment between terraces S7 and S8 (Fig. 1A; Fig. 4B). It is clear that in this area the top of the divide was eroded during the Late Pleistocene, but that the erosion did not erase entirely the morphology shaped earlier.

The small valleys carved in the Buried Monferrato, including those that drain into the Fontanetto Po endorheic depression, may have orientations similar to those of tectonic structures even when they are not exactly overlapping these. In any case, the valleys have orientations generally different from those of the Alpine rivers (flowing mainly W-E) that shaped the Late Pleistocene and Holocene terraces.

The comparison between the shape and direction of the divide in the Buried Monferrato below the alluvial sediments and the current divide between the basins of the Po and of the Stura stream in the adjacent Monferrato Hills (Fig. 2B, box A) shows that they are very similar in shape and that their west-east stretches are parallel to the Cavourrina fault, while those oriented approximately north-south are almost parallel to the Fontanetto Po deformation zones (Fig. 2B, box A).

This correspondence does not seems to be accidental because the Buried Monferrato and the Monferrato Hills consist of the same marine sediments and suffered a common displacement towards the north during the last phase of the thrust front migration (Giraudi, 2016). Also from Fig. 2B (box B), it can be observed that a series of valleys in the Monferrato, and the buried divide east of the RIT, change direction becoming NW-SE, as does the northern edge of the hills.

As stated above, the directions of the hill streams and of the current and buried divides have a pattern very similar to that of the Cavourrina fault, but Fig. 2A (box B) also indicates that the main change of direction of the buried morphological features occurs just south of those affecting the Lucedio fault and the axis of the depression parallel to the fault. The buried morphological and tectonic features assume a NNW-SSE and NW-SE direction on the northern and southern prolongations of the Trino deformation zone, which corresponds to the eastern branch of the Cavourrina fault (Giraudi, 2016).

In box C of Fig. 2B, it is possible to note that, at the southern continuation of the Salera Line deformation zone, the northern edge of the hills, the valleys carved in the hills and in the Buried Monferrato, after a short west-east stretch, change direction, assuming a SW-NE or WSW-ENE trend.

Overall, therefore, the trend of the buried valleys and divides on the Buried Monferrato is similar to that of the Monferrato hills, as can be expected from areas that have undergone a common geological and tectonic evolution.

The changes in the direction of the buried morphological features, of the drainage network and of the divides between the catchment basins, lie almost in correspondence with the most important tectonic structures surrounding the area between the Lucedio fault and the Cerrina Valley, that was subject to the common geological evolution until 400 kyr ago, according to Giraudi (2016). This general correspondence suggests that the drainage evolution was directly or indirectly conditioned by tectonics affecting the area until, at least, the last periods of activity of the Lucedio fault.

The most singular buried morphology occurs just north of Fontanetto Po: it is a closed basin which includes some small valleys that converge towards the deepest part of the depression. The direction of the longer valleys is mostly parallel to the Fontanetto Po deformation zone (NNE-SSW), while two shorter valleys run NW-SE. The parallelism between the longer valleys and the direction of the deformation zone suggests that their incision could have been influenced by tectonics.

The closed depression, and the small drainage network that it contains, may have originally been a continuation to the NW of the valleys lying east of the buried divide, but later, the continuity of the valleys could have been broken by the activity of the Fontanetto Po deformation zone that produced the subsidence of the western area.

However, the presence of Messinian sediments (Fig. 4B) with compact gypsum near the deepest part of the closed depression suggests a hypothesis that may be alternative or complementary to that presented above.

The closed basin may have formed due to the development of salt-karst in the gypsum. The presence of a karst swallow-hole could have attracted the streams that carved small valleys. The presence of salt-karst in the gypsum and of small closed depressions that drain into the karst systems are known in the southern slope of the Monferrato hills (Fioraso et al., 2004) and confirms that the hypothesis of the presence of salt karst in the gypsum in the Buried Monferrato is quite likely.

Apart from the closed depression possibly produced by karst, the wider and longer buried ridges and depressions are superimposed or lie close to and are parallel to tectonic structures: it is thus assumed that the shaping of the buried morphology was directly or indirectly influenced by the tectonics.

6. AGE AND EVOLUTION OF THE BURIED DRAINAGE NETWORK

The maximum possible age for the beginning of the shaping of the drainage network of the Buried Monferrato corresponds to the age of its emersion from the sea. The core of the Monferrato hills, being surrounded by Pliocene sediments of littoral facies, would have emerged already during the Pliocene (Sacco, 1889; Carraro et al., 1980; Dela Pierre et al., 2003).

The Buried Monferrato, made up of Tertiary marine sediments, is surrounded by littoral sediments dated at the beginning of the Gelasian (Giraudi, 2016). It follows that during the Gelesian the Buried Monferrato could already have emerged from the sea.

Other chronological data stem from the RIT: the portion of the main divide buried below the oldest continental sediments (MIS 22, started 0.87 MA ago) was shaped during the Early Pleistocene.

In its southern part, the main divide lies buried beneath the sediments that form the Late Pleistocene and Holocene terraces, is a very gently sloping ridge and, in theory, could have been formed in the whole period between the Gelasian emersion and the Late Pleistocene-Holocene.

The differences in elevation between the various sections of the main divide, discussed before, allow it to be hypothesized that the whole divide was formed during the Early Pleistocene and was partially eroded during the erosional and depositional processes that led to the formation of the Pleistocene and Holocene terraces.

9. CONCLUSIONS

The morphology of the basal surface of the alluvial sediments that host the unconfined aquifer in the southern Vercelli plain allows new hypotheses to be advanced as to the geological evolution of the area north and south of the Lucedio and Cavourrina faults.

The main depressions are located just north and are parallel to the Lucedio fault and Crescentino and

Morano flexures, they overlap the area subsiding until the first half of the Middle Pleistocene, and are broken or end in correspondence with tectonic elements transverse to said structures.

When the Alpine rivers flowed north of the Lucedio fault, the small streams, fed by the uplifting area south of the fault, flowed towards the rivers, carving small valleys.

South of the Lucedio fault, on the Buried Monferrato, there are ridges covered by alluvial sediments, and small valleys originated by erosion connected to the Alpine rivers and local streams.

The main buried ridge lies at the northern and western margins of the area uplifted by tectonics along the Cavourrina fault and the Fontanetto Po deformation zone, and is almost parallel to these structures. This ridge can be interpreted as a divide between catchment basins of short streams, that drained to the SE, and the Po basin.

In the area between the Lucedio fault and the hills lie other small buried ridges, corresponding to minor divides between the basins of local streams. The buried valleys and ridges were carved mainly during the period between the Gelasian and the late Early Pleistocene, but in part of the area south of the Trino isolated hill they were eroded until the Late Pleistocene and the Holocene.

The direction of the small buried valleys was similar to that of the present-day valleys in the Monferrato hills, to the course of the Po and to the belt of its most recent terraces. In addition, changes in the direction of the valleys occur in correspondence with tectonic elements transverse to the Lucedio and Cavourrina faults and the Crescentino and Morano flexures. The direct or indirect connection between the shaping of the drainage network and tectonic activity is, therefore, likely.

The trend of the main buried features, thus, has been influenced by tectonic movements along the Lucedio and Cavourrina faults and the transverse deformation zones.

The direction of the small buried valleys north of Fontanetto Po, conversely, was mainly conditioned by the presence of a karst system developed in Messinian gypsum.

After the Late Pleistocene diversion of the Po south of the Trino isolated hill the former divides have been partially eroded, and the alluvial sediments filled the small valleys and shaped low terraces.

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