Suppl. Geogr. Fis. Dinam. Quat.
III, T. 3 (1999), 7-20, 12 figg.

FOURTH INTERNATIONAL CONFERENCE ON GEOMORPHOLOGY - Italy 1997
Plenary Lecture

GIOVANNI BATTISTA CASTIGLIONI (*)

GEOMORPHOLOGY OF THE PO PLAIN

INTRODUCTION

The Po Plain (fig. 1) is, in itself, a «simple» morphological region - not so much because a plain must be a uniform region as such, but because it may also be «exemplary», that is, a «model». However, it is also a «complex» area. Its complexity derives from the interactions among different overlapping processes: spatial displacements of the coastline, due to eustatic phenomena, have taken place several times and were extensive. These displacements also interfered with tectonic movements and with the overall evolution of the sedimentary basin. Sediment supply from both Alpine and Apennine slopes differed in time. Lastly, anthropic morphogenesis overlapped everything, creating changes in trend but also, in certain cases, rigidity in evolutionary development of coastal and river landforms. Interpreting all these elements requires analyses referring to: 1) the present day; 2) the short term; 3) the long term; and also to: 1) limited spaces; 2) the large-scale environment of the whole plain, including the part now submerged by the Adriatic; and 3) the slopes of the three mountain chains.

A choice must be made in order to select the relative knowledge. Some «simple» aspects will therefore be highlighted, allowing readers to perceive which and how many are the underlying «complex» problems. Much progress has been made since our late colleague and friend Clifford Embleton asked the author to write a few pages on the Po Plain in the volume *Geomorphology of Europe*, of which he was editor. At that time a Working Group on Geomorphology of River and Coastal Plains of the I.G.U. was active. Two of the results, after many years of work, are the maps published on the occasion of this Congress. Many colleagues have made significant contributions, which cannot be summarized adequately here. Now the publication of the *Carta Geomorfologica della Pianura Padana* in scale 1:250,000 (M.U.R.S.T, 1997a), a coordinated work of many Italian geomorphologists, gives not only semi-detailed information on the region but also allows a discussion of general problems.

At least one preceding author must be mentioned: Pierre Gabert (1962) devoted an important monograph to this region, in his study about the «piedmont» of the western part of the plain.

Three aspects must be highlighted: the role of recent and active tectonics; the sequence of depositional and erosive events in time; and the environmental theme. All three may be combined in a single observation: the Po Plain is a young morphogenetic system, fragile and, especially as regards the most recent Holocene, «sensitive» to human intervention.

ROLE OF MORPHOTECTONICS

Recent and active tectonics explain the existence of this structural trench, enclosed between mountain chains which are approaching each other. Among others, Castellarin & *alii* (1992) have highlighted the effects of compressional tectonics in various phases and shown evidence of the parts of two chains which developed new accretionary wedges along their advancing fronts in the Pliocene and Quaternary: the Apennines and, in the Southern Alps, mainly the Prealps of the Veneto. At present the plain be-

(*) *Dipartimento di Geografia, Università di Padova, via del Santo, 26 - I-35123 Padova.*

A contribution to the M.U.R.S.T national project «Catene montuose e pianure: morfologia strutturale ed evoluzione in Italia ed in aree mediterranee», coordinated by P.R. Federici, University of Pisa. Publication co-funded by M.U.R.S.T. 1996 and 1997, national project «La risposta dei processi geomorfologici alle variazioni ambientali». The author is indebted to A. Bondesan, University of Padova, for his kind help in planning some figures of this paper, and to all colleagues who carried out the project of the Geomorphological Map of the Po Plain.

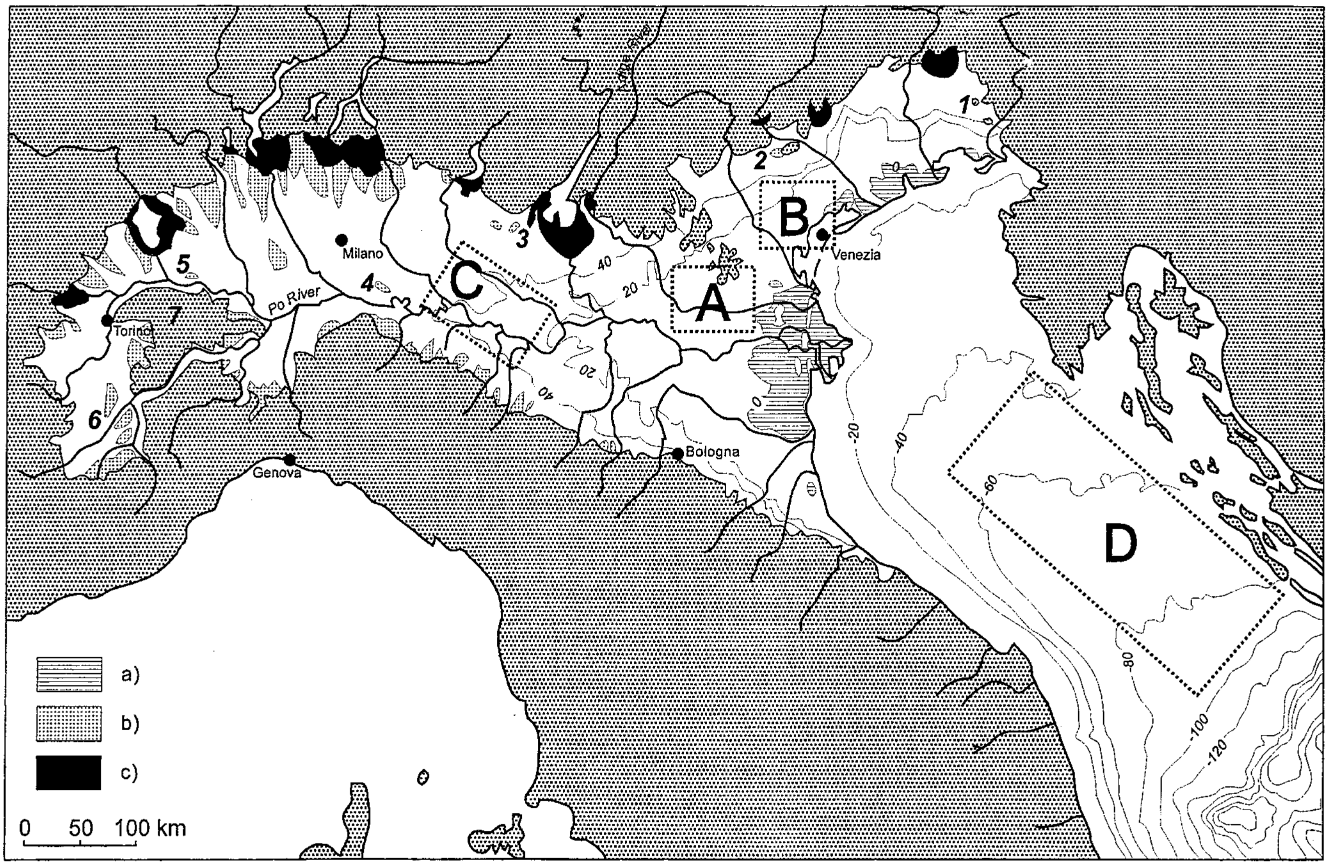


FIG. 1 - The Po plain and northern Adriatic (location map). *Contours* are indicated at 20-m interval only from +40 to –240 m: a) Deltaic and coastal zones below sea level; b) Old Pleistocene surfaces; c) Complex moraine systems. *Numbers*: isolated hills and terraces corresponding to uplifted areas mentioned in text (outcropping neotectonic structures). 1) isolated hill of Pozzuolo del Friuli; 2) hill of Montello; 3) terraces of Castenédolo and Monte Netto near Brescia; 4) hill of San Colombano; 5) terrace of Trino Vercellese; 6) terraces of Fossano; 7) hilly land of Monferrato and Torino. *Capital letters*: Examples discussed in text about proposed hypothesis of tilting movement.

longs almost entirely to the Apennine foredeep, so that it may be interpreted as a complex monocline dipping south-southwest (Doglioni, 1993). According to the above authors, the Alpine thrust front in Lombardy was essentially active until the Miocene, while the Apennine front, accompanied by a much deeper foredeep, is still active. New accretions have come into being along the Alpine thrust front mainly in the eastern section, in the Veneto and Friuli Prealps. In the *Geomorphological Map* (M.U.R.S.T, 1997a), the main development of the margin of the Veneto Prealps, mapped by G.B. Pellegrini and V. Favero, and the external morphology, with emerging morphostructures in relief with respect to the plain, are particularly evident. Doglioni (1993) has briefly discussed the different pattern of this more linear outcropping east-Alpine tectonic front and the irregular pattern of the morphologic Alpine margin in Lombardy (fig. 2); in his opinion, in the western part this fact is related to the Plio-Quaternary onlap over pre-existing erosional morphology, because of the propagation of the northern Apenninic lithospheric flexure (shaded area in fig. 2), involving a large part of the Southern Alps. In fact, several buried valleys near the border of the Lombardy Prealps preserve marine sediments of Pliocene age, so that many erosional forms may be considered as relics of late Tertiary age (Felber & *alii*, 1991), even though they also reveal young tectonic displacements.

It is well known that extremely thick Pliocene and Quaternary sediments lie under the present-day plain. In structural maps, particularly in the *Structural Model of Italy* (C.N.R., 1990), the depth of the base of the Pliocene is indicated, and is related to the complexity of the buried tectonic units of the Apenninic belt. The thickness of the Quaternary sediments has recently been reconstructed (Bartolini & *alii*, 1996), so that it is now estimated as being, on average, 0.92 km in the whole basin. The total volume is about 95,000 km^3.

Let us now focus on the morphological contact between the plain and the Apennines. Gentle hills and low terraces interfinger the many alluvial fans. The continental deposits of the plain become very thick right up to the foot of the hills, under the «Pede-Apennine Lineament», called also «Pede-Apennine Thrust Front». In Romagna, towards Rimini, the boundary between fluvial deposits and the sub-

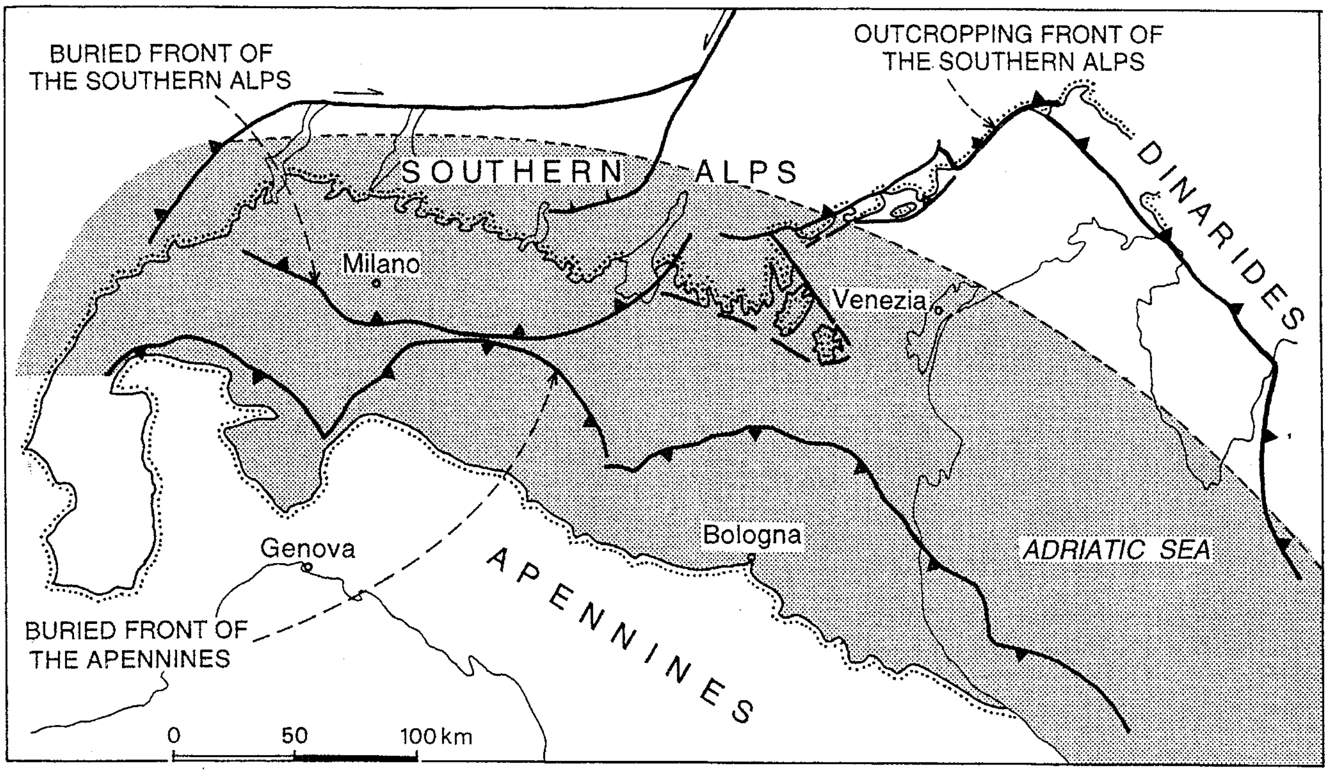


FIG. 2 - Late Miocene-Quaternary north-north-east propagation of northern Apenninic lithospheric flexure (from Doglioni, 1993; modified). *Shaded*: Apenninic foredeep.

strate, formed of older marine sediments, suddenly dips steeply; in this sector, the evidence of the terraces too disappears a few kilometres from the hill line (Elmi & *alii*, 1987).

Near Bologna, research-workers of the Geological Service of Emilia-Romagna have established a precise correlation between the alluvial sediments buried in the plain and the terrace systems of the Apennine valleys, as shown in profiles crossing the «Pede-Apennine Thrust Front» (Amorosi & *alii*, 1996). The profiles give a clear picture of the tendency of the plain to sink, together with uplift of the chain, countered by erosion.

As a simple comparison, let us examine the margin of the Veneto Prealps where, as already mentioned, the external morphology is characterized by emerging morphostructures in relief with respect to the plain: a fault scarp even cuts the apex of the large fan of the Brenta river. However, the evidence of these reliefs depends on the fact that they are composed of more resistent materials than the hills of the external Apennines. The large, well-exposed Pleistocene fans can still be distinguished clearly at a great distance from the Alpine border; some distal parts of these Pleistocene surfaces extend as far as the narrow coastal plain at the lagoon fringe near Mestre and, in Friuli, along the fringe of the Marano-Grado Lagoon. Important phases of construction and erosion of the terraces in these pede-Alpine plains are controlled more by variations in the discharge and load of rivers than by tectonic movements (which do occur, as will shown later).

As a first conclusion, taken from two simple examples, not only the diversity of the structural arrangement of the north and south margins of the plain should be emphasized, but also some important consequences for the morphology of the surfaces of fluvial origin in a large part of the Po plain. From the structural viewpoint, a platform or monocline dips gently south from the Alpine border, on which lie the fluvial and fluvioglacial forms of the Alpine side, created by large rivers with extensive catchment basins in the mountains and by the repeatedly active meltwater streams from large Pleistocene glaciers. Instead, on the Apennine side, the numerous but shorter rivers have built up many steep alluvial fans, tending towards progressive burial, on a substrate which tends to sink.

The buried tectonic structures will not be discussed here in detail, because attention will be focused on the surface effects. However, something does emerge from the deep structures, about which we have knowledge due to research for fossil fuels by Agip. These reliefs are briefly described here (for locations, see numbers in fig. 1). Apart from some isolated terraces in the province of Udine (Pozzuolo del Friuli, and the hill in the city of Udine itself) connected with a Dinaric system of faults, other interesting terraces are known in the province of Brescia, which must be connected with south-Alpine buried structures (terraces of Ciliverghe, Castenedolo, and Monte Netto). In southern Lombardy, there is the Colle di San Colombano al Lambro, a typical emerging structural high, belonging to an important buried structure of the Apennine system. In Piedmont, there is the terrace of Trino Vercellese, also north of the Po, and connected with Apenninic structures; and in the southern part the old terraces of the Fossano area, also uplifted by tectonic movements.

In fig. 1 other much higher morphostructures have also deliberately been numbered, such as the hill of Montello (number 2) on the eastern side, and the system of Monferrato - Collina di Torino (number 7) on the western side. These structures have been greatly exposed to and also reworked by erosion; their uplift explains the repeated changes in course of important rivers such as the Piave, the Tànaro and the Po itself. The Monferrato system of hills occupies a very advanced position in the plain, forming a grandiose morphostructure now integrated in the mountain Apennine system - unlike many other buried frontal tectonic ridges, which were involved in the general sinking of the foredeep.

LARGE ACCUMULATION FORMS AND TIME

Let us now turn our attention to the large depositional systems. On the Alpine side, these are often linked with sediment transport caused by glacial processes right into the plain. There is no general agreement about the chronology of glaciations and related depositional/erosional cycles in the southern slope of the Alps. The Italian Quaternary experts preparing the new geological map (scale 1:50,000) distinguish mainly lower, middle and upper Pleistocene into both glacial and fluvioglacial stratigraphic units and are aware of difficulties in correlating subregional units. As an example, the well known «livello fondamentale della pianura» (main level of the plain formation), a very extensive morphological unit mainly of upper Pleistocene age (Cremaschi, 1987a), is probably a composite polychronological one.

For these reasons, this simplified presentation is limited to distinguishing depositional systems of the «Old Pleistocene», «Young Pleistocene» and «Holocene», without going into detail about morphochronological distinctions.

The *Old Pleistocene forms* are clearly recognizable in the western and central sectors of the plain at the foot of the Alps, with a smaller extension to the foot of the Apennines, but in any case far from the sea (fig. 1).

The old surfaces are distinguished not only by considerable weathering of sediments, which originally must have been mainly gravelly and then covered by loess (Cremaschi, 1987b); they are also mostly dissected by a dense network of small valleys.

The *Young Pleistocene depositional systems* have left much larger surfaces, including those directly linked with morainic amphitheatres, and surfaces deriving from the activity of independent torrents (fig. 3). On the Apennine

FIG. 3 - Main Young Pleistocene surfaces in Po plain and northern Adriatic bottom: a) Drowned delta of Po into the «Middle Adriatic Depression»; b) Main surfaces dating from Young Pleistocene; c) Complex moraine systems (of various ages).

side, there are only alluvial fans; on the Alpine side, torrential fans and true fluvioglacial outwash plains alternate and overlap; they flatten out towards the low plain, where silty/sandy sediments become prevalent and gravels diminish. This gives rise to the characteristic «spring line» or «spring belt». However, an overall view of this depositional system also requires us to bear in mind its intermediate and extreme distal parts, composed of the old Po Delta (fig. 3), clearly recognizable at the boundary with the «Meso-Adriatic Depression», and the transitional plain which, with a slope of 0.25-0.6 per mil, we still find preserved in the bottom of the northern half of the Adriatic (Ciabatti, 1981; Ciabatti & *alii*, 1987; Trincardi & *alii*, 1994).

In this framework, let us suggest what is specific to the set of forms created by torrents in the proximal sectors with high gradient (the «high plain»), what is specific to the «low plain», by means of gradual or marked transitions, and lastly, what is characteristic of the distal plain, now drowned.

Although the connection between the preserved exposed surfaces of the «low plain» inland and the drowned plain in the Adriatic is buried under the Holocene sediments of the coastal belt, the peaty layers intercalated with Pleistocene ones continue to give us new detailed information on morphostratigraphic evidence through radiometric chronology. In this way, we can identify the old profile at the top of the Pleistocene continental layers which, near Venice, also seem to be distinguished by hard horizons, interpreted as the residues of buried paleosols.

In the Sub-Alpine sector, braided river systems appear to dominate in building the high plain, sometimes accompanied by the transport of enormous blocks by fluvioglacial torrents (M.U.R.S.T, 1997a) and by the formation of multiple channels and large bars. Sandy bars and levées created long fluvial ridges or, in the mid-plain, were associated with meandering channels with a very large curvature radius (fig. 4).

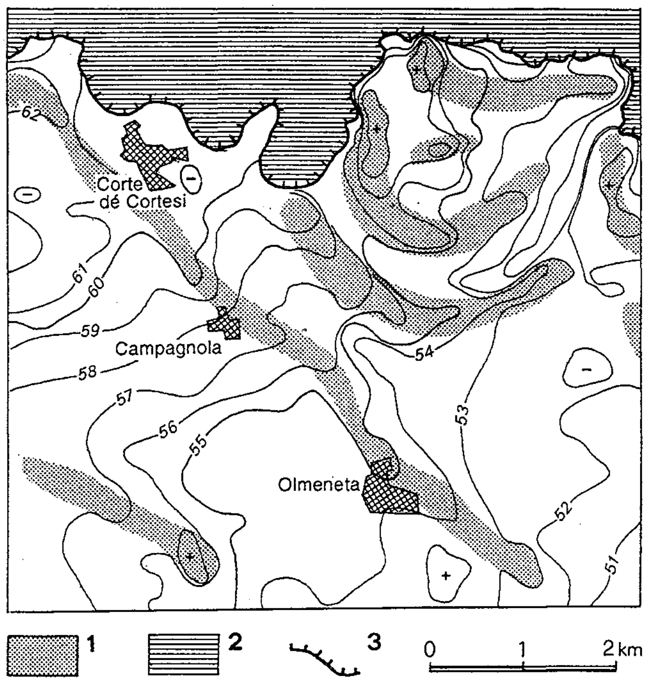


FIG. 4 - Details in Young Pleistocene plain north of Cremona (from M. Marchetti, 1992). 1) Fluvial ridges; 2) Floodplain of «Holocene valley» of river Oglio; 3) Scarp.

Indirect calculations of fluvial discharge during the phase of final aggradation of the «Last Glacial Maximum» have tentatively been proposed by Marchetti (1996). He has also compared the quite different hydrodynamic conditions which characterized some tributaries of the Po in the Holocene, bearing in mind the morphometry of meanders and cutting phenomena.

The examples of central Lombardy are not exactly repeated in the Veneto where, for example, the outwash plain with braided pattern from the old Adige glacier was constantly associated with very large channels arranged in a fan (Sorbini & *alii*, 1982). Of this fan, fig. 5 shows only the central zone downstream from Verona, but its direct connection with the moraines of Rivoli Veronese is clear. The same figure gives an example of younger entrenched terraces which demonstrate transitional stages from the typical braided system of Pleistocene age and the following meandering fluvial forms of Holocene age.

In Friuli, aggradation continued after the end of the Pleistocene in the large torrential rivers which we see today, because of the important bedload yield deriving from catchment basins characterized by high relief energy, active seismicity and abundant precipitation. However, downcutting occurred in several sectors of the «high plain», being the response of Alpine torrents to the desappearance of glaciers and periglacial conditions. Also typical in this eastern part of the plain is the clear evidence of the «spring belt» («linea delle risorgive») not only as a hydrographic and hydrogeologic feature but also as an important geomorphologic boundary, visible in the rapid change of gradient and in type of sediment. Near Pordenone, most of the several small rivers which have their origin along this line appear capable of significant morphologic activity in dissecting low plain sectors built up of fine sediments during the Pleistocene. Dissection took place quickly in areas where aggradation by major torrents ceased as a consequence of change of course, being independent of proper climatic changes. In the eastern Friuli sector, noteworthy are the preserved surfaces of Pleistocene age, which extend downwards until they reach a narrow zone bordering the present-day lagoon belt. For this reason, one may imagine that some specific fluvial features like entrenched channels of late Pleistocene or early Holocene age continue from inland to the submerged part of the plain.

Observing the entire depositional system as far as the remote Pleistocene mouths of the Po, we must recall Luigi De Marchi's interpretation of the existence of a drainage system cut in the morphology of the drowned platform of the northern Adriatic (De Marchi, 1922). The bottom topography is now better known thanks to modern maps, which do not confirm De Marchi's ideas. However, a few buried river channels have been identified in uniboom profiles, and correlated with deltaic sediments prograding

FIG. 5 - Young Pleistocene and Holocene geomorphologic units of Adige system near Verona (from Sorbini & *alii*, 1984; modified). 1) Young Pleistocene outwash plain related to Adige glacier, with evidence of large braided stream patterns; 2) Low terrace, with small braided patterns; 3) Holocene flood plain with meandering patterns; 4) Alluvial deposits of local streams.

seawards (Trincardi & *alii*, 1994). The plain was mainly a large depositional plain, in which a dominant role was played by the Po.

Area of Holocene sedimentation

For reasons of brevity, the area where the Holocene sediments are thickest are described here, that is, on that large «sedimentary wedge» which formed over the last 6000 years, corresponding to the phase of «high stand» (fig. 6): 10-20 m along the Lido of Venice, 35 m at the present-day apex of the Po Delta (fig. 7), and 30 m under the Ravenna littoral. The position of this belt and its southward extension are clear: marine geology studies on the submerged platform of the northern Adriatic and knowledge of sea currents and fluvial sediment transport explain the very thick recent deposits prograding seawards from the Po Delta south (Van Straaten, 1970; Ciabatti, 1981; Bartolini & *alii*, 1996; Correggiari & *alii*, 1996).

The space involved in Holocene fluvial morphogenesis is also very extensive and penetrates the continental area, invading the «low plain» throughout the Veneto sector but particularly in the Emilia-Romagna sector, where it forms a large triangle on the right bank of the Po. A region like this is called a «base-level plain». This term is used here in a more extensive sense with respect to the true «coastal plain», which is the part characterized by a set of mixed constructions, fluvial, littoral and lagoonal.

Let us now examine this entire area of great Holocene sedimentation. It is fragile and geo-ecological problems emerge frequently, partly because it is the area most subject to geomorphological instability as regards ongoing processes, and also the most sensitive to anthropic pressures. The very fact of the presence of thick recent sedi-

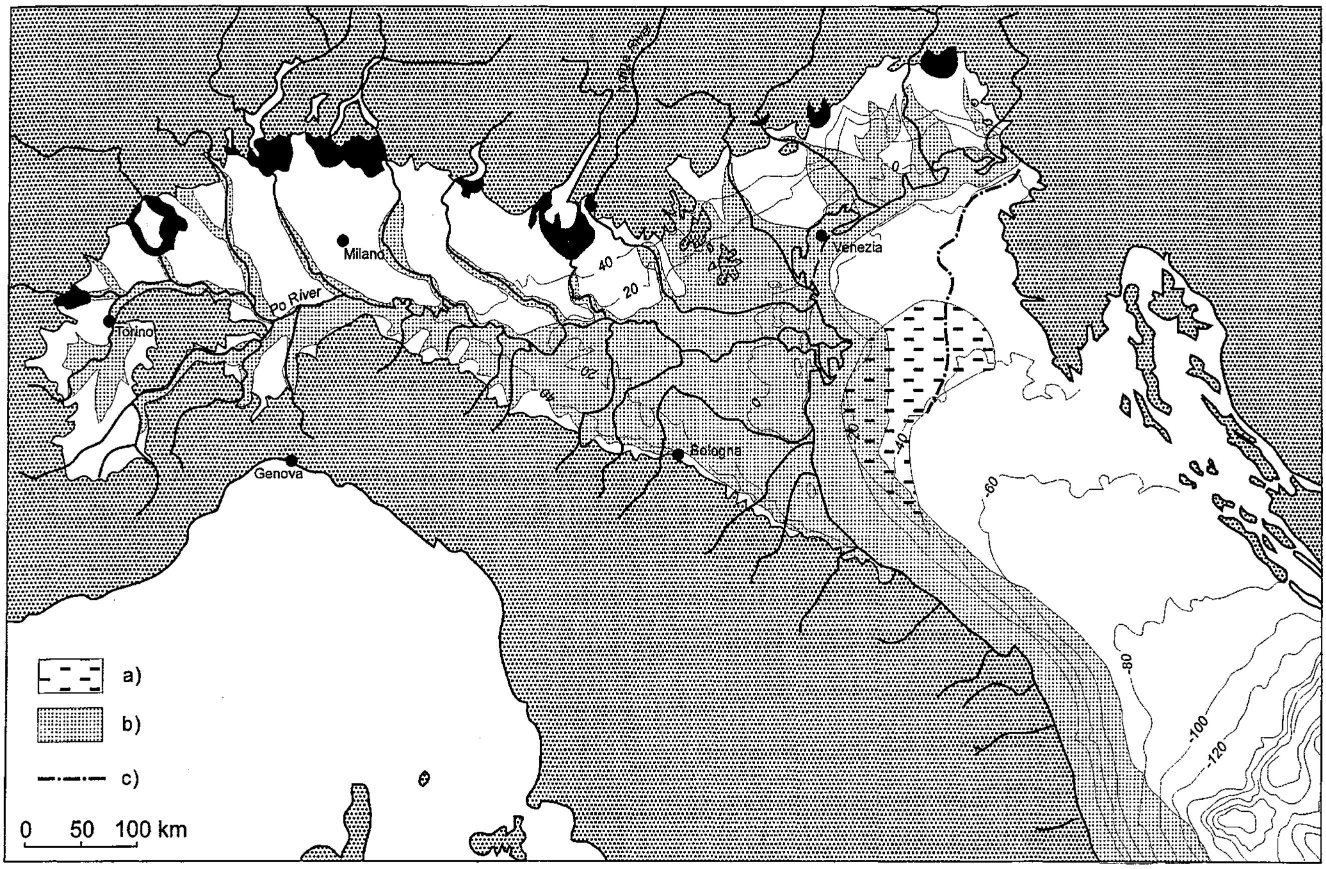
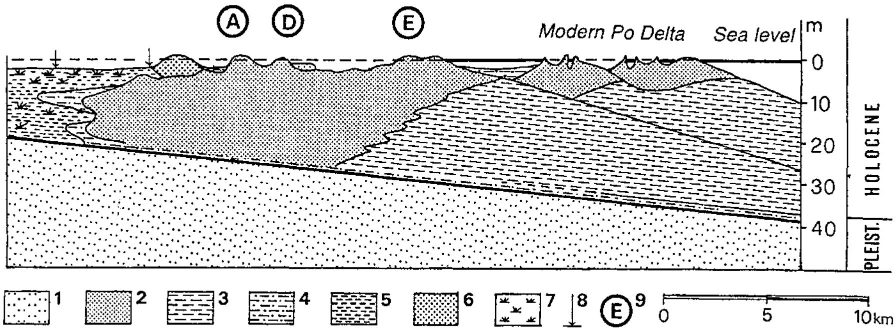


FIG. 6 - Holocene surfaces in Po plain and main depositional area of Holocene sediments in northern Adriatic: a) Barrier-lagoon-estuary system at about 10,000 years B.P. (from Correggiari & *alii*, 1996); b) Holocene sediments; c) Shoreline 10,000 years B.P., according to Marocco (1991).

ments already indicates instability, because it presumes subsidence by natural compaction. To these phenomena must be added subsidence due to tectonics and to other processes induced partly by artificial extraction of fluids from the subsoil and artificial draining of surface soils. Seawards, not only erosion but also, locally, gravitational collapse occur along the prograding slope. These are low-lying areas, so that problems of hydraulic safety are important (Selli & Ciabatti, 1977; Bondesan, 1989; Castiglioni & *alii*, 1990; Bondesan & *alii*, 1995a; Marocco & Pessina, 1995; Simeoni & Bondesan, 1997).

At this point, the author would like to report an anecdote from his personal experience, about Prof. Hans Boesch of Zürich, when he took his students on an excursion to the Po Delta in 1960. Those were the years of the fastest soil sinking, about 20 cm per year, which meant that the whole system of embankments, sea defences, reclamation canals and roads were called into question. There was

FIG. 7 - Geological cross-section of Po Delta (from M. Bondesan & *alii*, 1995b). 1) Sand and silt of continental facies, Pleistocene; 2) Coastal sand facies (Holocene); 3) Marine silt and clay facies; 4) Lagoonal silt and clay facies; 5) Continental silt and clay facies; 6) Fluvial sand; 7) Peat; 8) exploration borehole; 9) Main outcropping beach ridges, with ages: A = subboreal-subatlantic transition; D = about 5th century AD; E = about 10th century AD.



a fall in population, partly as a result of the flood which had occurred nine years previously. Standing on a river bank, Prof. Boesch exclaimed: «The only thing stationary here is the sea! We must look to the sea to understand how the earth moves!»

Nearby forty years later we now have many more data on the speed of subsidence, which was not uniform in time (Bondesan, 1989; Bondesan & alii, 1997). New altimetric maps (Bondesan & *alii*, 1995a; M.U.R.S.T, 1997b) show areas between 2 m above sea level and zero, others between zero and –2 m, and those under –2 m. These maps were constructed on the basis of large-scale technical maps from aerial surveys of 8-20 years ago. As the maps represent altimetry, they allow the study of only one of the physical components, and should in any case be used as documents expressing the sum, the outcome, of a series of multiple events distributed over time, linked to various kinds of geomorphic processes.

Only one example will be described, with a note remarking on the clearly visible difference between the area north of the present-day river Reno (which runs artificially near the course of the old branch of the Po called Po di Primaro) and the area to the south, directly influenced by rivers descending from the Apennines (fig. 8). The northern area, at very low altitudes, derives from the recent reclamation of the Valli di Comacchio, first occupied by brackish bodies of water: today, these are true polders, going back to about the middle of this century. Conversely, the southern area, practically all above sea level, has risen over the last two centuries, artificially facilitating the distribution, in the so-called «casse di colmata», of sediments from rivers descending from the Apennines. The «cassa di colmata of Lamone» was completed in the 1920s and 1930s. This area, clearly, also suffers from subsidence of various types. A 17th-century map of the territory near Ferrara shows the almost natural previous situation, when «internal deltas» developed, created by the Reno and other Apennine rivers terminating in flood basins (fig. 9).

The geomorphologists are hard at work. Ongoing changes must be monitored; answers must be provided, as

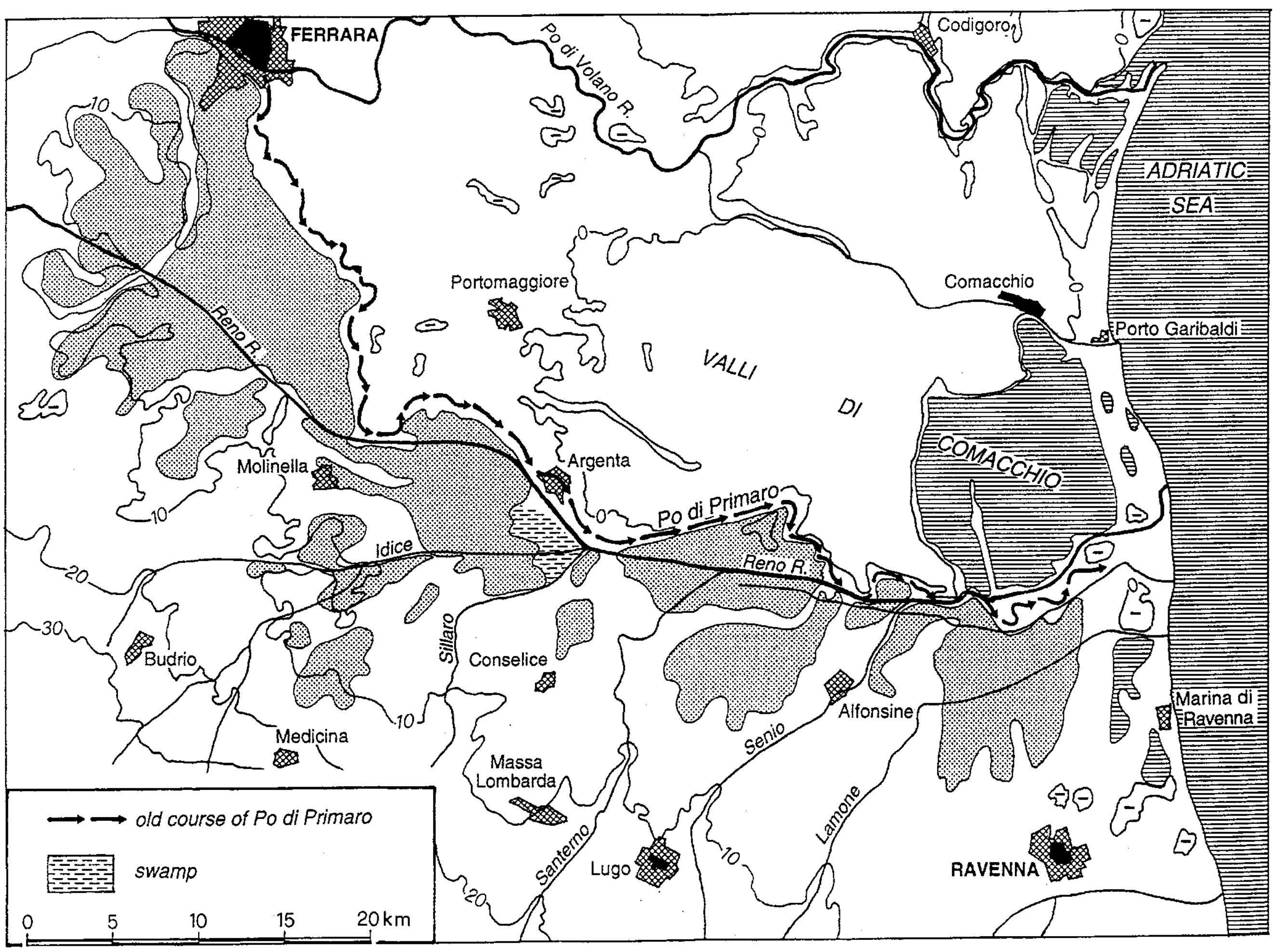


FIG. 8 - Main areas of artificially controlled fluvial fills in Emilia-Romagna («colmate»), as represented on Geomorphological Map of Po Plain (*dotted areas*). *Contours* (10-m interval) are added. For conditions before reclaiming, when floods and rivers were not controlled, see fig. 9, representing western part of this map.

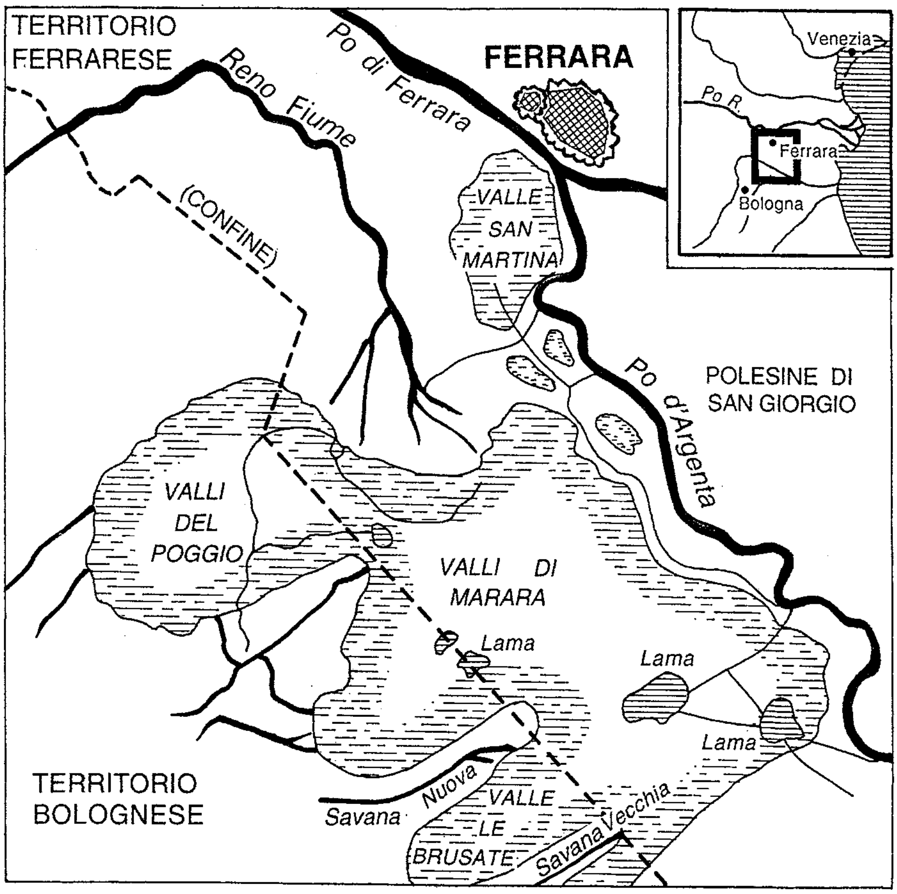


FIG. 9 - «Valli» and «interior deltas» of rivers Reno and Sàvena before regulation (17th century). This area was later reclaimed mainly with «colmata» system (sketch derives from coloured maps by Alberto Penna, kept in the Biblioteca Comunale Ariostea of Ferrara; courtesy Prof. M. Bondesan). «Valli» are here seasonally flooded depressions. «Lame» are semi-permanent swamps. *Dashed line*: ancient boundary of territories of Bologna and Ferrara, respectively.

well as possible with objective data, to questions faced by public or private bodies engaged in land management. However, more generally, there is the task of supplying an interpretation of the surface evidence, by means of genetic analysis which bears in mind past events as well as present ones, exploiting geological and geophysical data, data from direct geomorphological research, not neglecting those from historical documents and archeological findings. The delta and lagoons are not only described in field surveys but also in historical documents with a wealth of detail.

The ways in which human requirements have been adjusted in the face of the variability of geomorphological processes continually come to the fore whenever we study short- or long-term events. In some rivers the present embankments are still insufficient to contain floods like that which occurred in November 1966. For the river Reno, breaching of the bank in 1990 may be taken as an example (fig. 10).

Responses to these phenomena do not only involve strictly technical analysis of each engineering work. The overall evolution of the territory must be borne in mind. In the last few decades, several north Italian rivers have entered a deepening phase which has required defence works on bridges and banks using new criteria. What environmental factors have changed and caused these contrasting responses by fluvial processes? They are factors conditioned by human activities, both in mountain basins and along river beds (Castiglioni & Pellegrini, 1981; Castiglioni, 1995). This problem is one of the central themes of geomorphology, in the sense of geo-ecology.

The bed of the Po is not free from phenomena of this type. In natural conditions, many stretches in Piedmont, Lombardy and Emilia exemplify the type of meandering river bed, persisting over centuries, as shown by the relict morphology of whole meander belts. The present-day evolution shows the tendency to both reduced sinuosity and greater instability, with deepening of the main channel (Govi & Turitto, 1993; Dutto & Maraga, 1994; Castaldini & Piacente, 1995). The artificial cuts of the meanders made in the past and the present-day embankments do not entirely explain why some stretches seem to pass to the «wandering» type, which some Italian geomorphologists call «transitional».

Let us now look at the stretch of the Po from near Mantova to the delta: the classic type of meandering bed is less easy to recognize in the present-day course and in some of the paleo-beds identified on the sides. A typical basin-ridge association prevails, i.e., one with fluvial ridges elevated due to the development of natural levees defining depressed flood basins; selective compaction of sediments has certainly enhanced altitude differences between ridges and basins. Without establishing any particular rule, it

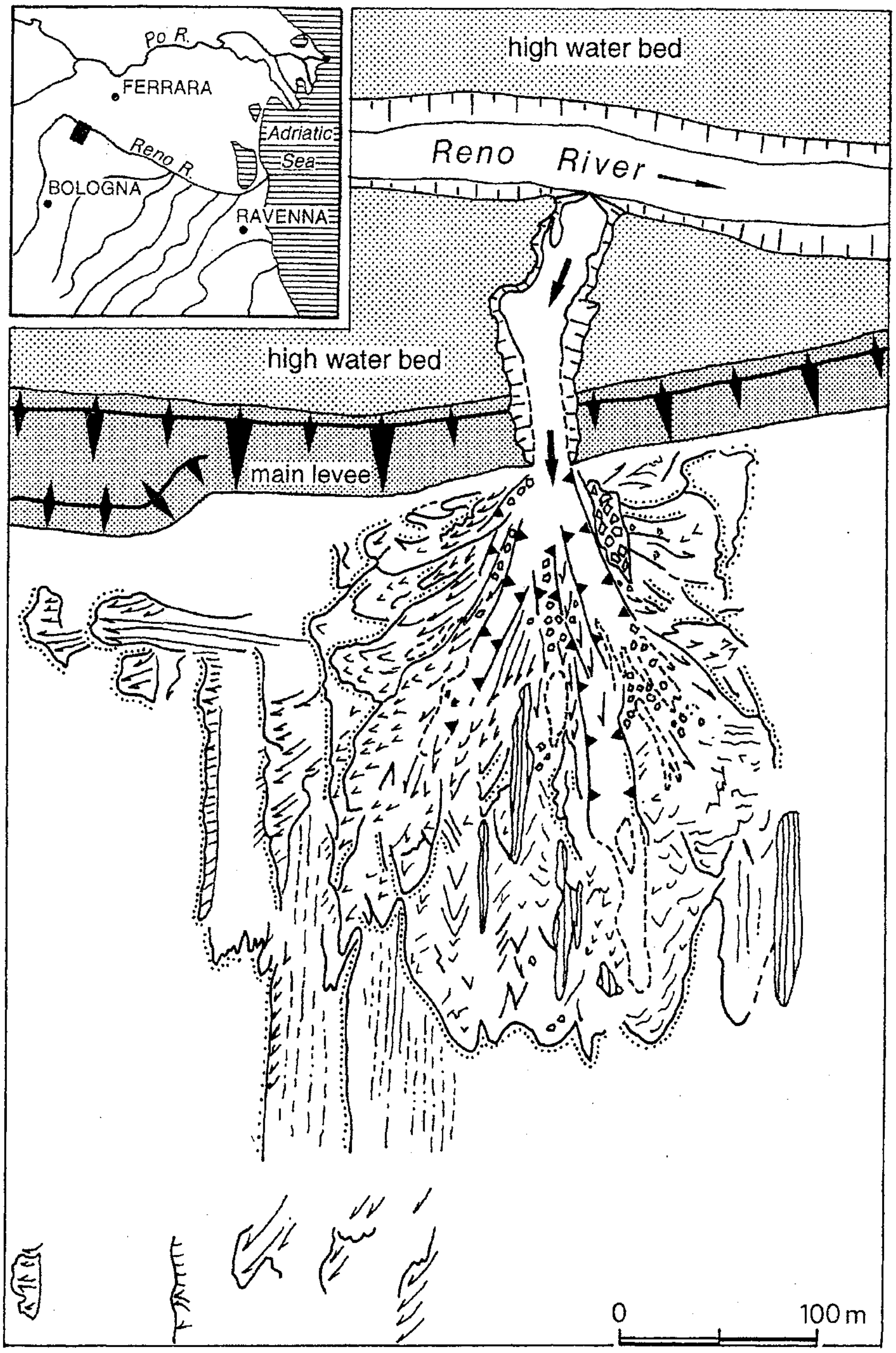


FIG. 10 - Recent crevasse splay of Reno River, December 1990 (from Cremonini, 1993-1994; modified).

should be noted that the relative scantiness of typical meandering river beds is probably due not only to recent artificial changes but also to the high number of breaches and crevasse splays, with frequent avulsions with respect to the normal sideways oscillation which would allow a quite well-defined course to create a regular series of meanders. The concept of an «anastomosing» pattern, frequently found in recent literature concerning rivers in coastal plains, does not seem at present to fit into the framework of the region.

Tectonic tilting of large fluvial surfaces?

The irregularities of the regimes and the differences in altitude created by sedimentary processes are among the principal causes of the complex mobility of Holocene rivers. Researchers have tried to identify some kind of tectonic or climatic control to explain changing river courses. One of the most interesting examples is that of the river Mincio which, near Mantova, changed course due to the effects of a fault held to be active (Castaldini & Panizza, 1991). Beyond the scope of the present paper is the analysis of situations in those sectors of the Holocene plains in which the drainage network may have been influenced by recent tectonic movements of the complex buried Apennine structures. Instead, a stretch of plain belonging to the large pede-Alpine monocline will now be described: that of the river Adige, with one large change in its course. Its old courses are shown in fig. 11: to the north is the course, with its branches, which ceased to be functional around 600 A.D.; to the south is the present-day river with other branches, some old, some modern and sometimes influenced artificially. This example (*example A* in the index map of fig. 1) provides the opportunity to discuss the role of large-scale tectonic movements. The overall difference in average altitude between the northern and southern parts of the plain (fig. 11) may be estimated at about 3 m, or more. This difference, which may be observed over a large area, cannot be explained only by more sedimentation to the north and less to the south. It has been hypothesized that this is a case of a tilting, a tectonic lowering movement in the southern sector, and that this movement was the main cause of the definitive abandon of the northern course of the river (Castiglioni, 1995). The soil movement occurred in the Holocene and historical times.

A similar interpretation may also be applied to the old depositional surfaces of the Young Pleistocene. Three more examples are examined here.

Example B (see index map in fig. 1): a well-preserved stretch of the Pleistocene plain near Venice, has an average slope of one per mil; it made up the distal part of a large fan of the river Brenta. On its apparently uniform surface, with sandy-silty sediments, using detailed analysis, the young research-worker P. Mozzi was able to highlight an original depositional microrelief with longitudinal elements. These fit the system of present-day watercourses, now no longer fed by the Brenta but by plain springs. fig. 12 shows present-day drainage entering the Lagoon of Venice and the contour lines as published in the *Geomorphological Map* by V. Favero (M.U.R.S.T, 1997b). Mozzi was also able to collect many samples used for radiocarbon analyses (until now unpublished), for which G. Calderoni of the «La Sapienza» University of Roma is kindly thanked.

The aim here is to highlight the incongruence of drainage with respect to the slope, and an interpretation for this anomaly which appears to be both simple and convincing is put foreward (fig. 12). Whereas the watercourses have almost entirely kept their original directions caused by Pleistocene accretionary processes, the direction of the slope has rotated southwards by an angle of about 23 degrees. In other words, the contour lines have moved clockwise by about 23 degrees. A tilting movement, therefore, towards the south-west, is probable.

As reported in another paper (Castiglioni, 1997) simple calculations have enabled the extent of this movement to be estimated, expressed as a difference in altitude of about 9 m over a distance of 20 km. The maximum available time interval, given by radiocarbon ages for sediments lying just below the present surface, is about 14,000 years. It is also easy to calculate the (minimum) speed of the movement – 0.6-0.7 mm per year – as the difference in altitude between two points at a distance NE-SW of 20 km from each other.

To summarize therefore: the present-day form of the plain, as shown by the contour line trend, reveals a change - presumed to be tectonic in origin - with respect to the

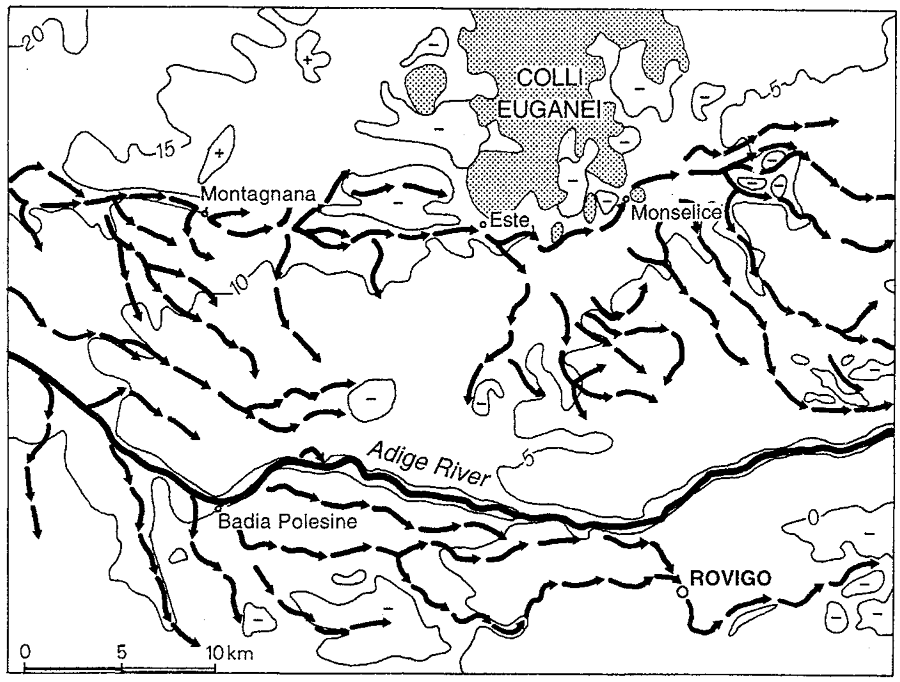


FIG. 11 - Adige river and old river course near Colli Euganei, with distributaries of various ages: relationships with present-day altimetry (contour interval: 5 m). For location, see fig. 1, example A.

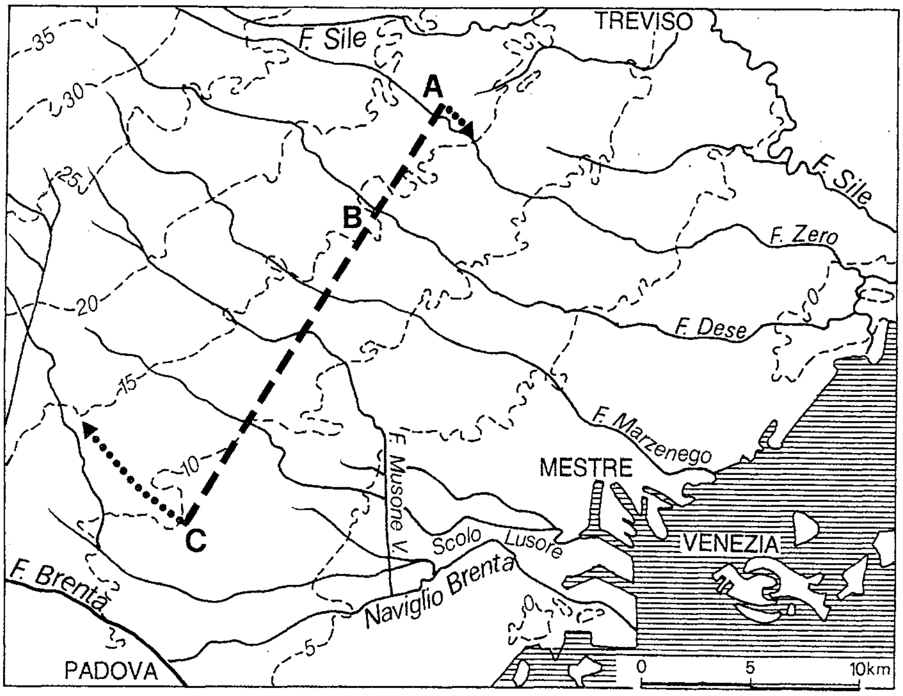


FIG. 12 - Late Pleistocene alluvial plain near Venice, showing anomalous contour trend with respect to rivers (from Castiglioni, 1997). For location, see fig. 1, example B. Only natural courses of small rivers between Sile and Naviglio Brenta are discussed in text. Musone Vecchio originally flowed to Mestre, but was artificially diverted south. *A - B - C*: inferred 15-m contour before tilting, supposed being originally orthogonal to Dese river in *B*.

form generated by Late Glacial sedimentation processes; the drainage, instead, is «inherited», «conservative».

Similar hypotheses for two other areas belonging to the Young Pleistocene depositional system may thus now be presented: one in the Adriatic and one in Lombardy. The proposal is tentative and based purely on the observation of the contour line trend. In low Lombardy, near Cremona (*example C* in fig. 1), the river Oglio now runs more or less parallel with the Po, and probably ran in the same direction in the Young Pleistocene too. However, the Pleistocene plain preserved between Oglio and Po has contour lines which are not at right angles to the two rivers, but which form an angle of 127 degrees clockwise. By analogy with the case considered near Venice, this surface probably tilted south or south-west. Although such tilting has also been proposed in the *Neotectonic Map* (C.N.R., 1987), it may only be considered a pure hypothesis: in this case, researches for the *Geomorphological Map* gave evidence of paleo-channels running south or south-east (Marchetti, 1992), oblique with respect to the present course of the Oglio, and approximately fitting the present-day slope as shown by contours. Interpretation of the trend of the low Oglio course is therefore open to further discussion.

In the northern Adriatic (*example D* in fig. 1) the sector of the submerged platform which was probably least modified during and after the rapid Flandrian transgression is here presumed to have preserved some original morphological characters of the plane linked to the aggradational activity of the Po. Again, the main trend of the slope as it is shown by contours, in this case by isobaths, is discussed. They should show a certain slope of the sea bottom to the south-east rather than to the south, as they are in fact now. Discussion is based on whether the Po river system really was responsible for modelling this surface (mainly by aggradation) during the low stand phases of sea level in the late Pleistocene. If it was, we may expect an alluvial plain gently sloping towards the Dalmatian coast, rather than south or south-southeast as it does. Here too, therefore, one may imagine post-depositional tectonic deformation and hypothesize clockwise rotation of contour lines, i.e., tilting of the old plain towards the Apennine side.

The following points may be proposed for debate: (i) the presence of residual sediments from the Po in the central part of the northern Adriatic (Van Straaten, 1970); (ii) the very thin transgressive sediments lying on top of 18-19 ka peats in the same area (Trincardi & *alii*, 1994); (iii) the presence, on both sides of the Adriatic, of the same mineralogic composition in Late Pleistocene loess deposits deriving from deflation of the ancient alluvial plain of the Po (Cremaschi, 1987b); (iv) the low sediment yeld of the rivers flowing to the Adriatic coast from Croatia; (v) the oblique trend of the 10 ka shoreline, as indicated by Marocco (1991), which, from north to south, crosses the –20 and –30 isobaths and finally joins the –40 isobath, off Ravenna (see fig. 6). This last point clearly shows the tendency of the sea bottom to tilt southwestward over the last 10 ka. Lastly, in support of the idea of a former alluvial plain of the Po gently sloping eastward, the results of seismic research by Agip indicate a late parallel-reflection unit overlying «Jugoslavian progradations» (Dondi & *alii*, 1982).

Taken together, the four examples are compatible with our knowledge of the current evolution of the Apennine foredeep, involving progressive sinking of the foreland belt (fig. 2).

Whether the deformational dynamics of the foredeep in these four areas fit the deformations obtained on the surface using geomorphological criteria remains to be verified. However, in one case, the range of movement may already be supplied.

When studies on neotectonic movements are based on vertical displacements of old coastal forms, the original forms must clearly have followed the horizontal trend of the sea level. When the same phenomena are approached from the viewpoint of fluvial forms, we start from depositional forms which must have had a gradient. What degree of gradient? This is a delicate problem, and at the same time it is interesting and deserves properly defined study methods. Geomorphology does have a role to play, together with structural geology, geophysics and stratigraphy.

ABSTRACT: CASTIGLIONI G.B., *Geomorphology of the Po Plain.* (IT ISSN 0391-9838, 1999).

Except for the noteworthy work of few authors and geomorphologic studies on specific aspects carried out in the past, Italian geomorphologists' attention for the plains developed relatively late. Progresses obtained on the geomorphologic knowledge of the Po plain will be presented here and proposed for further dicussion and research.

On principle, this geomorphologic region should be considered as a whole including both the part which is called today the Pianura Padano-Veneta and the part of the platform submerged in the Adriatic sea up to the Meso-Adriatic Depression. The relationship with the closeby ranges of mountains can be regarded as exemplary from the morphotectonic aspect and for the forms of sedimentary evolution and erosional phenomena; the plain should be considered in fact part of the Apennine's Foredeep.

The asymmetry of the two Po plain sectors, located respectively to the north and to the south of the River Po, is exemplary as well. The distinction between high and low plain, not only in terms of altitude, is also exemplary. Such distinction, characterized by the diversity of fluvial sediments and hydrogeologic and hydrographic conditions, is here represented by the aspects of surface morphology and genetic processes marking the two belts and the transition from one belt to the other. The connections between the alpine glaciation areas and the fluvioglacial and fluvial sedimentation area are also exemplary for a discussion about the nature of the Italian pro-glacial outwash plains, and about the terracing processes affecting not only the piedmont zone but also many sections of the low plain.

The Holocene plain shows a typical basin and ridge feature, with several examples of river changes due to avulsion; it presents a large area not only near the coastline but also inland especially on the right side of the River Po and in a few sectors close to piedmont bands, where young alluvial fans alternate with the older ones; moroever, «Holocene valleys», carved into terraces with meander belt features, belong to it. The delta and lagoon areas were most affected by recent changes caused both by natural processes and by artificial interventions on the coastline and river beds. The effects of subsidence, of changes in fluvial discharge and load, of coastal erosion and sedimentation are evidenced in two maps 1:250,000 now published.

Questions arise on particular themes. For example: which geomorphological correlation does exist between the sectors of the Pleistocene plains in the land and their possible continuation in the part submerged by the sea buried under Holocene sediments of different thickness? Which modifications and deformations can be attributed to the effects of continuing tectonic movements, on the basis of geomorphologic evidences?

KEY WORDS: Late Quaternary evolution, Fluvial and coastal plains, Fluvial surface tilting, Northern Italy.

BIBLIOGRAPHY

AMOROSI A., FARINA M., SEVERI P., PRETI D., CAPORALE L. & DI DIO G. (1996) - *Genetically related alluvial deposits across active fault zones: an example of alluvial fan-terrace correlation from upper Quaternary of the southern Po Basin, Italy.* Sedimentary Geol., 102, 275-295.

BARTOLINI C., CAPUTO R. & PIERI M. (1996) - *Pliocene-Quaternary sedimentation in the Northern Apennine Foredeep and related denudation.* Geol. Mag., 133, 255-273.

BONDESAN M. (1989) - *Geomorphological hazards in the Po Delta and adjacent areas.* Suppl. Geogr. Fis. Dinam. Quatern., II, 25-33.

BONDESAN M., CASTIGLIONI G.B., ELMI C., GABBIANELLI G., MAROCCO R., PIRAZZOLI P.A. & TOMASIN A.(1995a) - *Coastal areas at risk from storm surges and sea-level rise in north-eastern Italy.* Journ. Coastal Res., 11, 1354-1379; Appendix: *Elevation of the Po and Veneto-Friuli Plains*, scale 1:500.000.

BONDESAN M., FAVERO V. & VIÑALS M.J. (1995b) - *New evidence on the evolution of the Po-delta coastal plain during the Holocene.* Quaternary Intern., 29/30, 105-110.

BONDESAN M., GATTI M. & RUSSO P. (1997) - *Movimenti verticali del suolo nella pianura padana orientale desumibili dai dati I.G.M. fino a tutto il 1990.* Boll. Geod. Sc. affini, 56, 141-172.

CASTALDINI D. & PANIZZA M. (1991) - *Inventario delle faglie attive tra i fiumi Po e Piave e il Lago di Como (Italia Settentrionale).* Il Quaternario, 4, 333-410.

CASTALDINI D. & PIACENTE S. (1995) - *Channel changes in the Po River, Mantova Province, Northern Italy.* In: *River Geomorphology*, edited by E.J. Hickin, Wiley & Sons, London, 193-207.

CASTELLARIN A., CANTELLI L., FESCE A.M., MERCIER J.L., PICOTTI V., PINI G.A., PROSSER G. & SELLI L. (1992) - *Alpine compressional tectonics in the Southern Alps. Relationships with the N-Apennines.* Ann. Tectonicae, 6, 62-94.

CASTIGLIONI G.B. (1995) - *Risultati preliminari del nuovo rilevamento geomorfologico della Pianura Padana.* Mem. Soc. Geogr. Ital., 53, 13-72.

CASTIGLIONI G.B. (1997) - *A tentative evaluation of vertical movements in the alluvial plain near Venice, based on geomorphological evidences.* Atti Ist. Veneto Sc. Lett. Arti, Cl. sc. fis. mat. nat., 155, 301-314.

CASTIGLIONI G.B. & PELLEGRINI G.B. (1981) - *Two maps on the dynamics of a river bed.* Proc. Symposium Intern. Ass. Sci. Hydrol. «Erosion and sediment transport measurement», Florence, 223-228.

CASTIGLIONI G.B., BONDESAN M. & ELMI C. (1990) - *Geomorphological mapping of the Po Plain (Italy), with an example in the area of Ravenna.* Zeitschr. Geomorphologie, N.F., Suppl.-Bd.80, 35-44.

CIABATTI M. (1981) - *Le conoscenze sui fondali dei mari italiani.* Riv. Geogr. Ital., 88, 165-174.

CIABATTI M., CURZI P.V. & RICCI LUCCHI F. (1987) - *Quaternary sedimentation in the central Adriatic Sea.* Giorn. Geologia, 49, 113-125.

C.N.R. (1987) - *Neotectonic Map of Italy.* Progetto Finalizzato Geodinamica, Litografia Art. Cartografica, Firenze, 6 sheets, scale 1:500,000.

C.N.R. (1990), *Structural Model of Italy.* Progetto Finalizzato Geodinamica, S.El.Ca., Firenze, 6 sheets, scale 1:500,000.

CORREGGIARI A., ROVERI M. & TRINCARDI F. (1996) - *Late Pleistocene and Holocene evolution of North Adriatic Sea.* Il Quaternario, 9, 697-704.

CREMASCHI M. (1987a) - *Paleosols and vetusols in the central Po plain (northern Italy) a study in Quaternary Geology and Soil development.* Ediz. Unicopli, Milano, 306 pp.

CREMASCHI M.(1987b) - *Loess deposits of the plain of the Po and adjoining Adriatic basin (Northern Italy).* In: «Loess and periglacial phenomena», Pecsi M. & French H.M. eds., Inqua Commission on Loess, Studies in Geography in Hungary, 20, 125-140.

CREMONINI S. (1993-1994) - *Autopsia di una rotta fluviale. Note e riflessioni in margine all'evento del 1990 occorso nel fiume Reno Bolognese.* Il Carrobbio, 19-20, 339-362.

DE MARCHI L. (1922) - *Variazioni di livello dell'Adriatico in corrispondenza colle espansioni glaciali.* Atti Accad. Scient. Veneto-Trentino-Istriana, 12-13, s.III, 3-15.

DOGLIONI C. (1993) - *Some remarks on the origin of foredeeps.* Tectonophysics, 228, 1-20.

DONDI L., RIZZINI A. & ROSSI P. (1982) - *Quaternary sediments of the Adriatic Sea from the Po delta to Gargano promontory*. Advanced Research Institute, Mediterranean Basin Conference, 195-214.

DUTTO F. & MARAGA F. (1994) - *Variazioni idrografiche e condizionamento antropico. Esempi in Pianura Padana*. Il Quaternario, 7, 381-390.

ELMI C., NESCI O., SAVELLI D.& MALTARELLO G. (1987) - *Depositi alluvionali terrazzati del margine adriatico appenninico centro-settentrionale: processi geomorfologici e neotettonici*. Boll. Soc. Geol. It., 106, 717-721.

FELBER M., FREI W. & HEITZMANN P. (1991) - *Seismic evidence of pre-Pliocene valley formation near Novazzano (Ticino, Switzerland)*. Eclogae Geol. Helv., 84, 753-761.

GABERT P. (1962) - *Les plaines occidentales du Pô et leurs piedmonts*, Imprim.Louis-Jean, Gap, 531 pp.

GOVI M. & TURITTO O. (1993) - *Processi di dinamica fluviale lungo l'asta del Po*. Acqua Aria, 575-588.

MARCHETTI M. (1992) - *Geomorfologia ed evoluzione recente della pianura padana centrale a nord del Fiume Po*. Doctoral thesis, University of Milano, Dipart. Scienze della Terra, 164 pp.

MARCHETTI M. (1996) - *Variazioni idrodinamiche dei corsi d'acqua della Pianura Padana cantrale connesse con la deglaciazione*. Il Quaternario, 9, 465-472.

MAROCCO R.(1991) - *Evoluzione tardopleistocenica-olocenica del delta del F. Tagliamento e delle lagune di Marano e Grado (Golfo di Trieste)*. Il Quaternario, 4, 223-232.

MAROCCO R. & PESSINA M. (1995) - *Il rischio litorale nell'area circumlagunare del Friuli-Venezia Giulia / Coastal risk in the surrounding area of Marano and Grado lagoon (Friuli - Venezia Giulia, Italy)*. Gortania, 17, 5-35.

M.U.R.S.T. (1997a) - *Carta Geomorfologica della Pianura Padana / Geomorphological Map of Po plain*. S.El.Ca., Firenze, 3 sheets, scale 1:250,000.

M.U.R.S.T. (1997b) - *Carta Altimetrica e dei movimenti verticali del suolo della Pianura Padana / Map of relief and vertical movements of Po plain*. S.El.Ca., Firenze, 3 sheets, scale 1:250,000.

SELLI R. & CIABATTI M. (1977) - *L'abbassamento del suolo nella zona litoranea ravennate*. Giorn. Geologia, 62, 1-47.

SIMEONI U. & BONDESAN M. (1997) - *The role and responsability of man in the evolution of the Italian Adriatic coast*. Bull. Institut Oceanogr. Monaco, Spec.N.18; CIESM Science series, 3, 111-131.

SORBINI L., ACCORSI C.A., BADINI MAZZANTI M., FORLANI L., GANDINI F., MENEGHEL M., RIGONI A. & SOMMARUGA M. (1984) - *Geologia e geomorfologia di una porzione della pianura a sud-est di Verona*. Mem. Mus. Civ. St. Nat. Verona, 2, s.II, Sez. Sc. dalla Terra, 1-92.

TRINCARDI F., CORREGGIARI A. & ROVERI M. (1994) - *Late quaternary transgressive erosion and deposition in a modern epicontinental shelf: the Adriatic Semiclosed Basin*. Geo-Marine Letters, 14, 41-51.

VAN STRAATEN L.M.J.U. (1970) - *Holocene and late-Pleistocene sedimentation in the Adriatic Sea*. Geol. Rundschau, 60(1), 106-131.