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figg. 9

Three-Dimensional Representation of Permeability Barriers and Aquifers Recharge in the Pleistocene Deposits of the Parma Alluvial Plain

Rappresentazione tridimensionale delle barriere di permeabilità e ricarica degli acquiferi nelle alluvioni pleistoceniche della pianura di Parma

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ABSTRACT - The stratigraphy of the Parma alluvial plain stretching from the Apennines foothill (south) to the A1 highway (north) for a surface area of 400km^2 has been reconstructed on the basis of a grid of geologic cross-sections. At the northern margin of the study area the body of alluvial sediments reaches a thickness around 500m encompassing the geologic history of the last 800ky.
The subsurface sedimentological architecture is represented upon distinguishing between permeable coarse-grained and semipermeable or impermeable fine-grained alluvial deposits. The latter constitute Permeability Barriers of different lateral continuity. The laterally continuous barriers represent sedimentary drapes whose thickness reaches about 20m. They have been deposited during Pleistocene interglacial or interstadial phases when the alluvial plain was subjected to fine-grained sedimentation.
The Digital Surface Model (DSM) of the top of the Quaternary Marine Sequence, dated at about 800ky BP, has been constructed converting the depth values to the corresponding elevations a.s.l. and producing a kriged map. The DSMs of the overlying Permeability Barriers have been constructed by means of the interconnection of triangular geometric elements known as Triangulated Irregular Network (TIN).
The top of the following Permeability Barriers has been modelled in the Quaternary Continental Sequence: (1) Continental Sequence Qc_1, dated at about 470ky BP, (2) Permeability Barrier -80m, (3) Permeability Barrier -35m and (4) Permeability Barrier +3m which base is dated at about 24ky BP. The three latter Permeability Barriers have been labelled with their height a.s.l. in correspondence of the Parma Fair Exhibition site.
Although tectonically deformed by the Monticelli Terme-Madregolo-Fontanellato buried thrust front, Continental Sequence Qc_1 and several other barriers, up to Permeability Barrier -80m, form laterally continuous impermeable sedimentary drapes that effectively confine the underlying aquifers. The digital models of the top surfaces of Permeability Barriers -35m and +3m display a limited lateral extent and an ensuing possibility of leakage, thus effectively connecting the phreatic aquifer of the upper alluvial plain to the deep aquifers of the lower alluvial plain.

KEY WORDS: Digital Surface Model, Alluvial Sediments, Permeabilty Barrier, Interaquifer Flow, Parma Plain.

RIASSUNTO - La stratigrafia del sottosuolo della pianura alluvionale di Parma che va dal margine appenninico a sud all'Autostrada A1 a nord, per una superficie di circa 400km^2, è stata ricostruita per mezzo di una griglia di sezioni geologiche. Il corpo alluvionale si espande verso nord e raggiunge uno spessore di 500m circa in corrispondenza dell'A1 ove passa ai depositi marini datati a circa 800ka BP.
L'architettura sedimentaria del sottosuolo è stata rappresentata distinguendo i depositi grossolani, poroso-permeabili, e quelli fini, semipermeabili o impermeabili, che costituiscono barriere di permeabilità più o meno continue. Le maggiori rappresentano drappi sedimentari spessi fino ad una ventina di metri deposti nei periodi interglaciali o interstadiali quando la pianura era soggetta ad esteso colmamento con sedimenti fini.
Il Modello Digitale di Superficie (DSM) del tetto del Quaternario marino, detto Basamento Idrogeologico, è stato

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costruito convertendo i valori di profondità in quote s.l.m. successivamente interpolate tramite il metodo *kriging* utilizzando il modulo *Spatial Analyst* di ArcView GIS. I restanti DSM delle soprastanti barriere di permeabilità sono stati costruiti mediante l'interconnessione di elementi geometrici triangolari detta *Triangulated Irregular Network* (TIN).
Dal basso stratigrafico sono state modellate le barriere di permeabilità che rappresentano il tetto (1) del Quaternario marino, datato a circa 800ka BP, (2) del Sintema Emiliano-Romagnolo Inferiore (Qc_1), datato a circa 470ka BP e (3) di altre tre barriere di permeabilità, di particolare valore idrogeologico, interne al Sintema Emiliano-Romagnolo Superiore (Qc_2). Per ragioni pratiche queste ultime sono state identificate con l'altezza in metri s.l.m. del loro tetto intercettato dai sondaggi in corrispondenza delle Fiere di Parma. Si tratta delle barriere di permeabilità -80m, -35m e +3m.
Il DSM del tetto del Sintema Emiliano-Romagnolo Inferiore (Qc_1) esprime una barriera di permeabilità relativamente continua che tuttavia è significativamente deformata da una viva tettonica sinsedimentaria. Ad essa seguono altre estese barriere di permeabilità che ancora proteggono quasi completamente gli acquiferi sottostanti. Al contrario, i DSM del tetto delle barriere di permeabilità denominate -80m e -35m indicano una limitata estensione laterale ed il conseguente scarico interfalda dall'acquifero freatico dell'alta pianura agli acquiferi profondi della bassa pianura.

PAROLE CHIAVE: Modello Digitale di Superficie, Sedimenti alluvionali, Barriera di permeabilità, Scarico interfalda, Pianura di Parma.

1. - INTRODUCTION AND AIM OF THE STUDY

The study area, located around the city of Parma, is part of the southern Po River plain. It represents the elevated margin of the plain extending from the Apenninic front to the A1 highway, delimited by the area of influence of the Taro River to the west and of the Torrente Parma to the east, with an extent of approximately 400km^2. From the hydrologic and sedimentologic point of view the Taro River plays a primary role, with a drainage basin of 1470km^2 as opposed to the 430km^2 and 190km^2 surface extent of Torrente Parma and Torrente Baganza, respectively (fig. 1).

Recent studies on the subsurface of the Po River plain have demonstrated that Middle-Late Pleistocene sedimentation is climatically controlled (RAVAZZI, 2003) and shows phases of coarse-grained sediment transport (glacial) and phases of fine-grained sediment transport (interglacial and interstadial). The latter sediments drape the alluvial plain and represent allostratigraphic units, repeated in time, that form the main ground Permeability Barriers (e.g., GUADAGNINI *et alii*, 2002).

This work presents the reconstruction of the Parma alluvial plain, down to a depth of 500m, based on the execution of geologic cross-sections spaced 2-5km and oriented both parallel and normal to the depositional axis. The key aquifer bodies and associated confining layers (in the following: Permeability Barriers), i.e. hydrostratigraphic units sensu DOMENICO & SCHWARTZ (1998), have been identified by means of the correlation of closely spaced stratigraphic wells. The depth values of the top of the main Permeability Barriers have been sampled along the trace of the sections and interpolated with a Triangulated Irregular Network (TIN) that allows the construction of a three-dimensional surface. The analysis of the inclination and lateral continuity of these surfaces allows the identification of ground locations at which the unconfined aquifer becomes confined (PETRUCCI *et alii,* 1992) and of areas where superposed aquifers are hydraulically connected (CIVITA, 2005).

2. - STRATIGRAPHY AND QUATERNARY SEDIMENTATION

Quaternary marine and continental sedimentation in the Po River basin (ORI, 1993) forms diachronous depositional units controlled by tectonic pulses which are in turn modulated by climatic changes (DI DIO & VALLONI, 1997). This control is testified by numerous surfaces of stratigraphic unconformity recognized and mapped in the Apenninic margin (RICCI LUCCHI *et alii*, 1982). In order to define a new stratigraphic frame RER & ENI-AGIP (1998) used seismic and borehole data to extend these unconformity surfaces from the Apenninic margin to the subsurface of the alluvial plain.

A series of works (DI DIO *et alii*, 1997; SAGNE, 1998; DI DIO, 2001) completely revised the Plio-Quaternary succession of the Parma plain; stratigraphic subdivisions based on unconformity surfaces are shown in figure 2. The following allostratigraphic units have been recognized in the Quaternary: Quaternary marine unit, here named Quaternary Marine Sequence (Qm), with its top dated at about 800ky BP, covered in erosive unconformity by the Quaternary continental unit, here named Quaternary Continental Sequence (Qc). The latter is subdivided in two units (fig. 2): Sintema Emiliano-Romagnolo Inferiore, here named Continental Sequence Qc_1, with its top dated at about 470ky BP, overlain in erosive unconformity by Sintema Emiliano-Romagnolo Superiore (DI DIO, 2001), here named Continental Sequence Qc_2.

The recognition of a fine-grained sedimentary unit, substantially deposited in the Holocene

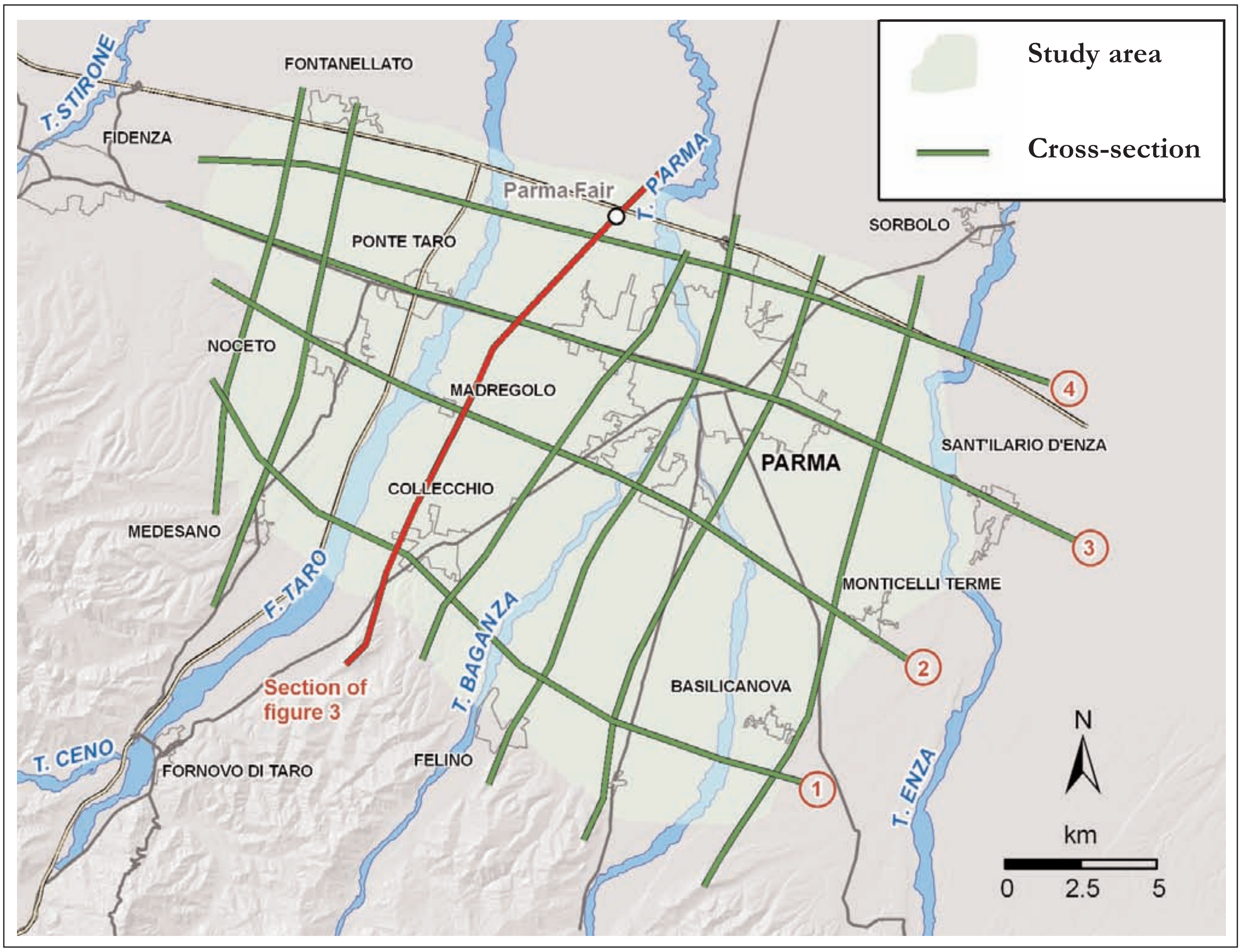

Fig. 1 - Location of the study area. Total surface is ca 400km^2 extending from the Apenninic front (south) to the A1 highway (north). Geological cross-sections are parallel and normal (numbered 1-4) to the depositional axes. In red the trace of the section intercepting the site of the Parma Fair Exibition presented in figure 3.
- *Ubicazione dell'area di studio, estesa dal fronte appenninico a sud all'autostrada A1 a nord, per una superficie di circa 400km^2. Sono riportate le tracce delle sezioni geologiche parallele e trasversali (numerate 1-4) agli assi deposizionali; la sezione in rosso che intercetta il sito Parma Fiere è presentata in figura 3.*

(AMOROSI *et alii*, 2004), levelling the ground surface and filling up the alluvial plain (e.g., SEVERI *et alii*, 2002), has been particularly important for the understanding of the paleoenvironmental conditions controlling Quaternary continental sedimentation (cf. KUKLA & CILEK, 1996). In a first approximation, the hydraulic regimen and depositional style of modern rivers is representative of Holocene sedimentation; here, the coarse-grained sediment transport is strictly confined to the river channels while the interchannel areas are covered by fine-grained alluvium (VALLONI *et alii*, 2003).

The draping of the alluvial plain with fine-grained sediments occurred repeatedly during Middle-Late Pleistocene times to create relatively thick and laterally continuous Permeability Barriers (CARCANO *et alii*, 2002). From the climatic point of view, the latter correspond to interglacial and interstadial phases (VITTORI & VENTURA, 1995); these phases alternated to others characterized by coarse-grained sediment transport with the extensive development of alluvial fans that, from the climatic point of view, correspond to glacial phases (REGIONE LOMBARDIA & ENI-AGIP, 2002; MUTTONI *et alii*, 2003). BEDULLI (2004) matched the warm and cold phases of the well known oxygen isotope curve (e.g., MARTINSON *et alii*, 1987) to the couples of coarse- and fine-grained sedimentary bodies (hydrostratigraphic units) of the study area. However, this climatically-controlled sedimentary architecture is disturbed by tectonics which is particularly effective in the Parma plain (fig. 3) and is thoroughly discussed in VALLONI & CALDA (this volume).

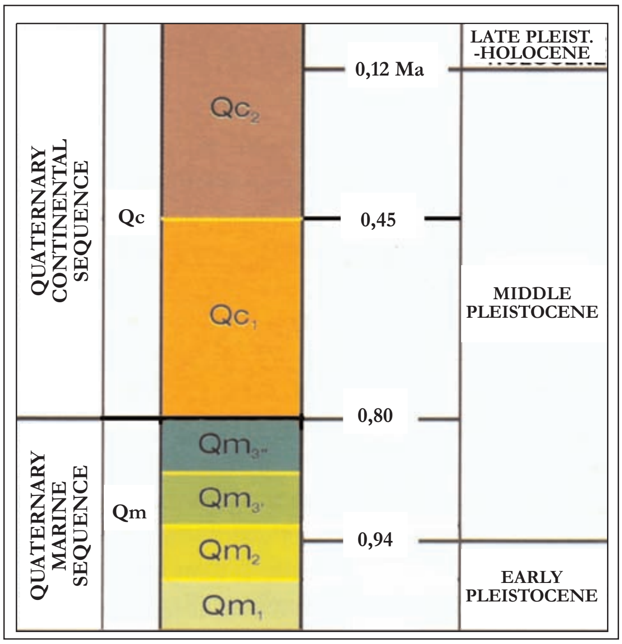

Fig. 2 - Stratigraphic scheme of the Quaternary sedimentary sequences and related units (modified after DI DIO, 2001). The study is concerned with the Quaternary Continental Sequence (Qc) subdivided into sequences Qc_1 and Qc_2.
- *Schema stratigrafico dei depositi quaternari dell'area di studio (da DI DIO, 2001, modificato). Lo studio riguarda il Quaternario continentale (Qc) suddiviso nei sintemi Emiliano-Romagnolo Inferiore (Qc_1) e Superiore (Qc_2).*

3. - GEOLOGIC CROSS-SECTIONS AND PERMEABILITY BARRIERS

The traces of seven longitudinal and of four transverse cross-sections, respectively oriented parallel and normal to the depositional axis, are drawn in figure 1. Figure 3 depicts the longitudinal section, intercepting the localities of Collecchio, Madregolo and the site of the Parma Fair Exhibition, indicating the crossings with the transversal sections 1, 2, 3 and 4 of figure 1. This section is highlyrepresentative of the study area sedimentary architecture here represented distinguishing the coarse-grained porous-permeable deposits and the fine-grained semipermeable or impermeable deposits (Permeability Barriers).

As in many other areas of the Apenninic front (BORTOLAMI *et alii*, 1979; BERNINI & PAPANI, 1987) the Parma plain is characterized by a buried thrust front in which the marine substrate is remarkably uplifted (e.g., Madregolo structural high; PETRUCCI *et alii*, 1975). This positive structure also affects the hydrostratigraphic units

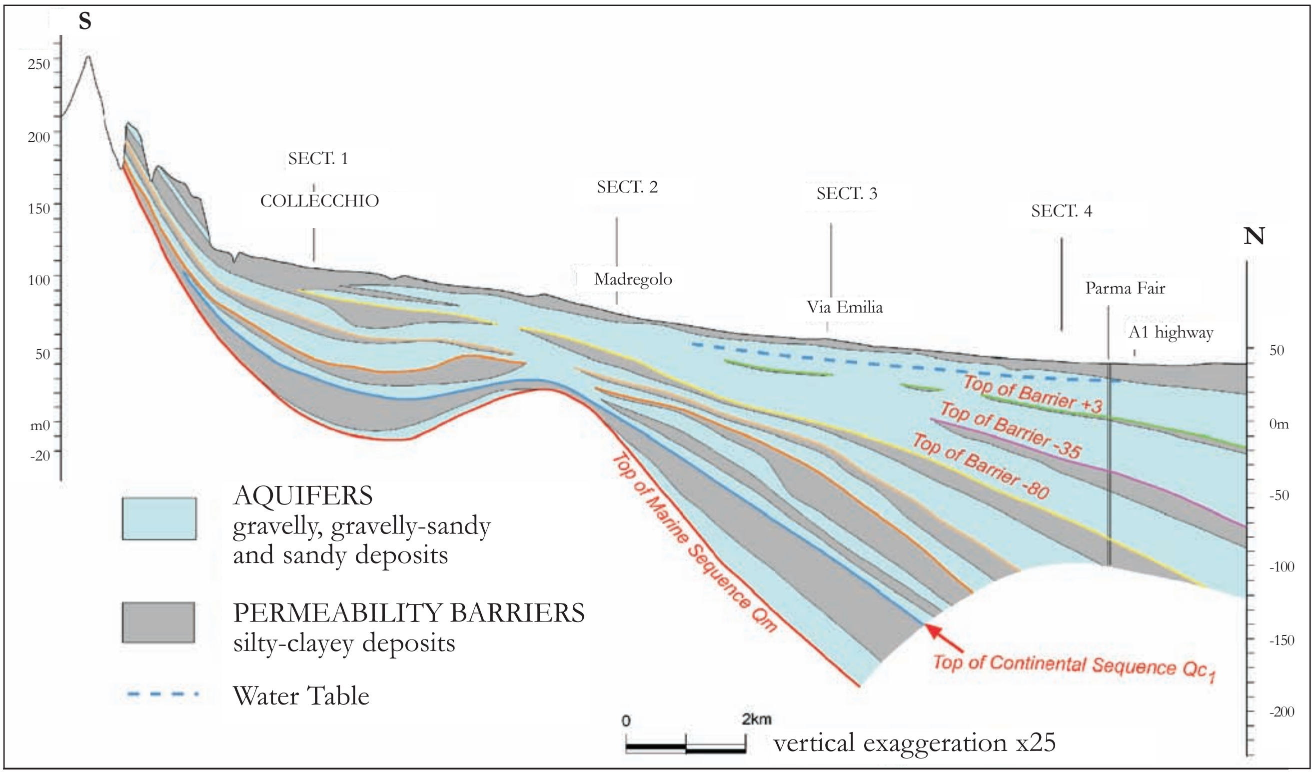

Fig. 3 - Geological cross-section across the Madregolo high; its trace and the crossing with sections numbered 1-4 are indicated in figure 1. Aquifers in blue and Permeability Barriers in dark grey (modified after BEDULLI, 2004). The DSMs discussed here are the top of the Quaternary Marine Sequence (Qm) presented in figure 4 and the top of the key Permeability Barriers presented in figures 6-9. The three latter are identified by their height a.s.l. at the Parma Fair Exhibition site.
- *Sezione geologica parallela agli assi deposizionali che attraversa l'alto strutturale di Madregolo con indicati gli incroci delle sezioni trasversali numerate 1-4 (cf. figura 1). Depositi grossolani sede di acquiferi in azzurro; depositi fini che costituiscono barriere di permeabilità in grigio scuro (da BEDULLI, 2004, modificata). I Modelli Digitali di Superficie discussi nel presente lavoro sono i tetti: del Quaternario marino (Qm), presentato in figura 4, del Sintema Emiliano-Romagnolo Inferiore Qc_1 (figura 6) e di tre barriere di permeabilità chiave intercettate sulla verticale delle Fiere di Parma alle quote di -80, -35 e +3 m l.m. (figure 7-9).*

of sequence Qc whose inclination increase with increasing age and depth (BEDULLI & VALLONI, 2004). In the structural high area, aquifers and Permeability Barriers are also affected by erosional unconformities that cause loss of lateral continuity (ANTOLINI *et alii*, 1999). On the eleven sections of figure 1 the top of the Quaternary Marine Sequence (here considered the Hydrogeologic Basement) and the overlying main Permeability Barriers have been drawn. In the latter the ratio between thickness and lateral extension is 1:1000 which makes it possible to graphically represent the Permeability Barriers only through their top surfaces.

The digitally modelled surfaces are (fig. 3): the top of the Quaternary Marine Sequence (Qm), dated at about 800ky BP, the top of the Continental Sequence Qc_1, dated at about 470ky BP, and the top of three Permeability Barriers, here assigned to Marine Isotope Stages 7, 5 and 3 (MARTINSON *et alii*, 1987; BEDULLI, 2004). The three latter are relatively young surfaces of particular importance to hydrogeology (ALIFRACO *et alii*, 1992; BERETTA *et alii*, 1999). For practical purposes they are identified by means of their height a.s.l. in correspondence of the site of the Parma Fair Exhibition: in ascending stratigraphic order -80m, -35m and +3m (fig. 3). Summarizing, from the bottom upwards the modelled surfaces are named: (1) Quaternary Marine Sequence Qm or Hydrogeologic Basement, (2) Continental Sequence Qc_1, (3) Permeability Barrier -80m, (4) Permeability Barrier -35m and (5) Permeability Barrier +3m.

4. - DIGITAL SURFACE MODELS

The DSM of the top of the Quaternary Marine Sequence Qm, coinciding with the base of the Quaternary Continental Sequence (Qc), derives from a specific database different from that created for the overlying Permeability Barriers. This surface is identified by a particularly large set of data which allowed the construction of a detailed three-dimensional surface model (fig. 4). The information provided by the geolo-

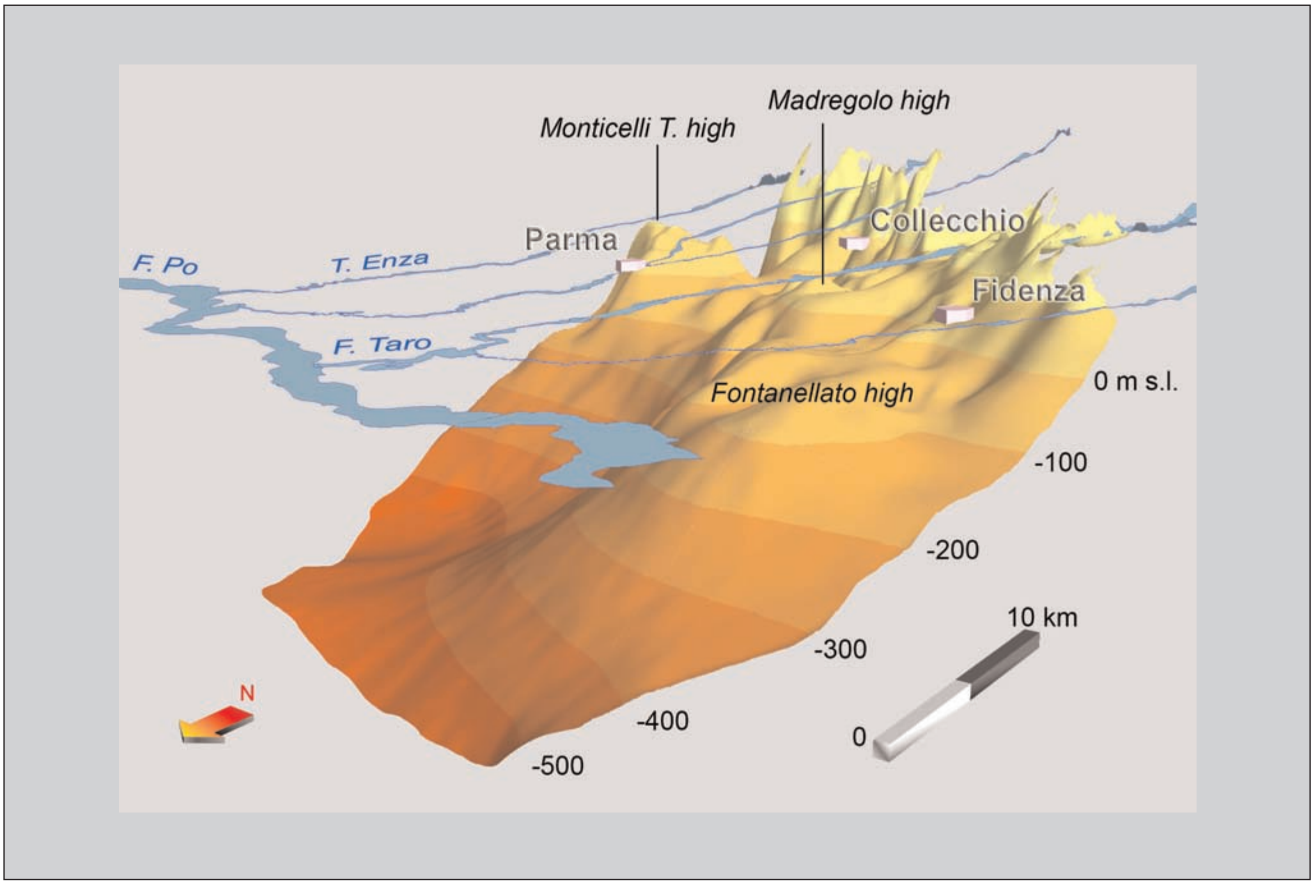

Fig. 4 - DSM of the top of the Quaternary Marine Sequence Qm (elevations in meters s.l.). The rivers network in blue simulates the topographic surface. A buried thrust forms an antiform on the alignment of the towns of Monticelli Terme, Madregolo and Fontanellato.
- Modello digitale della superficie di tetto del Quaternario marino (Qm, quote riferite al l.m.). In blu sono rappresentati i corsi d'acqua principali a simulare la posizione della superficie topografica. L'alto strutturale del thrust sepolto esprime tre culminazioni maggiori in corrispondenza dei paesi di Monticelli Terme, Madregolo e Fontanellato.

gical cross-sections has been implemented on the basis of numerous borehole data and by the digitization of the base-surface of the Quaternary Continental Sequence (Qc) represented on a 1:250.000 scale map published by RER & ENI-AGIP (1998). The (less precise) data acquired from this map, being limited to heights below -150m a.s.l, are of minor importance for this study.

The DSM of the top of the Permeability Barriers internal to the Quaternary Continental Sequence (Qc) is essentially based on cross-sections data implemented by information on the outcrop limit of key hydrostratigraphic units provided by the conventional geological map of the southern margin of the Parma plain (DI DIO *et alii*, 1997). Due to the extreme flatness of these surfaces the DSMs have been represented as a plan view with depth contours (fig. 6, 7, 8 and 9).

4.1. - DSM OF THE MARINE SEQUENCE Qm

Figure 4 presents the DSM of the top of the Quaternary Marine Sequence (Qm) together with the simulation of the topographic surface given by the rivers network in blue. The individual depth values of the surface to be modelled, totalling 429, have been transformed in values of elevation a.s.l. The outcome of the preliminary analysis of the spatial correlation of these data by means of the ESRI software *Spatial Analyst* showed that interpolation according to the kriging square-net method resulted geologically sound (DAVIS, 2002).

The prominent feature of the kriged map is the positive structure extending south and west of Parma on the alignment of the towns of Monticelli Terme, Madregolo and Fontanellato (fig. 1 and 3). It represents a thrust generated antiform with a modest synform on its southern limb and a steep monocline dipping north and northeast. This positive structure acts as an effective hydrologic threshold with respect to the aquifers of the overlying Quaternary Continental Sequence (Qc).

4.2. - DSM OF THE PERMEABILITY BARRIERS

The digital surfaces of the four modelled Permeability Barriers are mainly based on the digitization of the data extracted from the geological cross-sections (BONHAM-CARTER, 1994). The depth of the top of each Permeability Barrier has been measured at points distant 1km on the topographic trace of each cross-section. These measures, taken on the correlation lines of closely spaced stratigraphic wells, have been mapped to values of elevation above sea level by subtracting the altitude. The geographic database that contains the depth values of each of the four surfaces includes 230 points.

The digitization of the line of intersection between the calculated surface and the ground surface has been made using the geologic map of the Quaternary deposits of the Parma area, published by DI DIO *et alii* (1997). This line, known as breakline, represents an outcrop limit which is only manifested by the most important Permeability Barriers exposed in the southern margin of the Parma plain.

The subsurface interruption of Permeability Barriers is twofold; it may represent the contact with the culminations of the buried positive structure (fig.3, 4) or the interception on erosion surfaces which marks the base of coarse-grained (essentially gravely) sedimentary bodies. In the first case the breaklines resulted from the intersection of the DSM of each Permeability Barrier with the DSM of the Quaternary Marine Sequence (Qm); in the second case the breaklines have been traced graphically by correlating all available stratigraphic (cross-section and borehole) data.

The preliminary treatment of these irregularly distributed data indicated that the procedure commonly used in the construction of Digital Terrain Models, that takes the name of *Triangulated Irregular Network* (TIN), provided geologically coherent results. In the TIN method

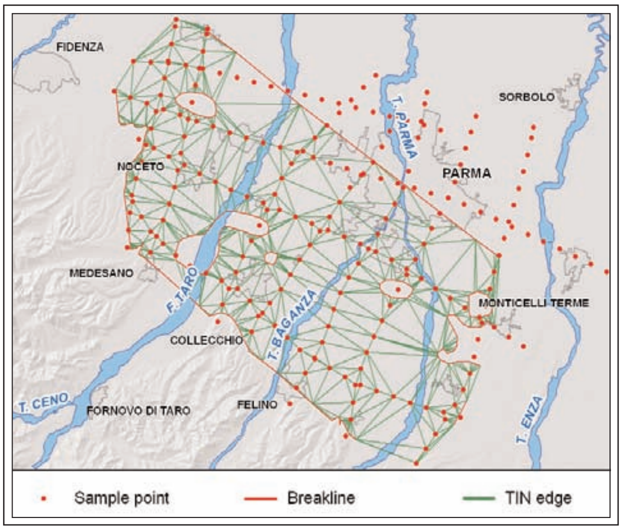

Fig. 5 - Example of a TIN structure representing the top of the Continental Sequence Qc_1; the corresponding calculated surface is presented in figure 6. The sample-points (in red) are the nodes of known altitude of the triangle network. Breaklines may indicate the outcrop limit or the subsurface interruption/termination of the modelled surface.

- Esempio di realizzazione del TIN relativo al DSM del tetto del Sintema Emiliano-Romagnolo Inferiore Qc_1 *mostrato in figura 6. La posizione di campionamento delle profondità è rappresentata dai punti in rosso allineati sulle tracce delle sezioni; essi fungono da nodi della rete di triangoli costruita per il calcolo della superficie tridimensionale. Le* breakline *indicano interruzione della continuità laterale della superficie ricostruita.*

the calculation of the DSM is simply based on the interconnection of triangular geometric elements, a form of linear interpolation of data points. The TIN structure, described in PEUKER (1978), is a set of adjacent triangles calculated on the base of irregularly distributed three-dimensional points (fig. 5). The model connects the triangles to nodes of known altitude represented by the sample-points disposed on the cross-sections and on the breaklines.

5. - PERMEABILITY BARRIERS AND GROUND WATER FLOW

5.1. - DSM OF THE CONTINENTAL SEQUENCE Qc_1

Figure 6 shows the DSM of the top of Continental Sequence Qc_1, an extensive body of fine-grained deposits constituting a Permeability Barrier of very high lateral continuity containing several thin lenses of coarse-grained deposits. Continental Sequence Qc_1 is strongly deformed on the alignment of the buried antiform, indicating Middle Pleistocene tectonic activity; the modelled surface is uniformly inclined in the north-east direction and reaches the height of about - 230m a.s.l. at the Parma Fair site (fig. 3).

The aquifer complex occurring in the coarse-grained bodies of Continental Sequence Qc_1 is highly confined because the overlying Permeability Barrier is interrupted only at culminations of the positive structure, namely the Monticelli Terme high and the Madregolo high, and partly on the vertical of the Taro River (fig. 6). These small windows are the only areas where aquifer interconnection might occur and contribute to recharge the aquifer complex of Continental Sequence Qc_1. To the

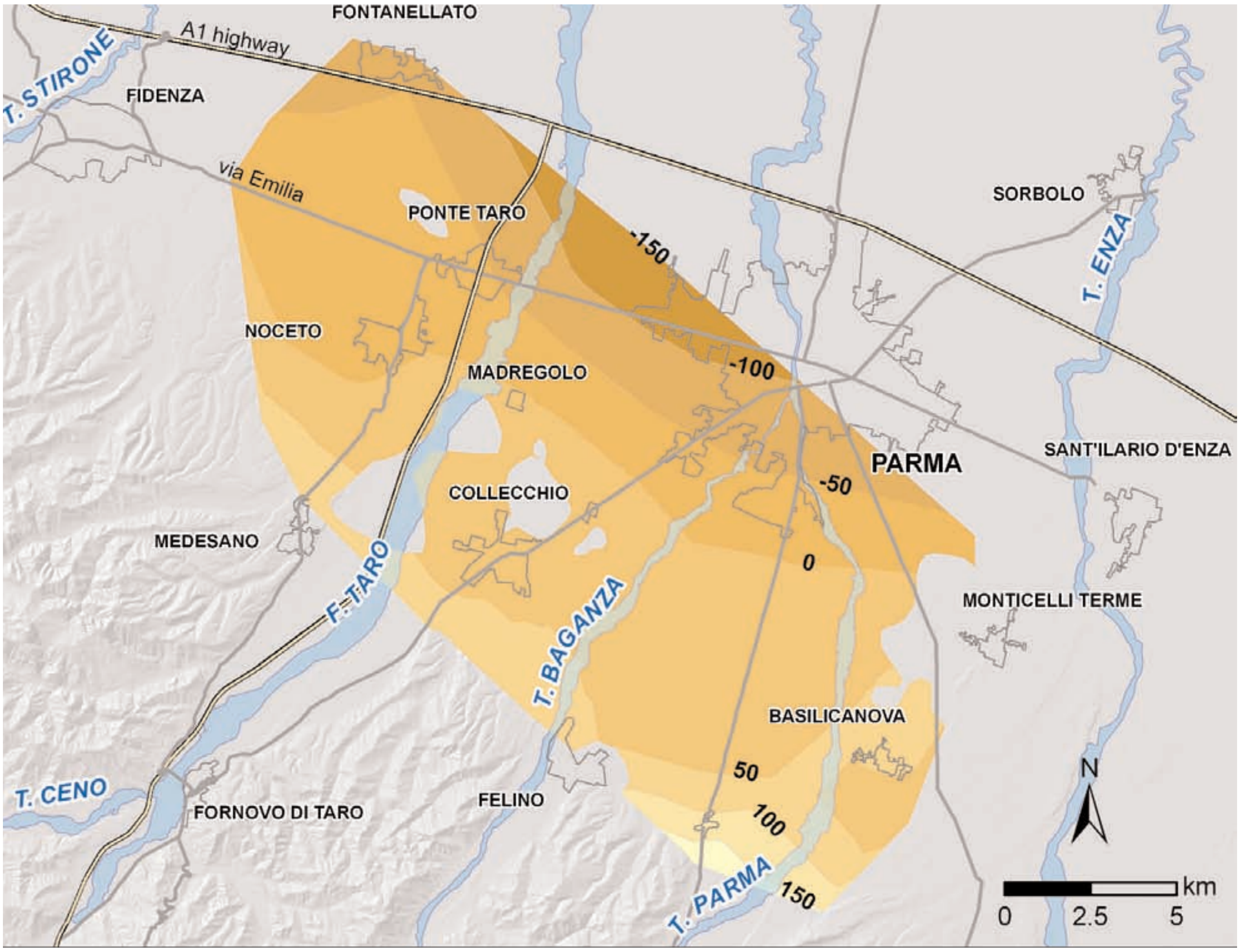

Fig. 6 - DSM of the top of Continental Sequence Qc_1, a Permeability Barrier of very high lateral continuity dipping northeast. Local interruptions are on the culminations of the buried positive structure and on the vertical of the Taro River.
- DSM del tetto del Sintema Emiliano-Romagnolo Inferiore Qc_1, una barriera di permeabilità di altissima continuità laterale con immersione media verso nord-est. Le locali interruzioni si verificano sulle culminazioni della struttura positiva sepolta e sulla verticale del fiume Taro.

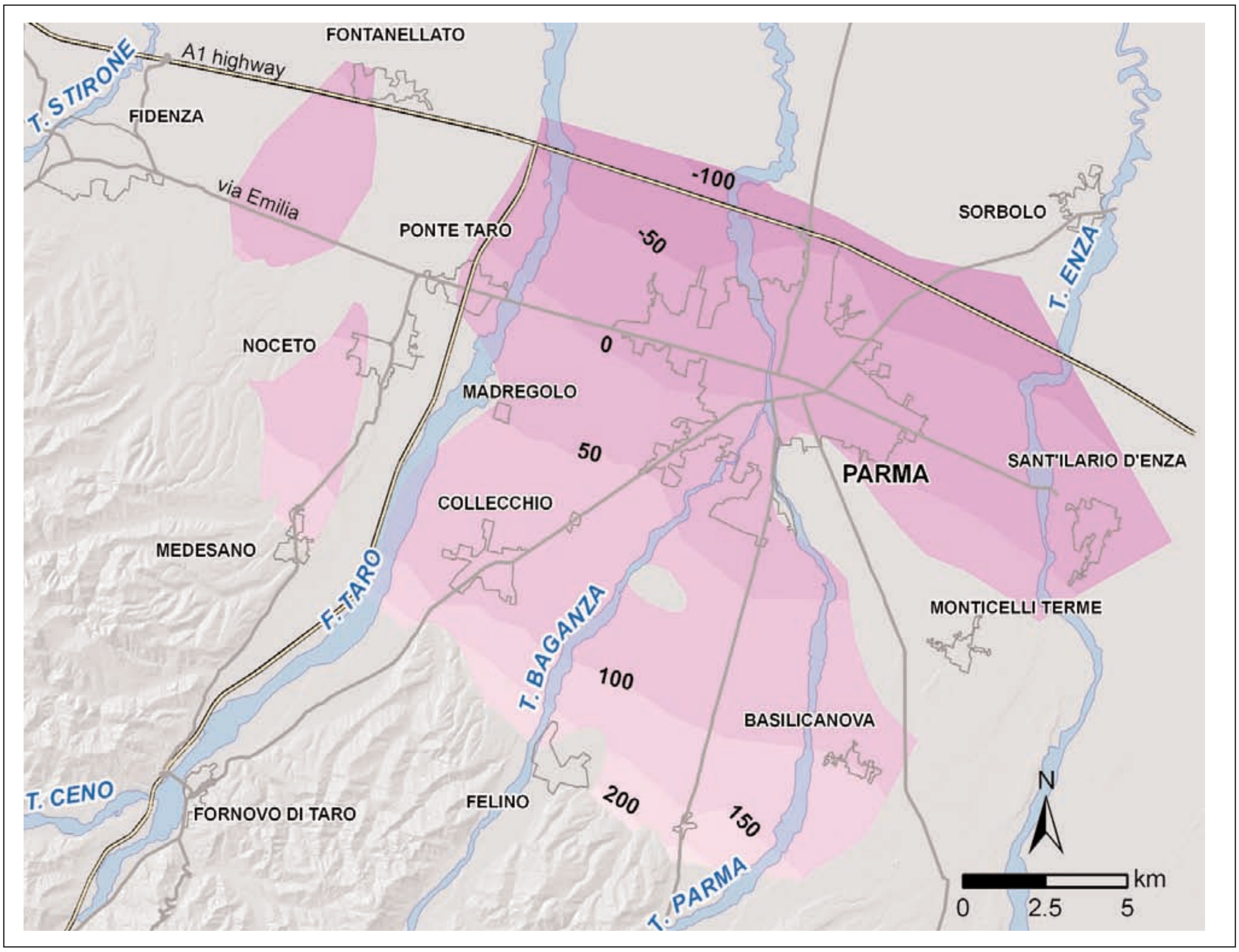

Fig. 7 - DSM of the Permeability Barrier intercepted at the height of -80m a.s.l. at the Parma Fair site. The surface dips north-norheast with an average inclination of 1.5 %. The underlying aquifer is extensively confined. Interaquifer flow may occur in the elongated window parallel to the Taro River course.
- DSM della barriera di permeabilità intercettata alla profondità di -80m s.l.m. sulla verticale delle Fiere di Parma. La superficie immerge a nord-nordest con inclinazione media di 1.5%. L'acquifero sottostante è estesamente protetto. Lo scarico interfalda può avvenire principalmente dalla finestra allungata parallelamente al corso del fiume Taro.

north of the antiform the deep aquifer of Continental Sequence Qc_1 shows a drainage axis placed immediately west of Parma; along this axis the hydraulic gradient is essentially controlled by the Madregolo high threshold (fig. 3).

5.2. - DSM of the Permeability Barrier -80

Figure 7 shows the digital model of a key surface, the Permeability Barrier -80m a.s.l., upon which the huge alluvial fan system of the Taro River rests. This barrier is tectonically much less deformed than the underlying ones (e.g., top of the Continental Sequence Qc_1), shows high lateral continuity and dips north-northeast with an average inclination of about 1.5%.

The aquifer underlying barrier -80m is thus well confined and the interaquifer flow is made possible only by the windows opened in the Permeability Barrier within a strip parallel to the left bank of the Taro River and along the alignment Monticelli Terme-Parma (fig. 7). The recharge is essentially represented by interaquifer leakage (Vigna, 1996) and circumscribed Apenninic outcrop areas (fig. 3).

5.3. - DSM of the Permeability Barrier -35

Figure 8 shows the DSM of Permeability Barrier -35m a.s.l. which is present in the eastern portion of the Parma plain and is completely absent in the western portion, an area where this Permeability Barrier was eroded by the Taro River during the (cold phase) depo-sition of the overlying coarse-grained deposits. This behaviour is also shown by the second major water course, Torrente Parma, responsible of the creation of south-north oriented erosive windows on the Permeability Barrier.

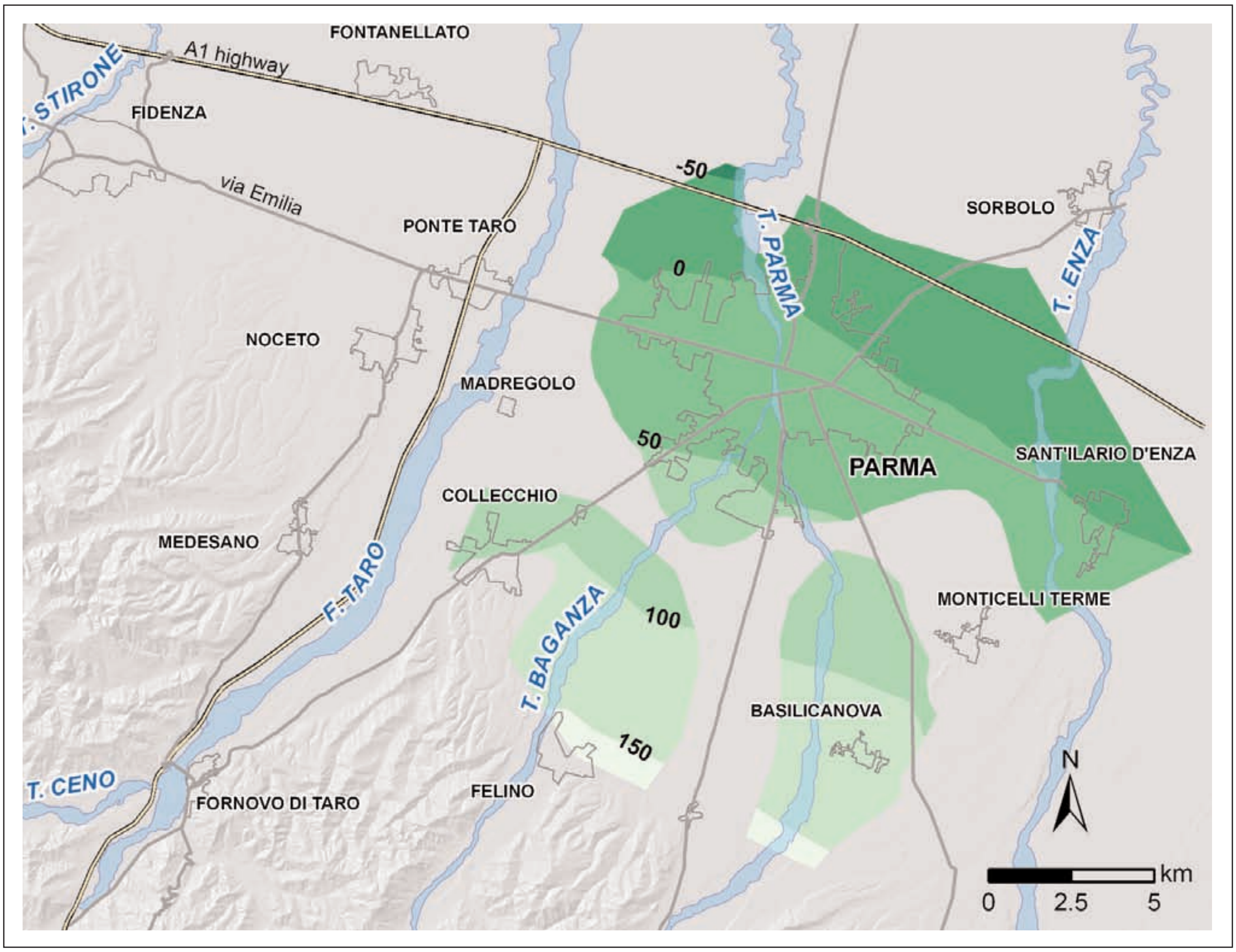

Fig. 8 - DSM of the Permeability Barrier intercepted at the height of -35m a.s.l. at the Parma Fair site. The surface dips north-norheast with an average inclination of 1.1 %. In the western portion of the Parma plain there is no confinement of the underlying aquifer.
- DSM della barriera di permeabilità intercettata alla profondità di -35m s.l.m. sulla verticale delle Fiere di Parma. La superficie immerge a nord-nordest con inclinazione media di 1.1 %. Nella porzione occidentale della pianura di Parma l'acquifero sottostante non è protetto.

The geometry of the modelled surface is particularly regular, dipping north-northeast with an average inclination of about 1.1%. Permeability Barrier -35m is unable to confine the underlying aquifer in the Taro River domain and is affected by large windows, suitable for interaquifer flow, in the eastern portion of the study area. Here the pattern of ground water circulation is: in the southern portion of the plain loosing streams recharge the amalgamated gravel bodies which are in hydraulic connection with the confined aquifers of the northern portion of the plain.

5.4. - DSM OF THE PERMEABILITY BARRIER +3

Figure 9 shows the DSM of Permeability Barrier +3m a.s.l. which is found only in the northern portion of the Parma plain; this barrier has been deposited in Marine Isotope Stage 3 immediately preceding the coarse-grained alluvial fan sedimentation of the last glacial maximum which strongly incised the entire southern portion of the study area. In its limited extension, Permeability Barrier +3m is uniformly dipping north-northeast with an average inclination of about 0.8%.

Inclination, geographic position and lateral extension of barrier +3m demonstrate that the controlling factors are here represented by fluvial erosional and depositional processes; in fact, even the tectonic high of Monticelli Terme is draped by the fine-grained deposits of barrier +3m (fig. 9). In the southern elevated portion of the Parma plain losing streams recharge the phreatic aquifer hosted in the amalgamated coarse-grained deposits (CONTI *et alii*, 1999) which in turn recharge the confined aquifers, protected by Permeability Barriers +3m and -35m, in the northern portion of the plain.

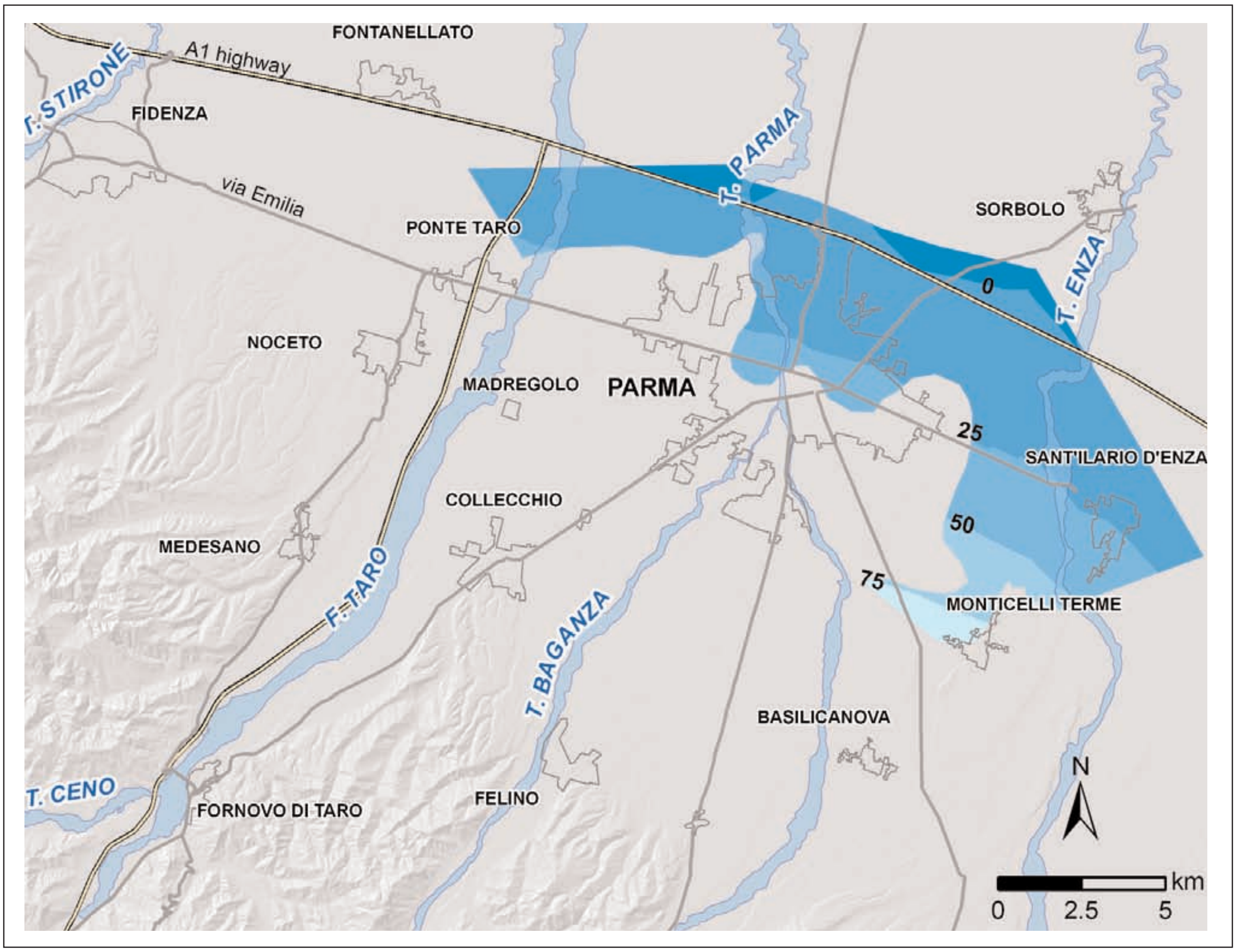

Fig. 9 - DSM of the Permeability Barrier intercepted at the height of +3m a.s.l. at the Parma Fair site. The surface, dipping north-northeast with an average inclination of 0.8 %, is preserved only in the northern portion of the Parma plain.
- DSM della barriera di permeabilità intercettata alla profondità di +3m s.l.m. sulla verticale delle Fiere di Parma. La superficie immerge a nord-nordest con inclinazione media di 0.8 % ed è preservata solo nel settore nord della pianura di Parma.

6. - CONCLUSIONS

The aquitards, internal to the Quaternary Continental Sequence (Qc) are laterally continuousup to Permeability Barrier -80m; they may be interrupted only within limited areas of the Monticelli Terme-Madregolo high and partly along the paleo-channel belt of the Taro River. These limited areas represent the only possibility of mass transfer between amalgamated coarse-grained deposits of superimposed aquifers. Interaquifer flow occur at the crest and especially in the front of the positive structure where the northeast dipping monocline provides an effective hydraulic gradient and influences the direction of groundwater circulation.

The key to understand circulation in the aquifer system is the DSM of the top of the Quaternary Marine Sequence (Qm) showing the thrust-generated antiform extending on the alignment of the towns of Monticelli Terme, Madregolo and Fontanellato. During Middle Pleistocene ages, specifically from the deposition of the Continental Sequence Qc_1 up to the deposition of the Permeability Barrier -80m, the tectonic deformation is particularly important.

Deformation, best shown by the geometry of Permeability Barriers, hampers recharge of the aquifers to the north because, due to the laterally continuous Permeability Barriers, the only possible recharge is from remote areas, also comprising the distant Apenninic front. In addition, the thrust-generated antiform acts as an effective hydrologic threshold controlling the direction of water flow in the aquifers of Continental Sequence (Qc).

The stratigraphic position, inclination and lateral continuity of Permeability Barrier -80m a.s.l. indicate a turning point in the history of the Continental Sequence. It still represents a laterally continuous barrier well protecting the underlying aquifer so that interaquifer flow is only possible at a strip parallel to the left bank of the Taro River and on the vertical of the alignment Monticelli Terme-Parma. Moreover, the physical structure of the overlying aquifer systems reveals the strong attenuation of tectonics and the fundamental control exerted by fluvial erosional processes. In practice, after deposition of Permeability Barrier -80m, i.e., at about 180ky BP, large alluvial fans initiated to develop, especially in the domain of the Taro River. The attenuation of tectonics is proved by the geometry of Permeability Barrier -80m which is much less deformed and less inclined (1.5% in the average) of the underlying ones. Reduced tectonic deformation is also shown by the constantly decreasing inclination of the overlying Permeability Barriers -35m (1.1%) and +3m (0.8 %).

The geometry of aquifers and aquitards overlying Permeability Barrier -80m demonstrate the fundamental role of fluvial erosional and depositional processes. The permeable coarse-grained bodies are particularly extended and may reach thicknesses up to 50m whereas the impermeable fine-grained drapes are vastly eroded. The youngest of the Permeability Barriers (+3m) is only preserved in the northern portion of the area. This barrier, probably deposited on the entire plain during Marine Isotope Stage 3 (preceding the last glacial maximum), has been removed from the areas to the south at the onset of the glacial-phase alluvial fan expansion.

In the southern portion of the Parma plain, along the Monticelli Terme-Madregolo-Fontanellato antiform, Permeability Barrier -80m is overlain by welded fluvial coarse-grained bodies, whereas, in the northern portion of the plain the same Permeability Barrier is overlain by three confined aquifers constituting the most important water reservoirs of the area. These aquifer systems exhibit a specific groundwater circulation model influenced by the position of the thrust-front positive structure; the hydrogeologic model being: phreatic aquifer of the upper plain in hydraulic connection with confined aquifers of the lower plain.

In the southern elevated portion of the Parma plain losing streams recharge the amalgamated coarse-grained deposits on the crest and front of the antiform; due to amalgamation these deposits express a phreatic aquifer which recharges the artesian aquifers to the north, confined by Permeability Barriers +3m and -35m. Actually this pattern has local exceptions due to the large windows shown by Permeability Barrier -35m which is unable to protect the underlying aquifer especially in the domain of the Taro River.

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