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STRATIGRAPHIC AND TECTONIC NOTES ON THE VILLAFRANCA D'ASTI SUCCESSION IN TYPE-AREA AND CASTELNUOVO DON BOSCO SECTOR (ASTI RELIEFS, PIEDMONT).

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ABSTRACT: Interest in the sedimentary succession in the Asti Reliefs fostered research since the beginning of the science of geology, before the designation by Pareto (1865) of the "Piano Villafranchiano" and its type area at Villafranca d'Asti. The villafranchian sediments have been the subject of many recent investigations, which focused largely on the palaeontology of vertebrates and plant remains.
Geological surveys in the type area and in the Castelnuovo don Bosco sector revealed that the sedimentary succession is stratigraphically and tectonically more complex than was previously supposed. The succession exhibits an important hiatus represented by an angular unconformity that allows for the differentiation of two complexes containing different facies. The Lower Complex (LC)(delta facies), which contains abundant fossils (vertebrates, pollen and plant remains, molluscs), is referred to the Piacenzian. The Upper Complex (UC) (fluvial facies), which is very sparsely fossiliferous, is uncertainly referred to the Calabrian.
New surveys in the type area of Villafranca d'Asti involve an integration of the stratigraphic and paleopedologic framework. These studies focused on a paleosol, including bodies of colluvial sediments, that lie on the unconformity which separates the two complexes.
All the sediments display significant deformation as indicated by the overall geometry of the succession, the presence of soft sediment deformation, the localized presence of deposits produced by gravitational reworking of the deltaic sediments and finally by the presence of deformational zones (T. Traversola Deformation Zone, C. Fagliaverde Fault Zone and Castelnuovo Fault Zone) and faults (Gariglio Fault, Serra Fault and Agagliate Fault). New data regarding the T. Traversola Deformation Zone suggest its southern extension, confirming the strike-slip nature.
The critical revision of mammal-fauna and micro- and macrobotanical evidence permitted to discuss the chronological and stratigraphical context of such sedimentary succession.

Keywords: Sedimentary succession, Plio-Pleistocene, Asti Reliefs, Villafranca d'Asti, Italy

1. INTRODUCTION

Interest in the sedimentary succession in the Asti Reliefs has promoted research since Pareto (1865), who defined the "Piano Villafranchiano" and its type area at Villafranca d'Asti. Pareto considered the Villafranchiano a continental stage which was first correlated to the marine Calabrian Stage of Gignoux (1916). During the18th I.G.C. of London (1948), the Calabrian was placed at the base of Pleistocene and consequently the Villafranchiano became the earliest continental stage of the Pleistocene.

The recognition of a great number of continental vertebrates and other significant fossil findings in the transitional deposits outcropping in Villafranca d'Asti and surrounding areas allowed to develop a better knowledge of their mammal assemblages. The paleontological studies carried out from pioneering works in the 1960s until the end of the last century allowed to define the Villafranchian Mammal Age as a biochronological unit. This unit represents a subdivision of the geological time of evolutionary stages of faunal assemblages and dispersal events (Rook & Martinez-Navarro, 2010 and references therein). The Villafranchian Mammal Age, and its chronological subdivisions, according to the International Stratigraphic Scale, corresponds to the Late Pliocene (Piacenzian, from 3.5 to 2.6 Ma) and to the Early Pleistocene (Gelasian and Calabrian p.p., from 2.6 up to 1.1 Ma, near to the base of Jaramillo subchron).

As a consequence, the term "Villafranchiano" lost its original chronostratigraphic significance: the name "Villafranchian succession" is maintained solely for historical reasons to indicate the various sedimentary successions outcropping in the Villafranca basin and in the Castelnuovo Don Bosco sector, including transitional deposits between the Pliocene marine succession and the continental sediments. The various "villafranchian" sedimentary successions fall within the Piacenzian, Gelasian and Calabrian Stages, utilizing the current chronostratigraphic scale and the connected stages nomenclature (Gibbard et al., 2010).

Most of the studies focused on localized outcrops

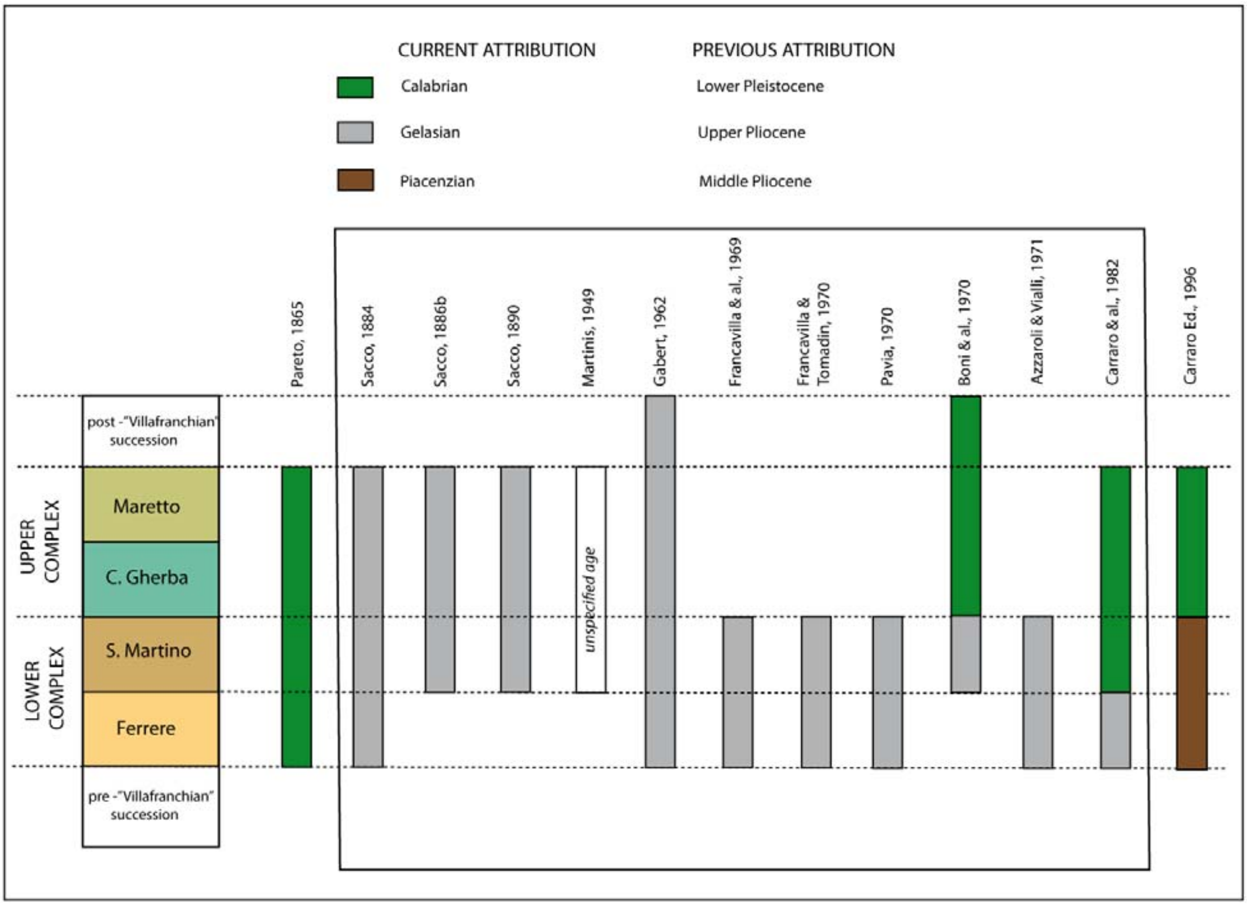


Fig. 1 - Various designations and subdivisions of the "Villafranchian succession" at various times. The current units (Ferrere, San Martino, Gherba and Maretto) are reported on the left side of the figure. Only the central unit of the succession (now the S. Martino Unit) was always regarded as part of the succession defined by Pareto. The stratigraphic significance of the sequence also changed over time.

that were selected for their lithostratigraphic features, mineralogical composition or peculiar vegetal content. Although the Villafranchian succession is among the most studied Quaternary continental sequences in Italy its interpretation is still very problematic, mainly due to a complex and not yet completely understood stratigraphy. Several units once defined as "villafranchian" were later designated as not belonging to the type section or were confused with the over- or underlying sediments (Fig. 1). Thus, the stratigraphic meaning of the entire succession has repeatedly changed over time.

In this uncertain stratigraphic framework, a revision of the entire set of geological knowledge has allowed to address and partly solve the primary questions (Carraro ed., 1996). Along with many other studies, that were the topic of an international conference in 1994, new geological mapping throughout the entire type area helped to solve most of the remaining questions (Boano & Forno, 1996).

Subsequent surveys included a new section north of the historical type-area, near Castelnuovo Don Bosco (Boano et al., 1997; Boano & Forno, 1999). This later work resulted in good agreement with the revised type-area, thus confirming the new updated stratigraphy. New findings regarding the structure in the succession also provided new insights, due to the peculiar deformation observed in the Castelnuovo section itself.

The present study provides for an improved and integrated stratigraphic framework by the use of different approaches and methods (geology, pedology, structural geology, mammal fauna, palynology, carpology). New findings include a previously unrecognized paleosol, often associated with unknown concentrations of fossil vertebrate remains, which are present in the succession at the top of the Lower Complex. Moreover, the ancient fossil remains were revisited based on modern knowledge and the current chronostratigraphic framework.

The structural study, still in progress, includes identification of soft-sediment deformation that diffusely involve the sediments and mapping the local faults. Specifically, this work clarifies the structural interpretation of the T. Traversola Deformation Zone, which offsets the stratigraphic succession of the type-area and of the Castelnuovo Don Bosco sector.

2. GEOMORPHOLOGIC AND GEOLOGIC SETTING

The hilly relief of the central Piedmont consists of the Turin Hill and the Monferrato Reliefs on the northern side, the Poirino Plateau, the Asti Reliefs and the Ales-

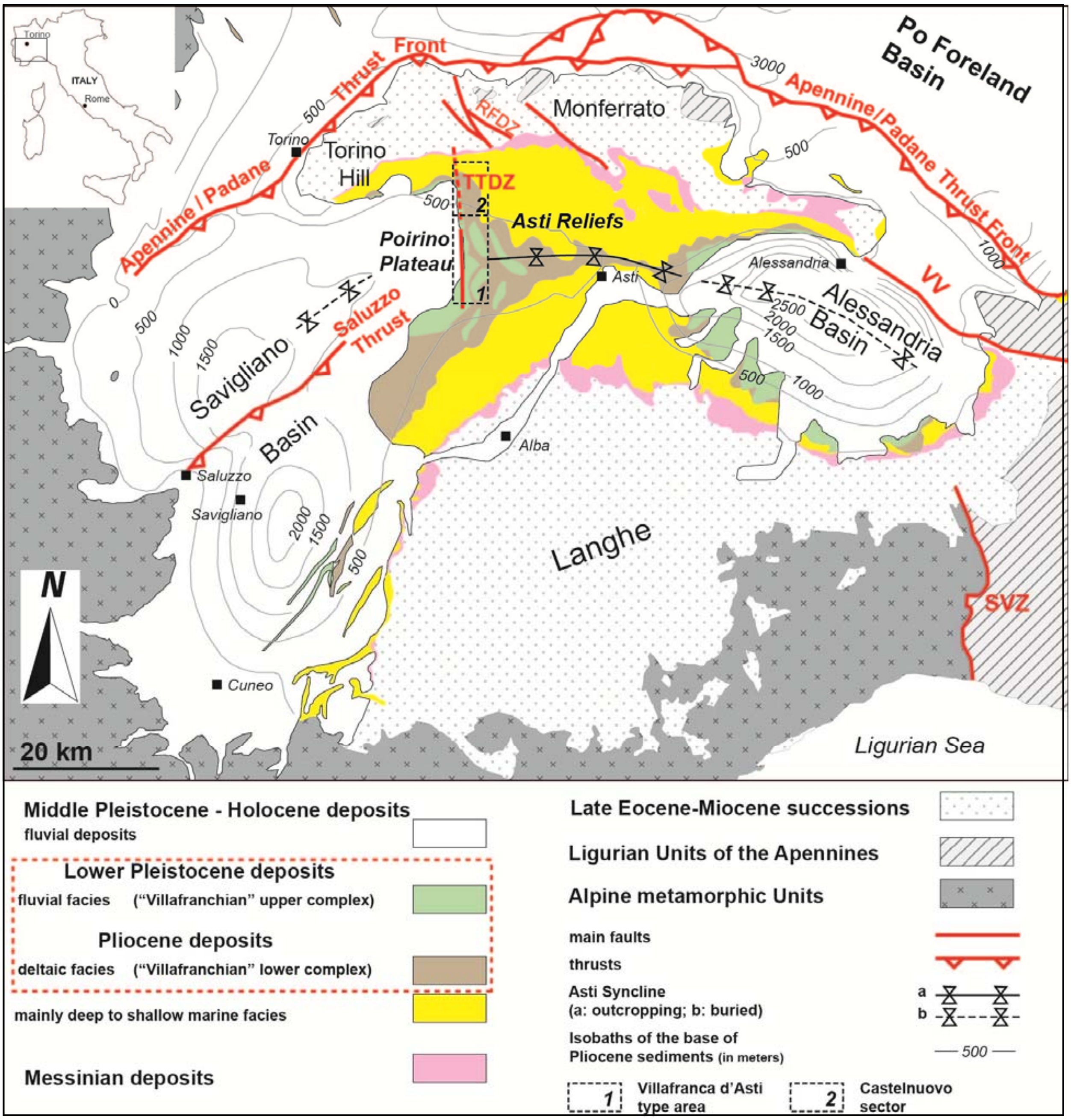
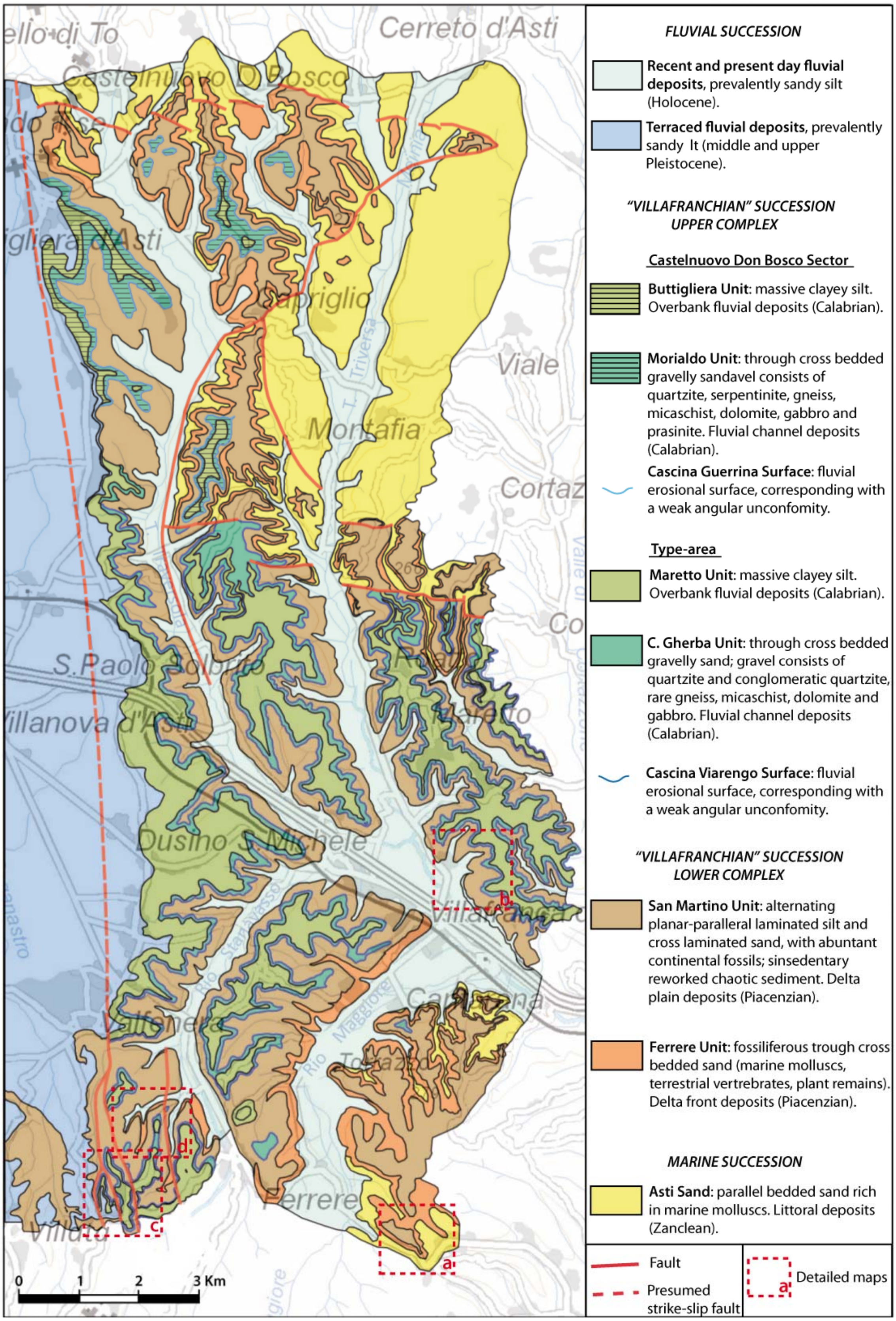


Fig. 2 - Structural map of the Piedmont hilly area, bordered to the NW and N by the Apennine Padane Thrust Front. The "Villafranchian succession" type-area and Castelnuovo don Bosco sector are shown. These sediments are involved in the T. Traversola Deformation Zone (TTDZ) with a prevailing dextral strike-slip displacement. The Rio Freddo Deformation Zone (RFDZ), the Vilalvernia-Varzi Fault (VV) and the Sestri Voltaggio Zone (SVZ) are also reported. The contiguous Savigliano, Asti and Alessandria basins correspond to the low central hilly sector, where the Asti Syncline developed during the Pliocene. In the Pleistocene, the ancient Po and Tanaro Rivers exploited this depression, thereby shaping the Poirino Plateau and the Asti Reliefs.

sandria Plateau in the centre, and the Langhe Reliefs on the southern side (Fig. 2).

The Turin Hill-Monferrato Hills, which ranges in elevation from 700 to 300 m a.s.l., form an E-W-oriented ridge. This ridge consists of a terrigenous Eocene-Pliocene marine succession with a thin, discontinuous, discordant Pleistocene fluvial cover. The Langhe Hills, which slope downward from the south (exceeding 800 m a.s.l.) to the north (average elevation of 300 m a.s.l.), form the foothill region of the Ligurian Alps. These reliefs consist of a terrigenous marine succession of Oligocene-Miocene age. Turin Hill and the Monferrato are cut by a NNW-SSE-trending transpressive deformation zone, the Rio Freddo Deformation Zone (Piana & Polino, 1995).


Cerreto d'Asti
Castelnuovo D. Bosco
Viale
Montafia
S.Paolo Solbrito
Dusino S.Michele
Ferrere
FLUVIAL SUCCESSION
Recent and present day fluvial deposits, prevalently sandy silt (Holocene).
Terraced fluvial deposits, prevalently sandy lt (middle and upper Pleistocene).
"VILLAFRANCHIAN" SUCCESSION UPPER COMPLEX
Castelnuovo Don Bosco Sector
Buttigliera Unit: massive clayey silt. Overbank fluvial deposits (Calabrian).
Morialdo Unit: through cross bedded gravelly sandavel consists of quartzite, serpentinite, gneiss, micaschist, dolomite, gabbro and prasinite. Fluvial channel deposits (Calabrian).
Cascina Guerrina Surface: fluvial erosional surface, corresponding with a weak angular unconfomity.
Type-area
Maretto Unit: massive clayey silt. Overbank fluvial deposits (Calabrian).
C. Gherba Unit: through cross bedded gravelly sand; gravel consists of quartzite and conglomeratic quartzite, rare gneiss, micaschist, dolomite and gabbro. Fluvial channel deposits (Calabrian).
Cascina Viarengo Surface: fluvial erosional surface, corresponding with a weak angular unconfomity.
"VILLAFRANCHIAN" SUCCESSION LOWER COMPLEX
San Martino Unit: alternating planar-paralleral laminated silt and cross laminated sand, with abuntant continental fossils; sinsedentary reworked chaotic sediment. Delta plain deposits (Piacenzian).
Ferrere Unit: fossiliferous trough cross bedded sand (marine molluscs, terrestrial vertrebrates, plant remains). Delta front deposits (Piacenzian).
MARINE SUCCESSION
Asti Sand: parallel bedded sand rich in marine molluscs. Littoral deposits (Zanclean).
Fault
Presumed strike-slip fault
Detailed maps
a
b
c
d
0 1 2 3 Km

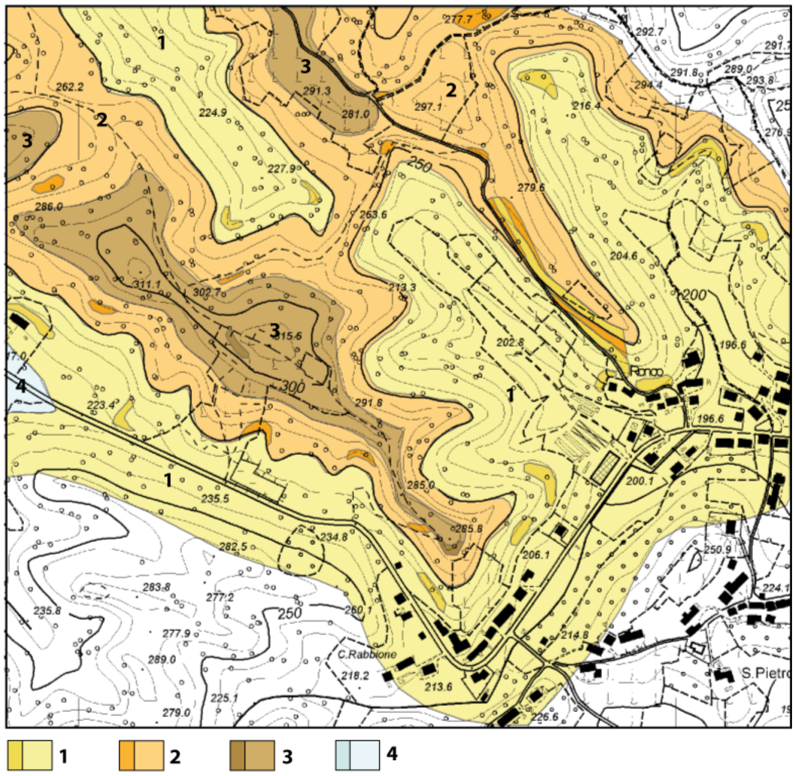


Fig. 4 - Detailed geological map showing the interfingering lenses at the contact between the littoral and deltaic sediments. Outcrop (dark color) and interpolating (light color) of the Asti Sand (1: fine-medium planar bedded sand, Zanclean), Ferrere Unit (2: cross bedded coarse sand) and the San Martino Unit (3: alternating silt and sand) forming the LC (Piacenzian). The area is located in the southeast corner of the type-area (a in Fig. 3).

The Villafranca d'Asti succession type-area and the Castelnuovo don Bosco section are located in the centre of these reliefs, where the Poirino Plateau (elevation 230-325 m a.s.l.) and the Asti Reliefs (elevation 130-320 m a.s.l.) occur. They are the geomorphic expression of the Asti Syncline, which represents the extension of the Savigliano and Alessandria basins (Fig. 2). This structure involves the littoral marine Asti Sand (lower Pliocene) and the deltaic and fluvial Villafranchian succession (Piacenzian and Calabrian) and is buried by a thin cover of fluvial sediments (middle-upper Pleistocene).

A N-S-trending scarp is evident in the western part of this syncline. This feature divides the Poirino Plateau, which slopes gently to the west, and the Asti Reliefs, which display an articulated morphology. This scarp runs nearly parallel to the tectonic structure referred to as the T. Traversola Deformation Zone, which offsets both the Pliocene and Pleistocene sequences (Gattiglio et al., 2015).

The Asti Reliefs correspond, therefore, to the central exhumed portion of the Asti Syncline, which is a basin-scale fold with a strongly arched axial trace (Fig. 2). These reliefs expose a succession consisting of shallow-water marine sediments (Asti Sand, Zanclean) and deltaic and fluvial villafranchian deposits differentiated into the Lower Complex (LC) (Piacenzian) and the Upper Complex (UC) (Calabrian), respectively in upward succession. This sequence is unconformably overlain by a discontinuous, thin cover of fluvial sediments of middle Pleistocene-Holocene age. From the Asti Reliefs, the syncline axis plunges to the SW and E, and the Pliocene successions are overlain by the less-deformed sub -horizontal Quaternary deposits of the Savigliano and Alessandria basins.

The Asti Syncline records the presence, during the Pliocene, of a large satellite basin that developed between the Alps and Apennine systems, at the back of the Apennine Padane thrust front. The evolution of this basin was controlled by the continuous growth of the Turin Hill and Monferrato arc and by the progressive uplift of the southern Langhe domain (Mosca et al., 2009; Irace et al., 2010). This basin evolution related to the activity of north-verging thrust systems and high-angle strike-slip faults (Pieri & Groppi, 1981; Mosca et al., 2009).

3. PREVIOUS WORK

An extensive geological and paleontological literature regards the succession of the Asti Reliefs. It began in the 1800s with the earliest published reports of fossil vertebrates (Cuvier, 1806; Amoretti, 1808). Most of the nineteenth-century papers concerned the vertebrate fossils in this area (Borson, 1820; 1823; 1930; Sismonda, 1849; Gastaldi, 1861). Sismonda and Gastaldi published their discovery of complete skeletons of mastodons at San Paolo Solbrito and Ferrere d'Asti. An excellent opportunity to study these fossils was provided by the excavation of a wide trench for the Turin-Genoa railway: many fossils of vertebrates and terrestrial molluscs were exposed (Baretti, 1880a; 1880b; 1880c; Sacco, 1884; 1886a; 1886b; 1888).

At approximately the same time, stratigraphers described the sedimentary succession. The main research was by Pareto (1865), who was responsible of the establishment of the "Piano Villafranchiano" based on transitional sedimentary deposits overlying the Pliocene

Fig. 3 - Geological map of the Villafranchian succession, which consists of two sedimentary complexes that are separated by the Cascina Viarengo Surface (type-area) and the Cascina Guerrina Surface (Castelnuovo Don Bosco sector) and are offset by fractures and faults. The dashed sectors indicate the detailed areas reported in Fig. 4 (a), Fig. 11 (b), Fig. 24 (c) and Fig. 25 (d).

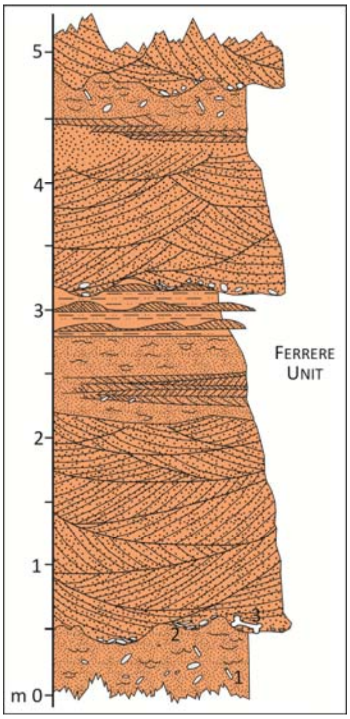


Fig. 5 - Most typical facies of the Ferrere Unit characterized by cross bedded coarse grained sand, with laminae dipping in opposite directions and fragments of marine molluscs. Massive bioturbated sand is also abundant near the bottom and the top of the log. Thin lenses of fine sand with ripples area also present in the medium part of the log. 1: bioturbated sand; 2: fragmented marine molluscs and minute gravel and clay-chips; 3: vertebrate remain. Cantarana Quarry in Ferrere d'Asti (central type-area).

marine sands [1].

Sacco (1886c; 1890) introduced a subdivision of the stratigraphic succession by distinguishing the lower sediments, which consist primarily of cross-bedded sand and were named the Piano Fossaniano, from the remainder of the succession. This interpretation was also used in the first edition of the Geological Map of Italy (1:100,000 scale) (Sacco, 1922). The stratigraphic succession and its palaeontology were again described by Martinis (1949), Gabert (1962) and Selli (1967). These authors, although they regarded the succession as undifferentiated, reported the presence of various facies attributed to littoral and deltaic environments.

A new impetus to studies of the Villafranca d'Asti area was provided by the opening of quarries for the construction of the A21 Turin-Piacenza motorway. Pavia (1970) published a detailed study of the succession exposed in the Arboschio Quarry (Cantarana) (see Fig. 5); this study focussed on the fossils of plants, vertebrates and marine molluscs. Francavilla et al. (1969; 1970) and Francavilla & Tomadin (1970) focused on the palynology and paleobotany of the sequence based on a detailed analysis of the exposures in other quarries that were open at that time (Cantarana, Crotino, Arondelli, Fornace RDB) and were subsequently restored. Azzaroli & Vialli (1971) studied the same quarries and published a summary study of the Villafranchian succession and its fossil vertebrates [2]. At approximately the same time, surveys were performed for the second edition of Geological Sheets 68 "Carmagnola" (Petrucci & Tagliavini, 1968) and 69 "Asti" (Boni et al., 1969) of the Geological Map of Italy. In these works, the presence of an erosional surface between the Villafranchian succession and the overlying Quaternary deposits was reported.

Subsequently, Carraro et al. (1982) suggested the presence of an angular unconformity in the Villafranchian type section that was recognizable on a regional scale but not on more-detailed scale.

A detailed geological survey of the entire type-area allowed for a complete reconstruction of the geometry of the various geologic units of the Villafranchian succession and clarified certain issues (Carraro ed., 1996). This research included the collection of sedimentological, paleontological, structural, geophysical and geotechnical data. The main results were:

- a detailed geological map of the entire type-area, which provided a comprehensive understanding of the geology based on more than scattered outcrops;
- a reconsideration, based on modern stratigraphic criteria, of the Villafranchian succession defined by Pareto; and
- a better locating of the remains and a refined chronologic interpreting of the fossil record.

This reinterpretation resulted in the definition of two main complexes (Lower Complex and Upper Complex), which represent deltaic and fluvial palaeoenvironments, respectively, and are separated by an erosional angular unconformity that is designated as the Cascina Viarengo Surface. The Lower Complex was referred to the middle Pliocene and of the Upper Complex was referred to as lower Pleistocene.

An investigation on the climatic conditions during deposition of the Lower Complex based on the fossil plant assemblages in the San Martino Unit suggested a warm temperate palaeoclimate (Martinetto & Mai, 1996). Further Study of the RDB section confirmed that the Lower Complex marks the "closure" of the Pliocene regressive cycle and is constrained to the Piacenzian (Lindsay et al., 1997). Magnetostratigraphic data (Gauss Chron) confirmed this age of the Lower Complex (Boano et al., 1999b).

The strong deformation of the Villafranchian succession was also described in a study of the soft-sediment deformation in the deltaic complex (Boano et al., 1997). An extension of the geological survey was also per-

1) These deposits, which were regarded as undifferentiated, consist primarily of stratified silt with horizontal laminations, cross-bedded sand and gravel and massive silt. The section at Villafranca d'Asti was therefore designated the type section of this unit.

2) None of these studies included an analysis of the entire stratigraphic succession in the type area; they focused instead on the succession in specific quarries and included no correlations between the various sections.

Fig. 6 - Ferrere Unit cross-bedded coarse sand with laminae dipping in opposite directions, rich in clay-chips. Buttigliera d'Asti Quarry (northwestern corner of the Castelnuovo Don Bosco sector).

formed in the Castelnuovo Don Bosco sector, where both the stratigraphy of the Villafranchian succession and the structural features are more complex than those in the type-area (Boano & Forno, 1999). This research confirmed the findings of the previous revision and produced further evidence of strong deformation of the sediments.

The findings presented in the map of the Castelnuovo Don Bosco sector (Fig. 2) were confirmed with the recent geological survey for the official map (Dela Pierre et al., 2003; Festa et al., 2009): the Lower Complex includes tide-dominated deltaic deposits, which are referred to as the Ferrere Sands (5-25 m thick), and fine-grained delta-plain and lacustrine deposits, which are referred to as the "San Martino Silt" (up to 60 m thick). The Upper Complex consists of fluvial gravel and sand designated as the "Morialdo Syntem".

This subdivision into two main stratigraphic units and the presence of a regional angular unconformity were also reported as a result of basin-scale hydrostratigraphic studies that focused on subsurface reconstructions beneath the plains surrounding to the Asti Reliefs. A recent study of the southern edge of the Alessandria Basin (Fig. 2) (Irace et al., 2012) provided evidence that the hiatus represented by this unconformity may be the result of a series of erosional-depositional events that started in the late Piacenzian and continued in the Gelasian. Part of the continental record corresponding to this stratigraphic gap may be locally preserved. A detailed integrated study of the subsurface west of the Villafranca d'Asti area suggested a Gelasian age of the C. Viarengo unconformity (Vigna et al., 2010), based on a possible correlation with the Gelasian surface in the Po Foreland Basin (Ghielmi et al., 2010; 2013).

4. STRATIGRAPHIC FEATURES OF THE VILLAFRANCA D'ASTI SUCCESSION IN THE TYPE AREA AND THE CASTELNUOVO DON BOSCO SECTOR

In the type-area and in the Castelnuovo Don Bosco sector, the Villafranca d'Asti succession generally rests conformably on the Asti Sand. This sand outcrops in the marginal sectors on the low parts of the slopes and exhibits a visible thickness of tens of metres (Fig. 3).

The Asti Sand consists of poorly bedded, medium- to fine-grained, horizontally laminated sand with localized current structures (symmetrical ripples). These deposits are generally yellow (2,5 Y 8/6 Munsell) and are strongly cemented, particularly where fossils are abundant. They are often rich in coastal marine molluscs concentrated in beds that are centimetres to tens of centimetres thick (see Fig. 12). The fossils are often complete, including their primary anatomic connection. The horizontal parallel lamination, the coastal fossils and the local tidal structures indicate a littoral marine environment. The fossil assemblage suggests an Early Pliocene age (Festa et al., 2009).

As mentioned above, the overlying succession consists of two complexes. Its sedimentologic features indicate the presence of various units in each complex.

4.1. The two sedimentary complexes (LC and UC)

The detailed geological survey of the type area revealed the stratigraphic framework of the succession, which was previously regarded as undivided (Boano & Forno, 1996; 1999). The succession is subdivided into two complexes, the Lower Complex (LC) and the Upper Complex (UC), which are separated by angular unconformities, specifically, the Cascina Viarengo Surface (type-area) and the Cascina Guerrina Surface (Castelnuovo Don Bosco sector) (Fig. 3).

4.2. Stratigraphic subdivision of the LC

The Ferrere Unit, which comprises the basal unit of the LC, is exposed locally along the edges of the type-area and in the central Castelnuovo Don Bosco sector (Fig. 3). This unit rests conformably on the underlying marine sediments (Asti Sand); this contact may be gradational, based on interfingering or alternating lenses of the two units (Fig. 4). The thickness ranges from 5 to 25 m.

This unit consists primarily of cross-bedded coarse sand with laminae dipping in opposite directions (Fig. 5). There are beds rich in centimetre-long fragments of marine molluscs and minute gravel and clay-chip (Fig.

Fig. 7 - Massive bioturbated sand of the Ferrere Unit. Outcrop N of Ronco village. Southeast corner of the type-area.

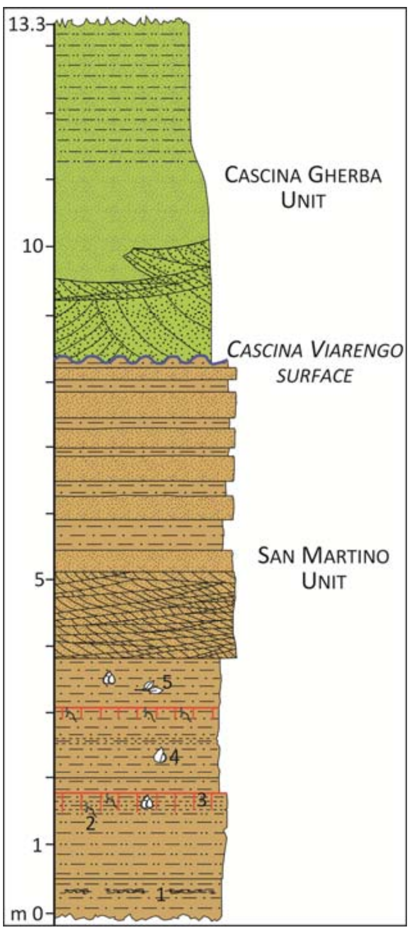


Fig. 8 - The Cascina Viarengo erosional Surface divides the San Martino Unit (silt alternating to fine sand) (LC, Piacenzian) by the C. Gherba Unit (gravel coarse sand) (UC, Calabrian). 1: soft sediment deformation; 2: root; 3: organic paleosol; 4: terrestrial and lacustrine mollusc; 5: leaf imprint. Cascina San Martino Quarry in Villafranca d'Asti (central type-area).

6). The textural features and the cross bedding are consistent with deposition of coarse sediment on a delta front, where the re-deposition of the shells of Asti Sand may have been frequent. The bedding suggests deposition associated with tidal channels, typically with opposite directions (Fig. 6). Massive bioturbated sand is also abundant (Fig. 7).

The Ferrere Unit was formed in the shallow water of a deltaic system in which coarse sand were deposited and strong reworking of sediments occurred. Thin lenses of fine sand with ripples (Fig. 5), alternating with silt, are locally also associated with the more-typical facies. These features are indicative of deposition in lateral deltaic areas, where there was a slower rate of sedimentation.

The Ferrere Unit, in addition to fragments of marine molluscs, includes numerous fragments of continental vertebrates (primarily mastodon and rhinoceros remains as specified in paragraph 6) and plants (as specified in paragraph 7) that were transported by rivers along the deltaic front. The sedimentologic and paleontologic features are consistent with a progradational delta front grading into a beach system. Petrographic analysis indicates that the clasts consist primarily of quartzite, conglomeratic quartzite, gneiss, dolomite, micaschist and gabbro, which indicate a genetic linked to the Tanaro Basin.

The overlying San Martino Unit, which constitutes the upper part of the LC, is exposed throughout the type-area and in the central Castelnuovo Don Bosco sector (Fig. 3). This unit rests conformably on the Ferrere Unit and the contact is often eteropic. The thickness of the San Martino Unit ranges from 20 to 65 m.

The San Martino Unit consists primarily of clayey silt interbedded with sand (see Fig. 8). These sediments form the most distinctive unit of the Villafranca d'Asti succession: they display the most characteristic facies and are the most abundant in fossils (fossil vertebrates, lacustrine and terrestrial molluscs and plant remains). The unit consists predominantly of planar bedded to massive clayey silt that is typically grey (Fig. 9). The bedded silt contains scattered leaf and reed imprints, plant fragments, stump in life position, roots and pollen (Fig. 10) and local levels of lignite. These fossils are typical of swamp environments where the mineral fraction and vegetal remains settled out of the water column.

Trough cross-bedded sand is also present in channel fills. These deposits locally contain fossils of continental vertebrates that are often preserved as entire carcasses (Campanino et al, 1994) (see Fig. 19). The sandy texture, cross bedding and local vertebrate remains suggest a stream paleoenvironment. This unit locally displays decimetre-thick organic paleosols, rich in roots, pollen, terrestrial molluscs and concretions (Fig. 8).

The sedimentologic and palaeontologic features of the San Martino Unit suggest that these sediments were deposited on a deltaic plain. Specifically, the silt was deposed in coastal swamps, and the sand filled the deltaic distributory channels. The very compact appearance of these sediments, which differs markedly from that of the soft UC, and their homogeneous grey color, which also differs from the various colours of UC, are the typical features that allow for distinguishing this unit from the other predominantly silty facies of the sedimentary succession.

4.3. Erosional surfaces

The top of LC is cut by distinct erosional surfaces (Fig. 3). The C. Viarengo Surface extends across the entire type area and displays a predominantly sub-horizontal morphology with local irregularities (Fig. 11). The Cascina Guerrina Surface is restricted to the Castelnuovo Don Bosco sector and exhibits a concave shape. The absence of unequivocal stratigraphic markers did not allow for the assignment of a single name to the two surfaces, although there is evidence for correlating the two surfaces.

These erosional surfaces comprise an angular unconformity between the LC, forming a syncline with axis dipping towards the west, and the UC, constituting instead a syncline with sub-horizontal axis (see Fig. 26).

The over-consolidation of the clays levels of the LC suggests that a remarkably thick portion of sediments was removed by erosion (up to 100 metres) (Carraro ed., 1996). It is possible, therefore, to infer that these surfaces deeply truncate the LC.

The deposits below and above the erosional surface differ markedly, which confirms the importance of the erosional phenomena (Fig.12). These differences include the type of depositional environment (which shows a switch from deltaic to fluvial), the fossil content (shift from very fossiliferous to essentially nonfossiliferous), the degree of lithification (shift from the very compact LC to the soft UC), the deformation structures (from the very deformed LC to the less-deformed UC), and the degree of weathering (from the locally weathered LC to the strongly weathered UC).

This erosional surface was shaped by a continental stream network. More than one fluvial system likely developed at different times, suggesting a polygenetic nature of this erosional feature.

4.4. Stratigraphic subdivision of UC

The Cascina Gherba Unit, which directly overlies the Cascina Viarengo Surface, is present across the type-area. The thickness of this unit is relatively uniform, ranging from 4 to 15 m. It is composed of grey to white gravelly sand and sand with large-scale trough cross-bedding (Fig. 9). A carbonate-rich bed (from a few decimetres to a metre thick) typically underlies zones of permeability contrast with other sediments.

The sedimentologic features of the facies suggest an alluvia plain dominated by braided streams. Petrographic analysis of the gravel indicated that the clasts are primarily composed of quartzite, conglomeratic quartzite, gneiss, dolomite, micaschist and gabbro, which indicate a genetic link with the Tanaro Basin.

These sediments did not directly provide fossil remains. Only a few vertebrate teeth of elephant preserved in the Regional Museum of Natural Science of Turin (Zuffardi, 1913), saving a little typical C. Gherba sediment attached to the remains, doubtfully comes by this unit.

The Maretto Unit is widespread across the type-area and forms the top of the ridges. The thickness isrelatively uniform, approximately 50 metres. Its contact with the Cascina Gherba Unit is conformable and gradational, based on interfingering of the two units. The Maretto Unit consists of homogeneous clay silt, massive or with a faint planar bedding (Fig. 13). These sediments are mottled, with color that varies from brown (7,5 YR 5/8 Munsell) to grey. They are often rich in carbonate concretions and display pseudogleys (Fig. 14). These pedogenetic features are observed not only in the surficial exposures but extend throughout the unit.

The Maretto Unit is interpreted as the product of the fine-grained sedimentation by rivers with a high amount of suspended load in an alluvial plain associated with river flooding. The clay texture, the predominant brown

Fig. 9 - Alternating planar bedded silt and cross-bedded fine sand of the San Martino Unit (LC), separated by the coarse, cross-bedded sand of the C. Gherba Unit (UC) by the Cascina Viarengo erosional Surface. The newly exposed sediments (at the base of the outcrop) preserve the typical grey colour of the San Martino Unit, not involved in the surficial weathering that involves the exposed for longer sediments, whose yellowish color is due to the lengthy subaerial exposure. Cascina San Martino Quarry in Villafranca d'Asti (central type-area).

Fig. 10 - Leaf imprint in the Cascina San Martino silt. Detail of the Cascina San Martino Quarry in Villafranca d'Asti (central type-area).

color, the abundant carbonate concretions and the presence of pseudogleys indicate strong weathering of the deposits that involved the entire thickness. These pedogenetic phenomena occurred over a long period of time, indicating pedogenesis contemporaneous with sedimentation.

The Morialdo Unit is restricted to the Castelnuovo Don Bosco sector directly above the Cascina Guerrina Surface (Fig. 3). This unit is composed of gravelly sand and sand, generally grey, with large -scale trough cross-bedding. Its sedimentologic features are very similar to those of the Cascina Gherba Unit, suggesting deposition by braided watercourse for these deposits. The petrography yielded a distinct composition: the clasts are composed of quartzite, serpentinite, gneiss, micaschist, dolomite, gabbro and prasinite. The abundance of green stones indicates a source different from that of the Cascina Gherba Unit of the type-area and a likely connection with the hilly network or an ancient course of the Po River.

The Buttigliera Unit is also restricted to the Castelnuovo Don Bosco sector. It also consists of homogeneous clayey silt with mottled colouring and abundant carbonate concretions, similar to the Maretto Unit. The presence of green stones is indicative of a source in an ancient hilly network or of an ancient course of the Po River.

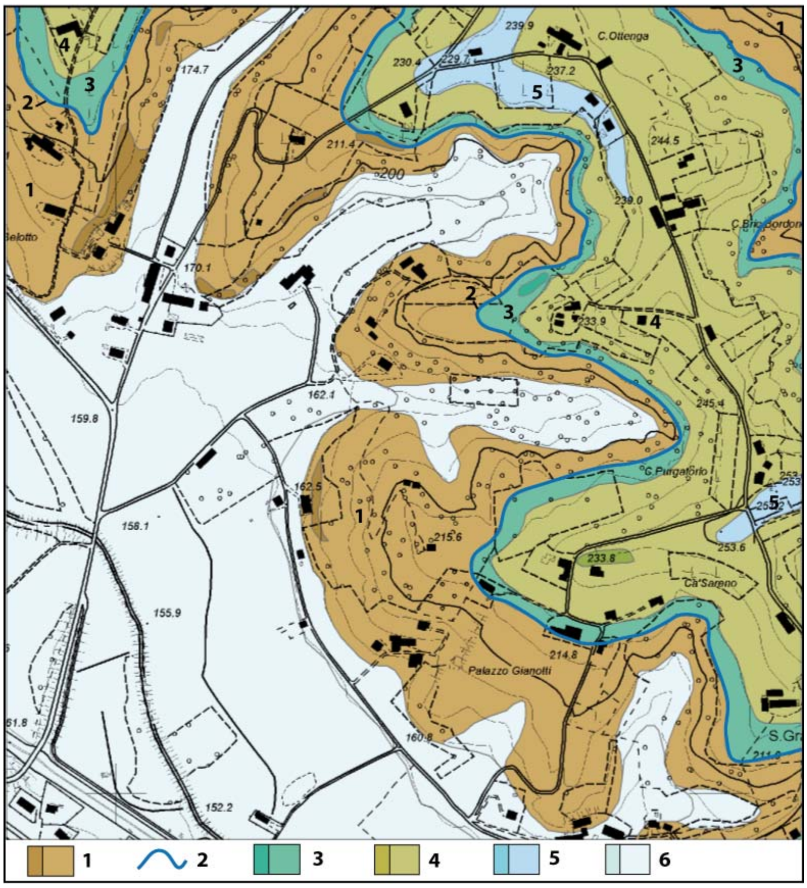


Fig. 11 - Detailed map showing the subhorizontal arrangement of the Cascina Viarengo Surface (2). Outcrop (dark color) and interpolating (light color) of the Piacenzian Lower Complex (1: San Martino Unit), the Calabrian Upper Complex (3: Cascina Gherba Unit; 4: Maretto Unit) and the middle-upper Pleistocene (5) and Holocene fluvial cover (6). Villafranca d'Asti in the central sector of the type-area (b in Fig. 3).

5. PALEOSOL BETWEEN THE TWO COMPLEXES

Recent discoveries of different contexts of vertebrate remains in the area, including rhinos (Campanino et al., 1994) and monkeys (Gentili et al., 1998), provide additional biostratinomic and taphonomic evidence for differentiating the local fossil assemblages. Abundant fossil concentrations just below the unconformity between the LC and UC suggest peculiar, constraining, nearly stable depositional conditions (Boano et al., 1999b).

Further geological surveys conducted as part of the present study indicate that these fossil concentrations are associated with weathered sediments not identified in earlier studies. These deposits, which are up to six metres thick, are characterized by a strong brown colour (7,5YR 5/8 Munsell), diffused clay skins and a strong cementation by iron oxides, representing a paleosol. It displays the typical stratigraphic position along the unconformity and wide diffusion in the entire western sector of the type-area.

There are other discontinuous, thin deposits associated with this paleosol. They do not correlate with any single facies of the Villafranchian succession and instead are marked by a mixture of features that suggests a colluvial origin. Due to the poor exposures, suitable sections with paleosol horizons are rare. Therefore, a horizontal trench was excavated near the Fornace RDB in Villafranca d'Asti to provide subsurface data (Fig. 15). This trench was approximately 40 metres long and 2.5 metres deep and was excavated to expose the top of the LC, the Cascina Viarengo Surface and the bottom of the UC.

The lower part of the trench exposed the top of the weathered, brown, clayey material of the paleosol developed on the LC (**P** in Fig. 16). The middle and upper parts of the trench exposed a lenticular body up to 2 metres thick that extended tens of metres laterally and lenses, each a few decimetres thick, of mixed sand, silt and clay of various colours and coherence separated by clear contacts. This sequence indicates the presence of a succession of various colluvial bodies.

The low colluvial body (1 in Fig. 16), located in a depression at the top of the LC, is composed of clayey silt of a strong brown colour (7,5YR 5/8) with grey mottles and pseudogleys and irregular centimetre-long fragments of red clay chips (5YR 3/3). The overlying colluvial body (2 in Fig. 16) consists of a brownish-yellow matrix with grey mottles mixed with centimetre-long rounded brown concretions (Fig. 17). The strong cementation of these two bodies by iron oxides suggests a subsequent weathering of these sediments, indicating a greater age and their involvement in the paleosol.

The next highest colluvial body (3 in Fig. 16) displays a homogeneous brown-yellowish colour (10 YR 4/4) and a soft consistency. Finally, silt and sandy silt covering the underlying colluvial bodies (4 in Fig. 16) are yellowish to brown and very soft (Fig. 17). The weak cementation of these two colluvial bodies by iron oxides suggests the absence of further weathering, indicating a more-recent age and their non-involvement in the soil developed on the LC. These non-weathered deposits are also ancient colluvial sediments included in the Villafranchian succession. The framework is visible in the stratigraphic scheme in which the paleosol and the various colluvial bodies are positioned between LC and UC (Fig. 18).

This recurrent evidence (concentrations of fossil remains, paleosol and colluvial sediments) indicates that the development of the succession was more complex than previously thought, based largely on the geological significance of the unconformity separating the two complexes (see Fig. 26). An old topographic surface developed at the end of the deltaic sedimentation, which indicates conditions of relative stability when extensive pedogenetic processes and little deposition occurred. The stratigraphic concentration and preservation of fossils was thus favoured by the slow accumulation of colluvial soil on the underlying horizons of the paleosol.

The colluvial sequence marks the end of the deltaic aggradation (LC) and the start of general erosion (UC), which was also marked by a sharp stratigraphic transition to the overlying, discontinuous alluvial sedimentation. The features of this paleosol are compatible with a pronounced pedological event (likely some hundred of thousands years long).

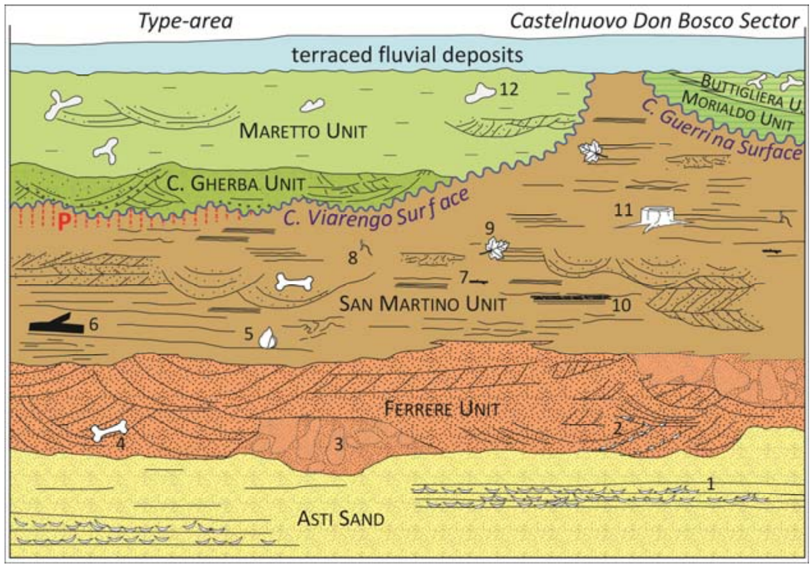


Fig. 12 - Stratigraphic sketch of the different units forming the Villafranca d'Asti type-area and Castelnuovo Don Bosco sector. 1: marine molluscs; 2: fragmented marine molluscs; 3: bioturbated sand; 4: vertebrates; 5: lacustrine and terrestrial molluscs; 6: branch fragments; 7: plant frustules; 8: roots; 9: leaf and reed imprints; 10: levels of lignite; 11: stumps in life position; 12: concretions; p: paleosol.

6. VERTEBRATE FOSSIL REMAINS

During the revision of the Villafranchian in the type area of Villafranca d'Asti, between 1992 and 1994 (Carraro ed., 1996), vertebrate palaeontologists tried to order the fossil material that had been collected beginning in the second half of the 18th century, the greater part of which is preserved at the Regional Museum of Natural Science of Turin and in Basel (Hurzeler, 1967).

Fig. 13 - Clayey silt with a hint of planar bedding, evidenced by different carbonate contents: the light horizons show a cementation and are rich of pedogenetic carbonatic concretions; the dark horizons (brown color 7,5 YR 5/8) appear strongly cemented by iron oxides and rich of peseudogleys. Outcrop of Maretto Unit N of Palazzo Gianotti (central sector of the type-

Fig. 14 - The clayey silt with mottled colour of the Maretto Unit, rich in pseudogleys and Mn concretions. Detail of the outcrop N of Palazzo Gianotti (central sector of the type-area).

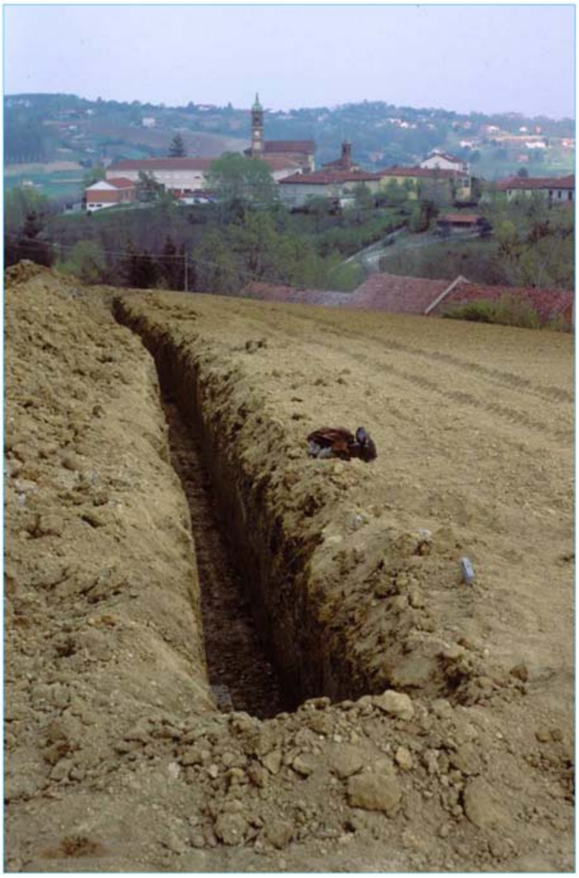


Fig. 15 - The trench located SW of Villafranca d'Asti (the village is located in the background of the photo) cut to study the paleosol between the LC and the UC.

Several bio-chronological notes were shared and, to place the mammal fauna from the area of Villafranca d'Asti in a wider biostratigraphic framework, researchers developed a table containing selected Italian mammal fauna referred to Villafranchian and Galerian (Masini et al., 1996).

The discussion also concerned the definition of the term "Villafranchian", which was introduced by Pareto in the 1865. Vertebrate palaeontologists noted that this term had been used a long time, particularly in Europe and North America, to indicate an "Age of Large Mammals". Moreover, Azzaroli (1977) had introduced the concept of the "faunal unit" as an internal subdivision of Mammal Ages, and proposed a definition of the "Val Triversa Faunal Unit". This FU included all the local mammal fauna coeval with the Pliocene fossils from the area of Villafranca d'Asti.

Today, the term "Villafranchian" is widely used by vertebrate palaeontologists working across the Holarctic region when referring to a specific "Mammal Age" (Savage & Russell, 1983), and Triversa remains the only FU of the Early Villafranchian, which also includes a few of the local fauna of central Italy, such as those of Santa Barbara (Castenuovo dei Sabbioni, Arezzo) (Gliozzi et al. 1997).

The localities in the area of Villafranca that have yielded the most significant fauna are Cava Arboschio, Cascina Arondelli, Cascina Crotino, Cascina Melona di Roatto (Fig. 19), Cascina Oggero, Cascina Viarengo, Dusino, Fornace R.D.B, S. Paolo Solbrito and Val Triversa (Ambrosetti et al., 1996).

The remains with certain stratigraphic position come from the LC (San Martino Unit), Piacenzian. Unfortunately, the large collections from the excavations for the construction of the railway in the 19th century and for the motor-way in the 1950s are not included among the fossil material of certain stratigraphic position. The latter was published by Sismonda (1852), Gastaldi 1860), Sacco (1895), Pavia (1970), Francavilla et al. (1970), Berzi et al. (1970), Mottura & Ardito (1992) and Campanino et al. (1994) and is represented by only a few species: *Anancus arvernensis*, *Mammuth borsoni*, *Mesopithecus monspessulanus*, *Stephanorhinus elatus* (sin. *S. jeanvireti*) and *Sus* cf. *minor*.

Only two remains not identified with certainty, a fragment of cervid antler and a tooth fragment of *Sus* sp., are attributed with certainty to the UC, which is provi-

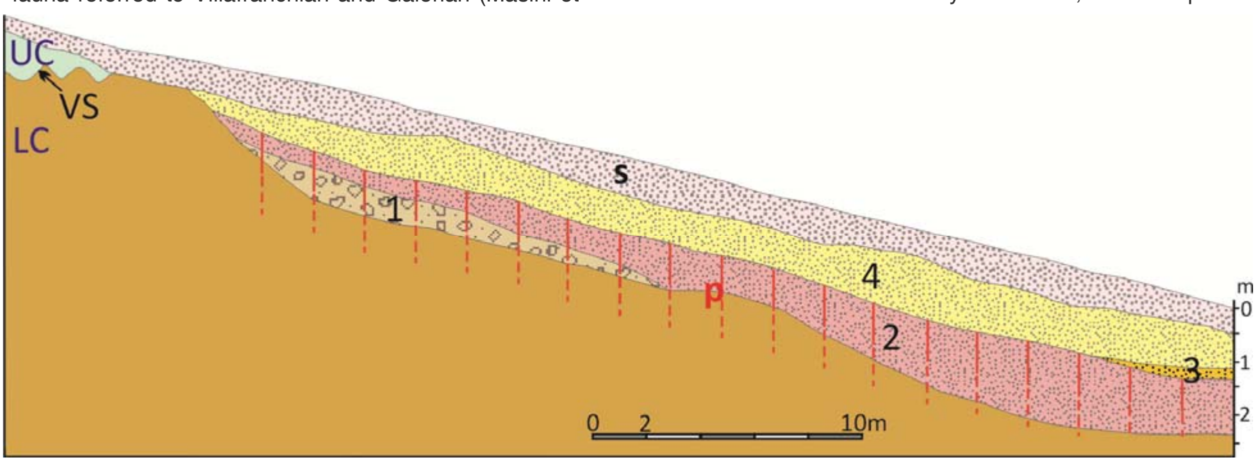


Fig. 16 - Cross section along the trench SW of Villafranca d'Asti. On the LC (San Martino Unit, Piacenzian) involved by the formation of the paleosol (p) ancient colluvial sediments are preserved in a wide depression (1 and 2), also involved by the paleosol. Above, more recent colluvia occur (3 and 4), not involved by the paleosol. The Cascina Viarengo Surface (VS) and the UC (Cascina Gherba Unit, Calabrian) are present at the top of the sequence. Finally, near the current topographic surface, agricultural soil is visible (5).

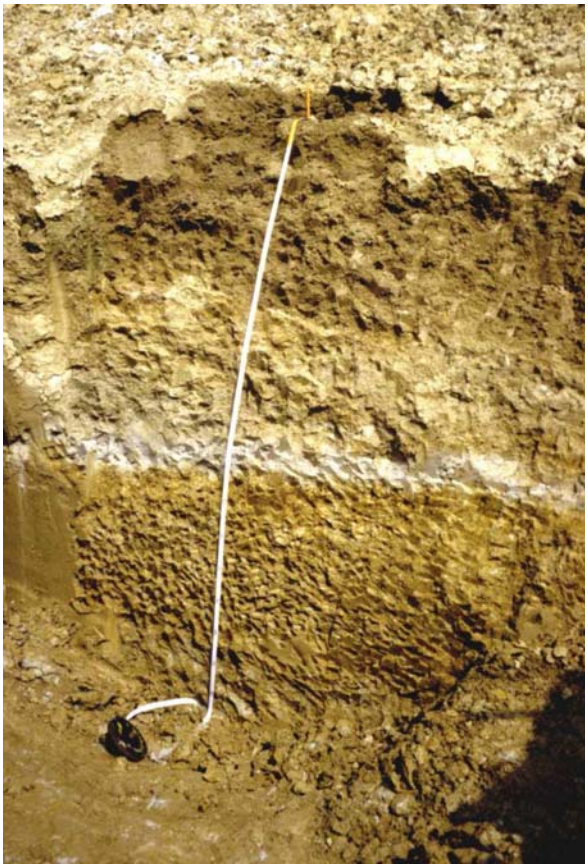


Fig. 17 - A detail of the trench of Fig. 13, with the thin succession of colluvium (2), involved in the formation of the paleosol, and the younger colluvium (3), not affected by the paleosol.

sionally assigned an Early Pleistocene, Gelasian and/or Calabrian age. Exploration for the remains of small mammals in this complex was fruitless.

Many species are represented in the Val Triversa Faunal Unit. A few of these are typical of damp, wooded, subtropical environments, such as two mastodons, *Anancus arvernenesis* and *Mammuth borsoni*, a small suid, *Sus minor*, a cercopithecus, *Mesopithecus monspessulanus*, a lesser panda, *Parailurus hungaricus* and a tapir, *Tapirus arvernensis*. There were also other mammals adapted to living in open woodland or parkland terrain, such as the large rhino, *Stephanorhinus elatus*, a heavily built antelope, *Leptobos stenometopon*, and a medium-size cervid, *Pseudodama lyra*. The carnivores are numerous: the mustelids *Baranogale helbingi* and *Enhydrictis ardea*, the viverrids *Megaviverra appennina* and *Viverra pepraxi*, a little forest bear, *Ursus minimus*, a hyaena, *Chasmaporthetes lunensis,* a cheetah, *Acinonyx pardinensis,* and a saber tooth tiger, *Homotherium crenatidens.* In addition, there are also several small vertebrates, primarily rodents of the Early Villanyian (a small Mammal Ages) (Fejfar & Heinrich, 1990).

The presence of two mastodons together with new species characteristic of open woodland or parkland is particularly important for establishing correlations with other Holarctic fauna.

7. THE PLANT FOSSIL REMAINS

7.1. Palynomorphs

Since 1969, palynological analyses have been performed by several authors (Francavilla et al., 1969, 1970; Francavilla & Tomadin, 1970; Lona, 1971; Lona & Bertoldi, 1972; Bertoldi, Caramiello & Siniscalco in Carraro ed., 1996) in the Piacenzian and Quaternary continental deposits outcropping in the Arondelli, Crotino and Fornace RDB quarries and at several other sites where the sediments of the Maretto Unit are exposed. Such data allow for the summarization and updating of the palynological documentation of both the LC and UC.

Lower Complex

The most-continuous palynological record is exposed in the RDB quarry (Bertoldi in Carraro ed., 1996), despite the fact that previous works here and in the other quarries produced rather discontinuous records due to the general scarcity of palynomorphs. Bertoldi, however, by applying a pollen concentration method, was able to produce a rich palynological documentation, which now serves as reference due to the high quality of both the approach and the results. The resulting qualitative and quantitative data are used here to reconstruct the main floristic and vegetational changes and to propose inferences regarding the climate. The latter were developed by also taking into account palynological evidence from other Pliocene and Quaternary sites in northern and central Italy (e.g., Bertoldi & Martinetto, 1995; Bertini, 2010 and references therein).

Fifty samples from the San Martino unit were collected by Bertoldi along the reference section, which is 38 m thick and was exposed in the cava RDB in 1994 and 1995 (see fig. 29 in Carraro ed., 1996). As shown by the original detailed and summary pollen diagrams (see figs. 50-53 in Carraro ed., 1996), here redrawn and updated (Fig. 20), palynomorphs are present only in the lower 18 m. In this portion, of 28 samples that were processed, 7 were barren of palynomorphs. In contrast, all 22 samples between 18 m and 38 m were either barren or contained few palynomorphs; the few palynomorphs were typically affected by degradation and/or corrosion, which sometimes prevented their identification. Such behaviours are directly related to the depositional processes in the deltaic system (Carraro ed., 1996). Pedogenesis during the formation of hydromorphs hydromorphic (dark grey) or well-drained sols (dark brown), soils, ended when the water level rose and promoted lacustrine to palustrine conditions with the occasional accumulation of lignite, as indicated at 1.8 m and 17.7 m in the RDB section. In corresponding parts of the succession and in other organic-rich sediments, higher pollen counts (up to 13,000 arboreal pollen grains/gram) were observed. In contrast, the samples from the paleosols (e.g., between 26.6 m and 32.1 m) were generally barren or contained very few pollen grains due to the effects of major taphonomic biases.

The rich pollen flora from the lower portion of the LC includes, as a whole, more than 100 pollen taxa, which have been attributed to 70 arboreal taxa and 30 non arboreal taxa.

Various pollen components (e.g. local and regional) were identified and described (Bertoldi, in Carraro ed., 1996). The local flora is especially abundant in hydrosols and in organic-rich clays deposits. It includes plants thriving in wetlands areas, dominated by swamps as indicated by the predominace of arboreal taxa such as *Taxodium* type, *Nyssa*, *Myrica*, *Carya* p.p., *Pterocarya*, Ulmaceae (*Zelkova*/*Planera*, *Ulmus*, …), *Parrotia*, *Aesculus*, *Platanus*, *Alnus*, *Salix*, cf. *Populus*, Hygrophilous herbaceous taxa are represented by Poaceae p.p., Cyperaceae, Ranunculaceae p.p., Liliaceae, and some hydrophytes such as Hydrocharitaceae, Lemnaceae, *Sparganium* type, *Thypha*, *Myriophyllum*, Nymphaeaceae, *Potamogeton*, Alismataceae. The local pollen flora shows repeated fluctuations frequently opposed to those of *Pinus*. For example, directly above 5 m in the section, the sharp decrease in subtropical to warm-temperate arboreal taxa accompanies a sudden and brief increase in hydrophytes initially and then of *Pinus* plus Pteridophyta. Such change in pollen assemblages most likely reflects strong modifications in the local depositional environment, with over-representation phenomena of the local pollen plants. The Pteridophyta curve shows successive fluctuations and higher abundances up to ca 7 m and then a decrease in the overlying interval up to ca 17 m; the hydrophytes exhibit a similar pattern. Along with Pteridophyta also Bryophyta as well some Fungi and Algae are abundant. Warm-temperate forest taxa in the dry sols of lowlands are principally represented by deciduous broad-leaf trees with minor evergreens: *Carya* p.p. and other Juglandaceae (e.g. *Engelhardia* and *Juglans*), the elements of Quercetum (e.g. deciduous *Quercus*, *Q. ilex* type, *Tilia*, *Acer*, *Carpinus*, *Corylus* and *Ostrya*), *Castanea*, *Liquidambar*, *Distylium*, *Liriodendron*, Vitaceae (*Parthenocissus* and *Vitis*), *Eucommia*, *Phellodendron*, Araliaceae, rare Arecaceae, Oleaceae (*Olea* type, *Fraxinus ornus* type, *Phillyrea*), *Magnolia*, *Celtis*, *Ilex*, *Rhamnus*, Celastraceae, *Rhus*. *Pinus* p.p., *Cedrus*, *Tsuga,* other Cupressaceae (cfr. Inaperturopollenites) and *Ephedra* were also present. Ericaceae, Amaranthaceae, Asteraceae Asteroideae, Caryophyllaceae, Plantaginaceae, Fabaceae, Dipsacaceae, Rosaceae p.p. were also distributed in this area; however such non arboreal plants do not exhibit significant expansions as indicated by their percentage values, which rarely exceed 20%.

Submontane to montane taxa are especially well represented by *Pinus* p.p., *Picea*, *Abies*/*Keeteleria*, *Fagus* and *Betula*. *Sequoia* type and *Sciadopitys* type were also present. *Pinus* is present at very high percentages in places whereas all the other taxa are present at low percentages (Fig. 20).

The analysis of floral and vegetal assem-

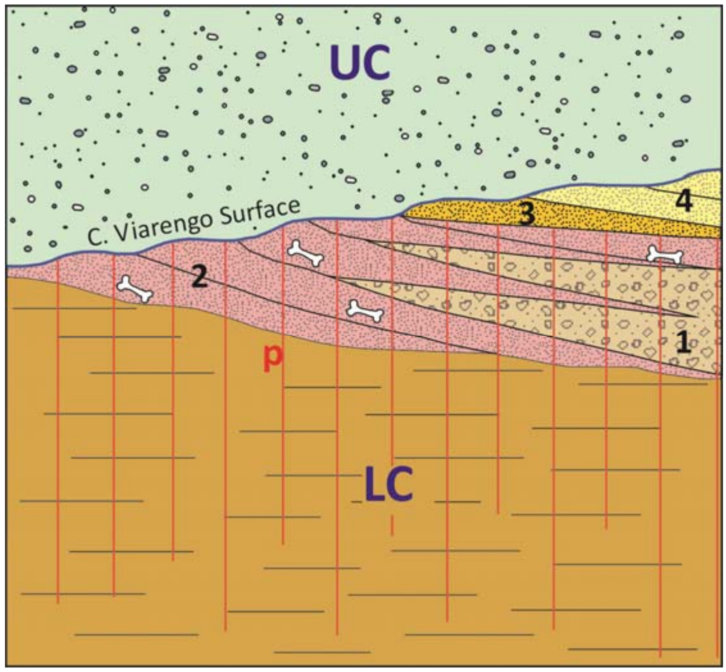


Fig. 18 - Stratigraphic sketch of the paleosol (p) and of the significant cumulative sequence of colluvial sediments (1, 2, 3, 4) observed at the top of silt (LC Piacenzian), subsequently cut by the C. Viarengo Surface and covered by sand (UC Calabrian).

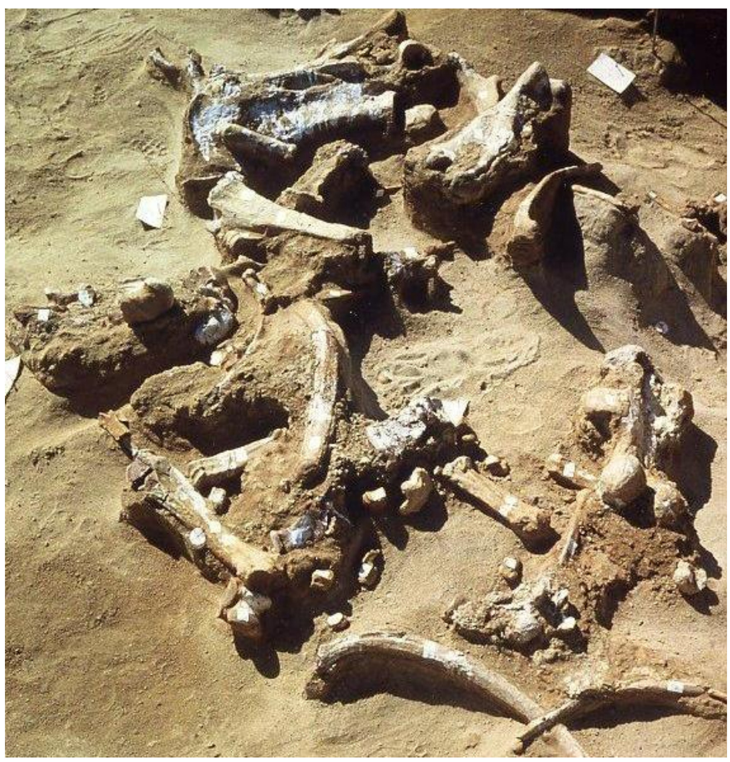


Fig. 19 - The nearly complete skeleton of Stephanorhinus jeanvireti collected into the Cascina San Martino Unit (Piacenzian). Cascina Melona outcrop (Roatto d'Asti) in the central sector of the type-area.

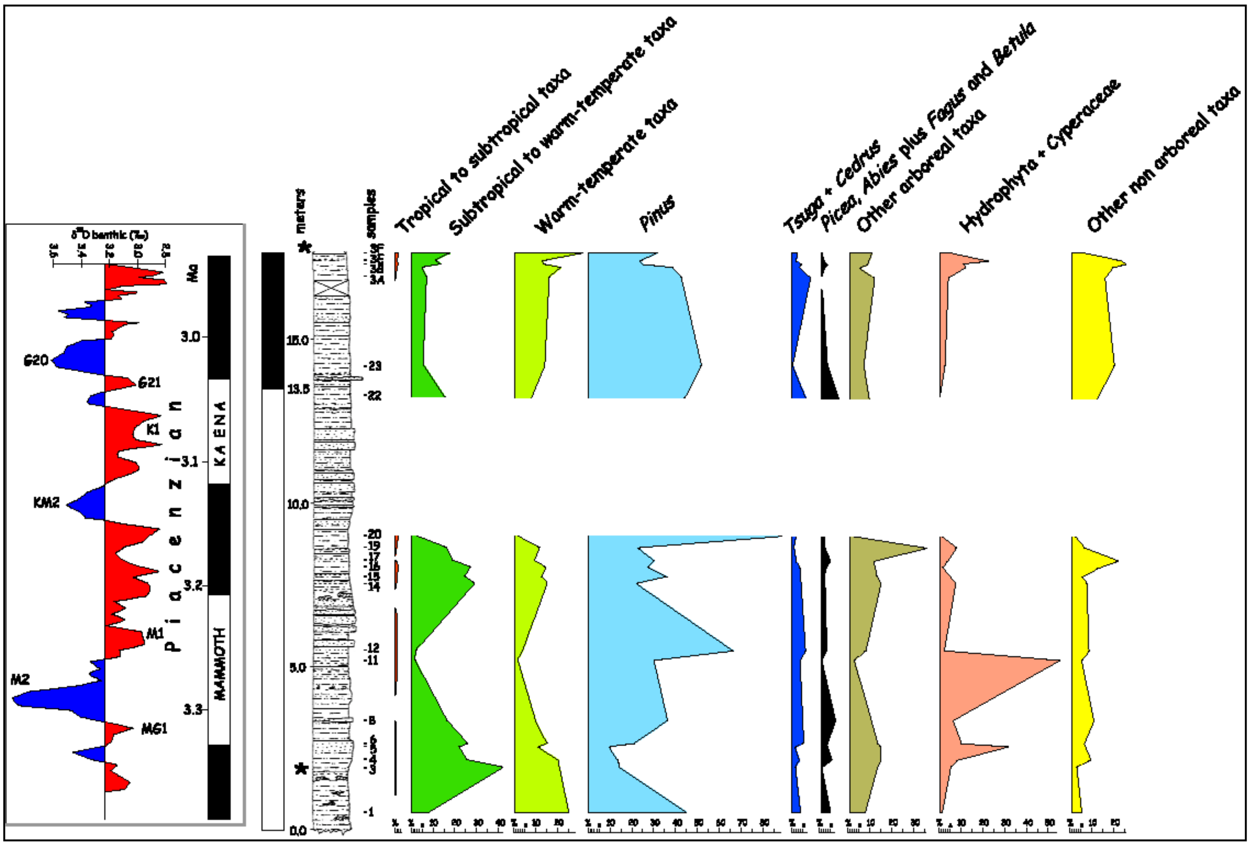


Fig. 20 - Summary pollen diagram of the RDB Quarry (modified from Bertoldi in Carraro ed., 1996). From the left: benthic oxygen isotope stratigraphy (in the square modified from Lisiecki & Raymo, 2005), paleomagnetism (Boano et al., 1999b) and lithologic column (modified from Carraro ed., 1996) of the RDB. For stratigraphic correlation of the RDB with global events, see Section 8.1.

blages provides evidence of past climates and environmental changes, which also needs to be placed within a chronostratigraphic framework. The RDB pollen record (in Carraro ed., 1996), after comparison with both the palynostratigraphic scheme traced for the continental Upper Neogene sections of northern Italy and data from coeval marine sections (Bertoldi, 1990, 1995; Bertoldi et al., 1994), was assigned by Bertoldi to the pre-Tiberian phase (i.e. within the Piacenzian). Indeed, the absence/presence and the abundance of peculiar taxa allowed Bertoldi to conclude that the RDB pollen record postdates the Macrian phase (due to the scarcity of tropical to subtropical taxa) and predates the Tiberian (due to the still good occurrence of the *Taxodium* type). Palaeomagnetic (Boano et al., 1999b) and biochronologic (e.g. Rook and Martinez-Navarro, 2010 and references therein) evidence allows for an evaluation of whether the main (reverse to normal) magnetic polarity reversal at ca 13.5 m in the section of Boano et al. (1999b) (which corresponds well to a portion of both sections described by Carraro ed. [1996] in figs. 29 and 64) refers to the transition from 2Ar to 2An.3n, from 2An.2r (Mammoth) to 2An.2n or from 2An.1r (Kaena) to 2An.1n.

On the basis of our present knowledge, we can assert that:

1. Palynological studies at RDB document the abundance of taxa typical of prevailing subtropical to warm-temperate climates, which is consistent with data from palaeobotanical macroremains (see below).
2. No major cold and/or dry phases, such as those associated with glaciations after 2.6 Ma, are evident, assuming, with good approximation, that the section spans a time interval of at least 40 kyrs.
3. Faunal data support an age for the magnetic polarity inversion (Boano et al., 1999a) younger than that corresponding to the upper Gilbert-lower Gauss. Such a hypothesis is not inconsistent with the pollen data and the interpretation proposed by Bertoldi (in Carraro ed., 1996). When we compare the succession of vegetal changes with those summarized in benthic oxygen isotopic curves (Lisiecki & Raymo, 2005), the most likely correlation is one with the time interval corresponding to the transition from 2An.1r to 2An.1n. However due to the absence of both a solid time-diagnostic framework and a more extensive and continuous pollen record it is impossible to exclude other hypotheses especially that proposing the correlation with the time interval corresponding to the transition from 2An.2r (Mammoth) to 2An.2n (Martinetto et al., 2007; see also paragraph 7.2).
4. According to this last hypothesis pollen fluctuations (Fig. 20) would correspond to M1-KM5 and the first phase of KM3 in the isotopic curve of Lisiecki &

Raymo (2005). Nevertheless the succession of pollen phases does not show an evident correlation with those expressed by the isotopic curve, e.g. the pollen record does not exhibit a cooler phase such as the M2 as well as a major warm phase at its top correlatable with KM5.

5. Based on the alternative hypothesis (correspondence to the transition from 2An.1r to 2An.1n) RDB pollen record would span only the younger portion of the so-called mid-Pliocene warm period (e.g. Prescott et al., 2014 and references therein) (Fig. 20). The lower portion of the pollen record may include (at least) K1 and G22 fluctuations (Lisiecki & Raymo, 2005). The short period, directly above 5 m in the RDB section, between the main two warm pollen phases is not clearly climatically marked because taphonomic biases (over-representation of hydrophytes) mask the true abundances of all the other taxa. A subsequent cooler phase (from approximately 8 m) is characterized by an increase of herbaceous taxa followed by the decline in subtropical to warm-temperate arboreal taxa; this change may correlate with the G22 fluctuation (Lisiecki & Raymo, 2005). The presence of numerous barren samples in the sand-dominated facies prevents a complete documentation of such a cooler phase. The pollen documentation is again available from ca 13.5 m (close to the magnetic polarity reversal). Here, a slight increase in subtropical to warm-temperate taxa is recorded; this increase may correspond to the first warm phase across the base of the 2An.1n (G21). The cooler phase up to 17.7 m (G20) is followed at the top, close to 18 m, by a warm fluctuation. However, the latter is suddenly interrupted because of the sterility of the overlaying samples in the sand-dominated portion of the section (up to 38 m).

In the RDB section, based on the succession of vegetal changes and their correlation to global events (e.g. Lisiecki & Raymo, 2005; Prescott et al., 2014; Fig. 20), once assumed the last hypothesis, the 18-m-thick pollen-rich succession (Bertoldi in Carraro ed., 2006) may span ca 100 kyr at the transition between 2An.1r (Kaena) and 2An.1n (Fig. 20). Consequently, the overlying portion up to 38 m, despite the lack of a clear palynological documentation, may represent deposition beginning at ca 2.9 Ma, i.e., during a progressive cooling preceding the instauration of glacial-interglacial cycles. This time interval is well documented by the pollen record from the Upper Valdarno intermontane basin (central Italy), which shows the effects of climate on the flora and vegetation and the complex interactions between the climate and tectonics since 3.3 Ma (Bertini, 2010; 2013). In the Asti area, an analogous interaction is clearly indicated by both the sedimentologic and structural records.

<u>Upper Complex</u>

The unfavourable lithologic features of the UC, which was affected by a strong weathering, have always discouraged palynological analyses since the first attempt by Caramiello and Siniscalco in Carraro ed. (1996). Nineteen samples were collected and analysed. Of these, 3 were barren of palynomorphs. The 16 pollen spectra are representative of 16 sites for which a precise chronostratigraphic framework is absent. Moreover, according to the information provided by previous authors, some of these were also affected by significant taphonomic biases most likely related to the mode of transport and deposition and to diagenetic effects. The collected data, although discontinuous, can be used to characterize the various lithostratigraphic units as part of the geologic mapping but not to reconstruct vegetational and climatic changes nor to develop detailed stratigraphic inferences. However, as a whole, it seems possible, on the basis of the comparison with the LC pollen assemblages and the integration with other evidence, that the UC was deposited primarily during the Early-Middle Pleistocene.

Fig. 21 - Shoot of Taxodium dubium from the San Martino Unit.

7.2. Macroflora

The Ferrere and San Martino units yielded rich plant macrofossil assemblages (Pavia, 1970; Mai, 1995; Martinetto & Mai, 1996; Martinetto, 2003), even if concentrated in a few sites and stratigraphic layers. Following the presentation of data by Mai (1995), Martinetto & Mai (1996) and Martinetto (2003) there have been new plant macrofossil findings in a single locality near Castelnuovo Don Bosco; these had been merely cited by Pavia et al. (2005). However, our knowledge of the Italian Plio-Pleistocene macrofloral assemblages has represented consistent progress, in particular for the climatic and biochronological interpretation of the carpological component. On the other hand, the leaf assemblages are useful for palaeoenvironmental reconstruction, and thus all the plant macrofossil data are reexamined in this study, particulalyr in light of the results of Martinetto et al. (2014). The available carpological assemblages originate from three sections of the San Martino Unit. The RDB section and Castelnuovo Don Bosco sections also contain species-poor leaf assemblages, whereas the Arboschio section provides rich leaf assemblages both in the Ferrere Unit and in the San Martino Unit.

From a palaeoenvironmental point of view, the assemblages of the three sections and the assemblage from layer A4 of the San Martino Unit in the Arboschio section can be attributed to swamp palaeocommunities that were often dominated by the bald cypress *Taxodium dubium* (Fig. 21). This is associated, in the RDB section, to fruits of *Alnus* sp., *Boehmeria lituanica, Proserpinaca reticulata, Nyssa disseminata* (Fig. 22) and *Sassafras lusaticum* (Ciangherotti et al., 2007), thus indicating an ancient plant community similar to that of the cypress swamps of SE North America, where *Taxodium* and *Nyssa* still grow together. Another element of such swamp communities is a maple related to the modern *Acer rubrum*. However, the fruit and seed assemblages also contained other elements which suggest a strong East Asian affinity of the palaeoflora: *Actinidia, Glyptostrobus, Melissa, Parrotia, Paulownia, Sinomenium, Symplocos* sect. *Lodhra* (Fritsch et al, 2008), *Toddalia, Zelkova*.

The explanation for this twofold similarity is that the Pliocene flora of southern Europe conserved several elements of the ancient Arctotertiary and Palaeotropical (or Tethyan) flora, which later went extinct in Europe (apart from a few species) and partly survived only in SE North America and/or East Asia (Mai, 1995; Rodríguez-Sánchez & Arroyo, 2008). The areas where these species survived share a warm temperate Cfa climate type (hot, wet summers), which can be included in a climate reconstruction of the Ferrere and San Martino units. In both the Ferrere and San Martino units, evergreen elements are present but scarce, such that a Mixed Mesophytic Forest vegetation type is most likely for the reconstruction.

The analysis of the biochronologically relevant taxa (Martinetto et al., 2014) was applicable only to the carpological flora and indicated the absence of Group 1 (typical of Zanclean assemblages) and Group 2 elements. The single exception is represented by a cast of an endocarp of Symplocos schereri (Group 2) found in the uppermost layer of the Arboschio section, in the upper part of the San Martino Unit. Aside from this exception, the assemblages of the San Martino Unit are characterized by good representation of Group 3 elements. Based on the lack of Group 1 elements and the abundance of Group 3 elements (Ficus potentilloides, Meliosma wetteraviensis, Sinomenium cantalense, Symplocos casparyi, Toddalia naviculaeformis, Toddalia rhenana, etc.), we conclude that the RDB1, RDB6 and RT1 assemblages are of a typical Piacenzian composition.

Fig. 22 - Fossil plants from layer RDB1 of the RDB section, San Martino Unit: endocarps of Nyssa disseminata (top) and cones, cone scales and seeds of Taxodium dubium (bottom).

The comparative study of the palaeofloras from the San Martino Unit and other Italian localities indicated that the interval between 3.2 to 2.6 Ma provided 3 distinguishable palaeofloral types, which are dated to the time intervals of 3.2 to 3.0, 3.0 to 2.8 and 2.8 to 2.6 Ma. The RDB1 and RDB6 assemblages provide information regarding the first interval (Martinetto et al., 2007). The RT1 assemblage is significant with regard to the presence of the biochronologically relevant *Symplocos casparyi* (Martinetto et al., 2007). This section is not well calibrated chronologically due to the lack of magnetostratigraphic data. However, the lithostratigraphic correlation with the RDB section (Boano & Forno, 1996) indicates an age very close to that of RDB1 and suggests an assignment of the RT1 macroflora to the same time interval between 3.2 and 3.0 Ma.

8. DEFORMATION OF SEDIMENTS

The Villafranchian succession appears to be deformed by a gentle syncline with an E-W axis. The LC is generally more deformed, as indicated by a syncline axis weakly plunging to the W. The UC appears to be less deformed, with a sub-horizontal syncline axis (see Fig. 26). This context suggests a long time of deformation, partly after the LC sedimentation and partly after the UC deposition. The activity recorded by the two sedimentary complexes has a possible correlation with the Gelasian phase, recognized in the Po Foreland Basin (Vigna et al., 2010).

At the western edge of the type area and Castelnuovo don Bosco sector, there is an important structural discontinuity, the T. Traversola Deformation Zone, which strikes N-S and dips nearly vertically (Fig. 23). Its morphological expression is a prominent N-S very long (30 km) and high (100 m on average) scarp that faces east and generally trends straight with local segmentation. This scarp divides a higher-on-the-west plain (Poirino Plateau) from a lower-on-the-east hilly region (Asti Reliefs) (Fig. 2). New data regarding this structural element suggest a dextral strike-slip displacement, often marked by contrasting stratigraphic successions on the two sides (Fig. 24 and Fig. 25).

There are other zones of vertical deformation in the Castelnuovo don Bosco region (C. Fagliaverde Fault Zone and Castelnuovo Fault Zone) and faults (Gariglio Fault, Serra Fault and Agagliate Fault) (Fig. 23). These discontinuities are marked by the distribution of the Villafranchian succession and the presence of sharp, subvertical contacts associated with the marine deposits and within the sequence itself. These structures indicate the presence of faults trending E-W and N10° E-N50°E with prevalent normal senses of offset (Fig. 23).

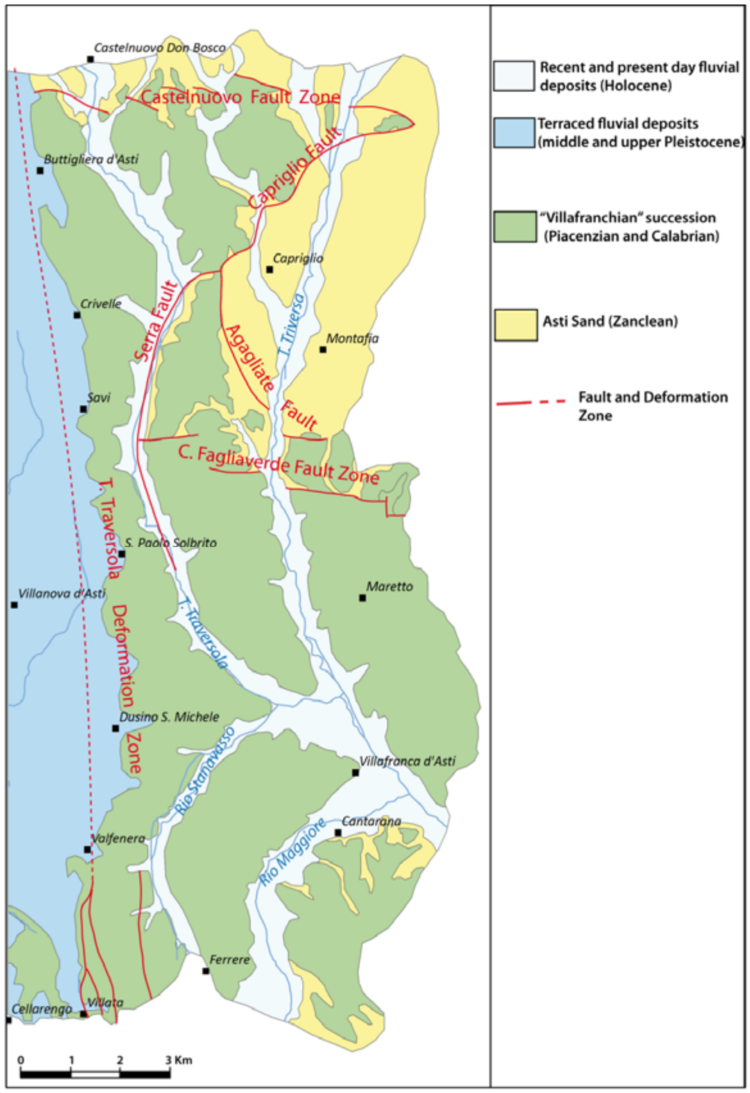


Fig. 23 - The main faults and deformation zones involving the "Villafranchian succession".

Finally, the sediments display diffuse soft-sediment deformation in the form of small folds, slumps, sedimentary dikes, and de-structured laminae. This soft-sediment deformation appears to be linked to syn-depositional and/or immediately post-depositional deformation of unconsolidated sediments. Reworked sediments are also present locally in the form of heterogeneous mixtures of various sedimentary facies affected by numerous fractures and faults and covered by undeformed sediments. This evidence suggests local gravitative re-sedimentation of the succession along the main faults.

9. DISCUSSION AND CONCLUSION

The revision of the type-area Villafranchian succession and the study of Castelnuovo don Bosco section allowed for the identification of a regional erosional surface (the Cascina Viarengo Surface and the Cascina Guerrina Surface), which represents an unconformity in a sequence that was previously considered to be continuous (Carraro ed., 1996; Boano & Forno, 1999). This unconformity separates the profusely fossiliferous deltaic Lower Complex (LC) from the generally barren fluvial Upper Complex (UC). The LC defines an E-W trending syncline with a 10-15° westward dip axis, whereas the UC is roughly sub-horizontal (Fig. 26).

The two complexes separated by the erosional surface can be differentiated based on the following contrasting features.

- Structure: the sediments form a syncline with an E-W axis that dips to the west in the LC and horizontally in the UC.
- Deformational features: the LC displays abundant soft-sediment deformation, such as folds, fractures, normal faults and reverse faults; the sediments of the UC are less deformed and display only folds, fractures and normal faults.

- Depositional environments: the LC is attributed to a deltaic depositional environment; the UC represents a fluvial environment.
- Facies: the sediments of the LC are very heterogeneous and display very different facies and sedimentary structures; the sediments of the UC are, in contrast, very homogeneous and often lack sedimentary structures.
- Fossils: the LC is highly fossiliferous,; the UC is sparsely fossiliferous and contains only minor pollen and vertebrate fossils.
- Consolidation: the sediments of the LC are well consolidated due to loading by the UC, which is poorly consolidated and consequently soft.
- Weathering: the LC is only locally weathered, in contrast to the UC, which is strongly weathered.
- Terracing relationships: in the Castelnuovo sector the UC is deeply entrenched into the LC, suggesting a strong deepening of the drainage network at the time of deposition.

In the LC the magnetostratigraphic data (Carraro ed., 1996; Boano et al., 1999b) along with the numerous fossil remains, including fossil vertebrates (bones and teeth) and plant remains (pollen and macrofloral assemblages) all are consistent with a Piacenzian age (see paragraphs 7 and 8). The ancient zonal vegetation was that of a mixed mesophytic forest both in the San Martino and Ferrere units, and the climate was warm temperate and humid, i.e., of the Cfa type, with a mean annual temperature of 13-16 °C, a warmest monthly mean temperature of 23-25 °C, and a coldest monthly mean temperature of 1-3 °C (Teodoridis et al., 2009).

The chronological record of the UC is, instead, uncertain. This complex unconformably overlies the LC, thereby covering the Cascina Viarengo Surface and indicating an age much later than the Piacenzian. The significant differences between the LC and the UC indicate that a long time interval elapsed between the deposition of the two complexes, during which the environmental conditions drastically changed. The transition from deltaic sedimentation rich in fossil remains and the subsequent fluvial sedimentation, which is predominantly nonfossiliferous, required the passing of a long time-span. The UC is further covered by the fluvial sediments of the middle Pleistocene (Forno, 1982), in agreement with its previously reported age.

The study of the rather discontinuous and scanty pollen record, which is however very different from that in the LC, suggests a possible early-middle Pleistocene age (see paragraph 7.1). Finally, a few elephant teeth preserved in the Regional Museum of Natural Science of Turin (Zuffardi, 1913) were not attributed to this complex with certainty but are likely also from the UC. This interpretation is based on the small amount of sediment attached to the fossils (compatible with the Cascina Gherba Unit) and because these remains are inconsistent with the Piacenzian association of the LC; an early-middle Pleistocene age is suggested. According to the literature, the UC is further covered by middle-upper Pleistocene sediments (Forno, 1982), in agreement with a tentative assignment of the UC to the Calabrian.

The only fossil vertebrates in this complex are a fragment of cervid antler and a tooth fragment of *Sus*

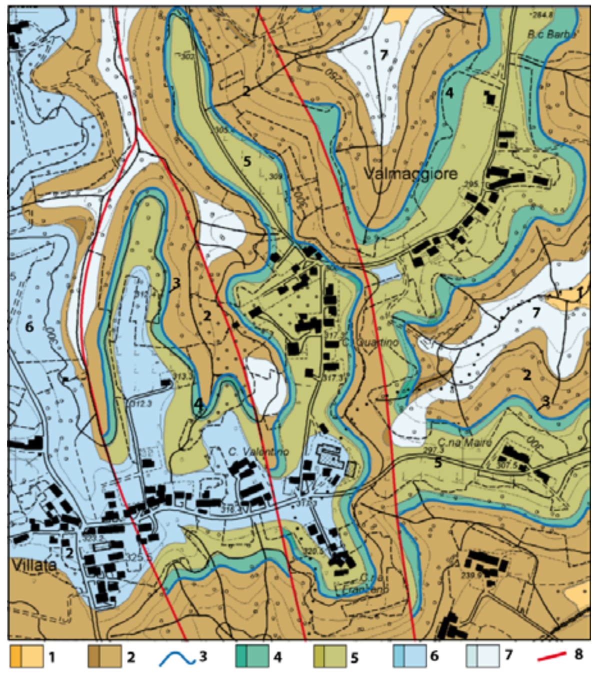


Fig. 24 - A set of N-S faults (8) dislocate the sedimentary succession forming the T. Traversola Deformation Zone. Outcrop (dark color) and interpolating (light color) of LC (Piacenzian) (1: Ferrere Unit; 2: San Martino Unit) and UC (Calabrian) (4: Cascina Gherba Unit; 5: Maretto Unit) separated by the Cascina Viarengo Surface (3) and covered by the middle Pleistocene (6) and Holocene fluvial deposits (7). Area of Villata in the southern sector of the type area (c in Fig. 3).

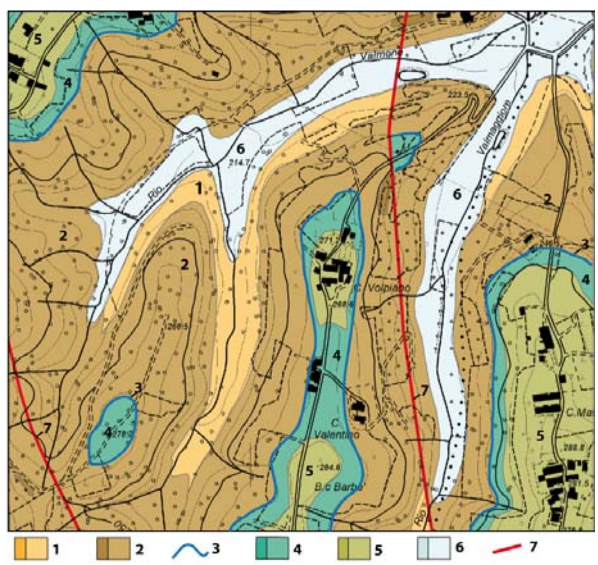


Fig. 25 - A N-S fault (7) referred to the T. Traversola Deformation Zone dislocates the sedimentary succession E of C. Volpiano. Outcrop (dark color) and interpolating (light color) of LC (Piacenzian) (1: Ferrere Unit; 2: San Martino Unit), the UC (Calabrian) (4: Cascina Gherba Unit; 5: Maretto Unit) separated by the Cascina Viarengo Surface (3). In the valley floors a cover of Holocene fluvial deposits (6) occur. Valmaggiore in the southern sector of the type area (d in Fig. 3).

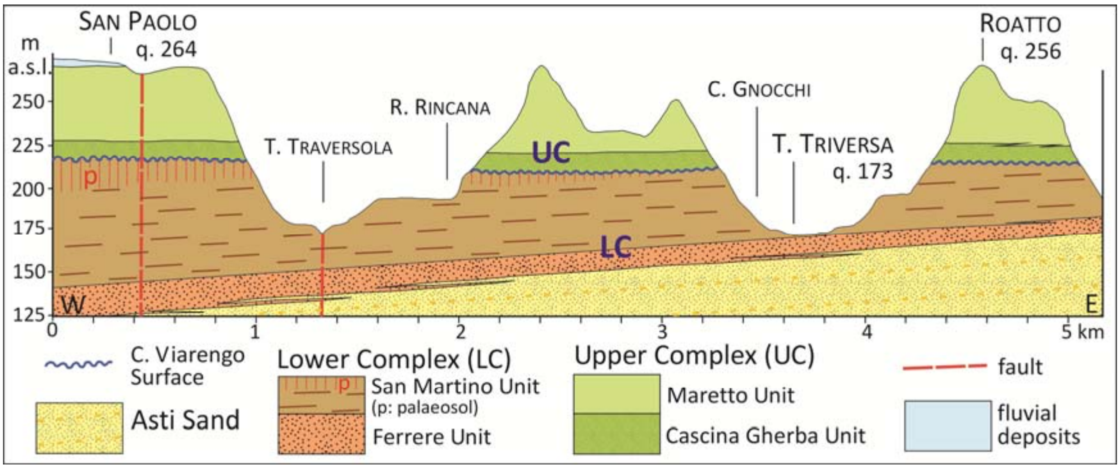


Fig. 26 - The LC dips to the west. A paleosol (p) at the top of LC (Ferrere and San Martino Unit) is preserved in the western part of the type area, associated to colluvial deposits and fragmented fossil vertebrates, indicating the presence of an ancient stable topographic surface on which the weathering could develop and the fossil remains were accumulated. They were eroded along the C. Viarengo Surface and subsequently covered by the sub-horizontal UC. The "Villafranchian succession" was progressively involved in the activity of the N-S T. Traversola Deformation Zone at the western edge of the study area.

sp., tentatively assigned to the Early Pleistocene, Gelasian and/or Calabrian age (see paragraph 6). Regarding the hiatus corresponding to the erosional Cascina Viarengo Surface, the possible reference to the Calabrian for the UC is the most consistent.

This evidence confirms the hiatus between the deposition of the two sedimentary complexes and emphasizes the long interval during which no deposition occurred.

Finally, the entire Villafranchian succession was progressively involved in the syncline development and in the activity of deformational zones, particularly the N-S T. Traversola Deformation Zone on the western edge of the type area and of the Castelnuovo Don Bosco sector (Fig. 23). The study of the strike-slip activity of this structure, with a dextral strike-slip displacement, is well indicated by the dislocation of sediments.

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