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New insights into the underground hydrology of the eastern Po Plain (northern Italy)

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ABSTRACT A series of studies concerning the surficial aquifers of the Emilia alluvial plain showed the existence of hydrochemical anomalies, suggesting a widespread vertical circulation of the various fluid phases hosted in the thick Pleisto-Olocene succession. The occurrence of liquid and gaseous fluid vents is easily detectable from their brackish character (with an electric conductivity, Ec**,** up to 18,000/22,000 μS/cm, at 25°C) and is related to various fracture systems that are difficult to study in detail. According to detailed stratigraphical and structural data (AGIP's seismic sections and industrial wells) the main source of the vertical salt uprisings is the Middle Pleistocene marine "Clinoforms Lithosome" ("Subsyntheme Marine Quaternary 3"), showing a wide distribution in the Po Plain-Adriatic basin. The occurrence of very low Ec freshwaters (250 μS/cm) sometimes accompanied by thermal anomalies (up to 7°C lower than the average annual temperature) is an interesting problem, hard to solve. The hydrochemical and thermal anomalies recorded in the underground waters were often very fast and penecontemporaneous over 30-40 km distances. These anomalies are genetically related to the earthquakes of the inner Po Plain zone and adjacent North-Apennine Chain. The active tectonic control played by the frontal zone of the North-Apennine Chain is fundamental for the explanation of the recorded anomalies. Ground collapse and disarrangements recorded and monitored over time are related to the loss in volume, underneath the surface due to the sediment compaction processes and other causes; also reminiscent effects of the deep gas-hydrates liquefaction, occurring in the distant past, cannot be excluded. Paroxysmal (explosive) fluid (methane) episodes and embankment underseepage ("suffosion") are not consistent with the recorded data.

1 . Introduction

A series of hydrochemical monitorings concerning the surficial aquifers of the middle and eastern Emilia-Romagna Plain were performed over the last ten years to test the existence of a link between the natural water hydrochemistry and tectonic stresses. Various monitoring areas over the buried tectonic axes of the Apennine Chain front were selected for this purpose. These sample areas identified a wide diffusion of poorly known and studied phenomena such as highly brackish water uprisings and surficial soil collapse (Bonori *et al.*, 2000). This required a large number of geognostic (hand borings up to 8 m depth) and geophysical surveys (electric and seismic tomographies and GPR profilings). Thirty new piezometers and a greater number (about 300) of old phreatic water wells were used to monitor water chemistry and its variations. Phreatic wells are availble in great quantities but are not used by the farmers today. These conditions guarantee an outline of the aquifer natural regime supply that is more realistic than the one provided by artesian water well-based studies. In fact, the artesian wells are made to search exclusively for freshwaters, excluding *a priori* every brackish aquifer. Monitorings were performed weekly or monthly depending on the various studied zones. Water electric conductivity was chosen as the main tool for the recognition of hydrochemical characters of the different sampled areas. In this study, some data are presented regarding four zones (Fig. 1) selected among various surveyed ones: Zones 1 and 3 display ground collapses and weakly brackish water uprising over a tectonic high and a syncline area, respectively; Zone 2 shows strongly brackish waters in phreatic as well as in artesian aquifers; Zone 4 indicates perennial, small, natural rising springs of strongly brackish waters.

2 . Structural and stratigraphical settings

The structural and kinematic evolution of the buried Apennine front (CNR, 1990) were studied in detail (Castellarin *et al.*, 1985; Castellarin, 2001 with references): the main structural elements are shown in Fig. 1. A wide and severe buried thrust belt has been documented by calibrated seismic sections (Fig. 2) across different Emilia-Romagna sectors of the Po Plain (Pieri and Groppi, 1981; Pieri, 1983). Similar structural settings originated mostly during the Po Plain-Adriatic compressional tectonic phase (Messinian-Lower Pleistocene). The syntectonic sedimentary successions involved in these deformations are made up of kilometric siliciclastic sequences, Messinian-Lower Pleistocene in age.

The post-tectonic successions (from hundreds of meters up to 2 km thick) are made up of clastic deposits arranged according to plain–parallel units with a top interval where marine sands and fine sediments, of delta and prodelta deposition prevail (Ori, 1993). This interval displays internal inclined bedding and forms the "clinostratified lithosome", up to 400 m thick, which directly underlies the Quaternary alluvial sediments (Figs. 2 and 3). This unit, corresponds to the "Marine-Quaternary 3" subsynthem (R.ER. and ENI-AGIP, 1998) and was related to an age encompassing the 970-650 Ka interval (Farabegoli *et al.*, 1997). It corresponds to the last record of the marine sedimentation in the Po Plain (R.ER. and ENI-AGIP, 1998). It is preserved in the syncline depocentral areas, while it is partially eroded or absent in the most prominent buried thrusts: its roof lies at a 400-500 m in depth (Fig. 3) in the wide Bologna syncline whereas its bottom attains 1000 or more meters in depth. The whole deformation of this stratigraphic interval is exemplified in Fig. 4. In Zone 2, the industrial seismic sections (Ecchia, 2005) testify the deformations involving the Plio-Quaternary boundary and part of the clinoform lithosome, attaining a depth of about 400 m underneath the plain surface.

3 . Preliminary surficial characters of aquifers

Generally, in the investigated areas, the presence of brackish waters near the ground surface is a natural phenomenon, often persistent in time (Puppini *et al.*, 1955) and not depending on anthropogenic causes (Cardelli, 2003) i.e. deep aquifers overwithdrawal, modifing the

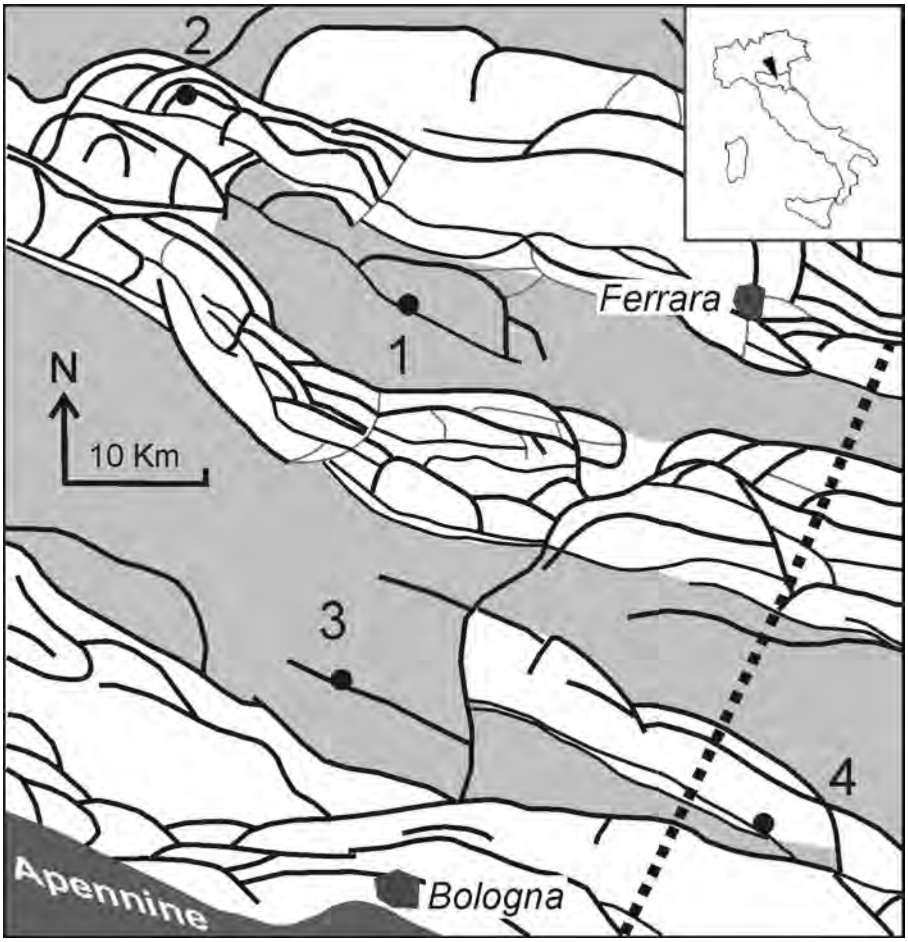

Fig. 1 – Model of the buried Apennine structural belt in the Bologna, Ferrara and Modena provinces [redrawn from CNR (1990)], showing the location of the four studied zones: 1) Reno Finalese, 2) Poggio Rusco, 3) Sala Bolognese, 4) Villa Fontana-Medicina. Synclines (grey) and thrust tops (white) are indicated as well as the location of Fig. 2 section (dotted line); the black lines indicate thrust and faults.

brackish/freshwater boundary (IRSA and CNR, 1982; R.ER. and CNR, 1982; R.ER. and ENI-AGIP, 1998). Furthermore, such presence is probably more frequent than known because up to now studies were always performed on artesian wells using freshwater (R.ER. and ARPA, 1997) and excluding brackish waters (due to their scarce value). The waters Ec topographical variability (Martelli, 2005) is often surprising even at a very detailed scale (100-200 m).

Data records for electrical water conductivity (corrected at 25°C) Ec, temperature T and level H (meters below the ground or a.s.l.) in the monitored zones, are shown in Figs. 5, 6, and 7. The most significant values concern the water sampled at the bottom of wells and piezometers, especially those located under six meters below the ground, where the seasonal variability has no appreciable influence (Grisanti, 2005). In Zone 1 (in a paleochannel alluvial plain of the Po River referring to the Bronze age) the monthly monitoring lasted about 7 years, whereas in the other

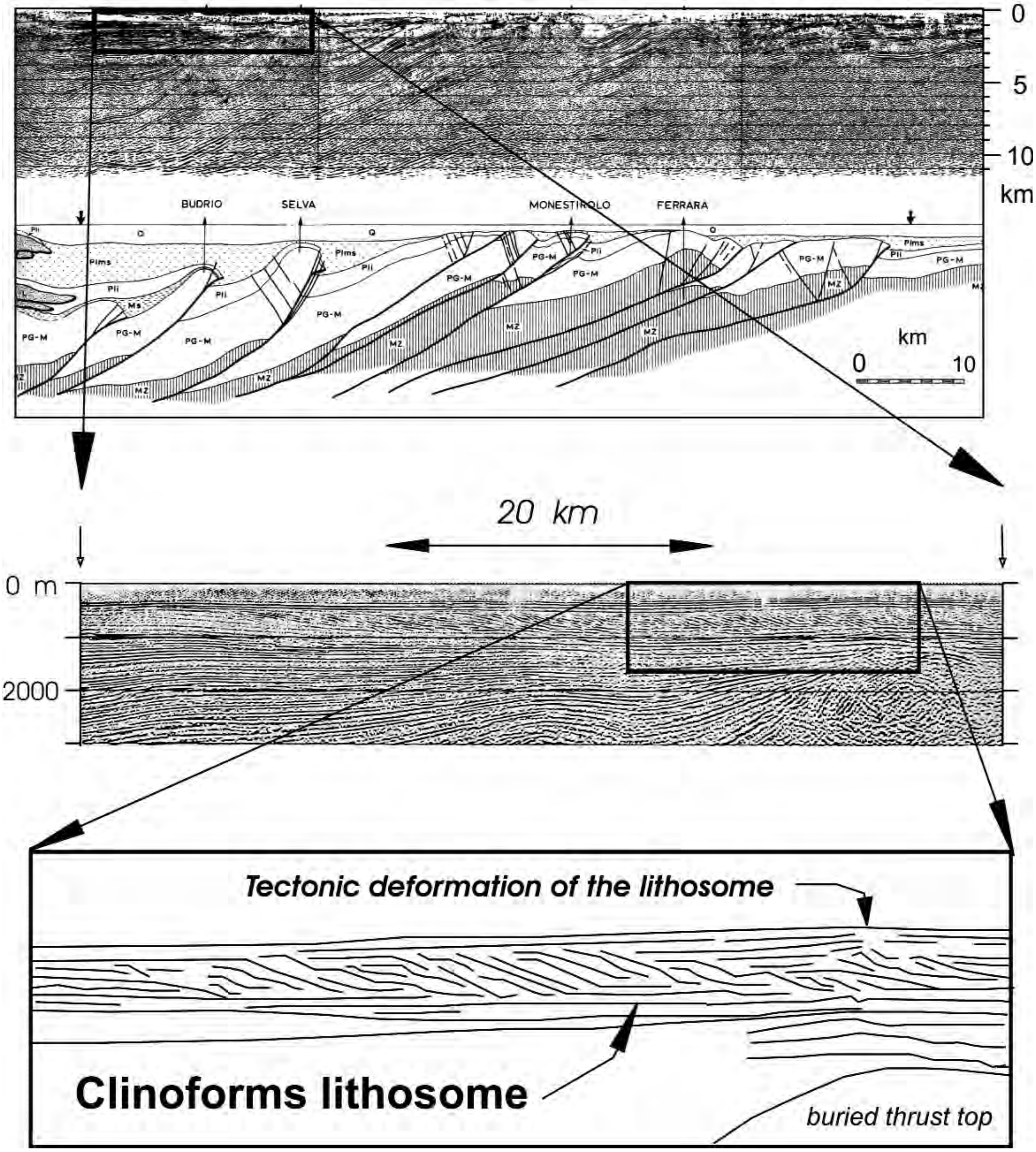

Fig. 2 – Thrust belt structure of the buried Apennine front zone, east of Bologna close to Zone 4 (from Castellarin *et al.*,1985). The central detail is redrawn from Dondi *et al.* (1982). The stratigraphic setting of Zone 4 is equivalent to that shown in the lowest square of the figure. Location of the section in Fig. 1.

zones (located in modern, clayey Apenninic alluvial basins) records were taken weekly to monthly, through a 1-3 year time span. Ec values of various kinds of water can be summarized for comparison, as in cases of snow-melting (60-70 µS/cm), free riverflow at a bankful stage (Apenninic river: 300-400 µS/cm), infiltration in the plowed layer (tube-drain: 1000-1100 µS/cm)

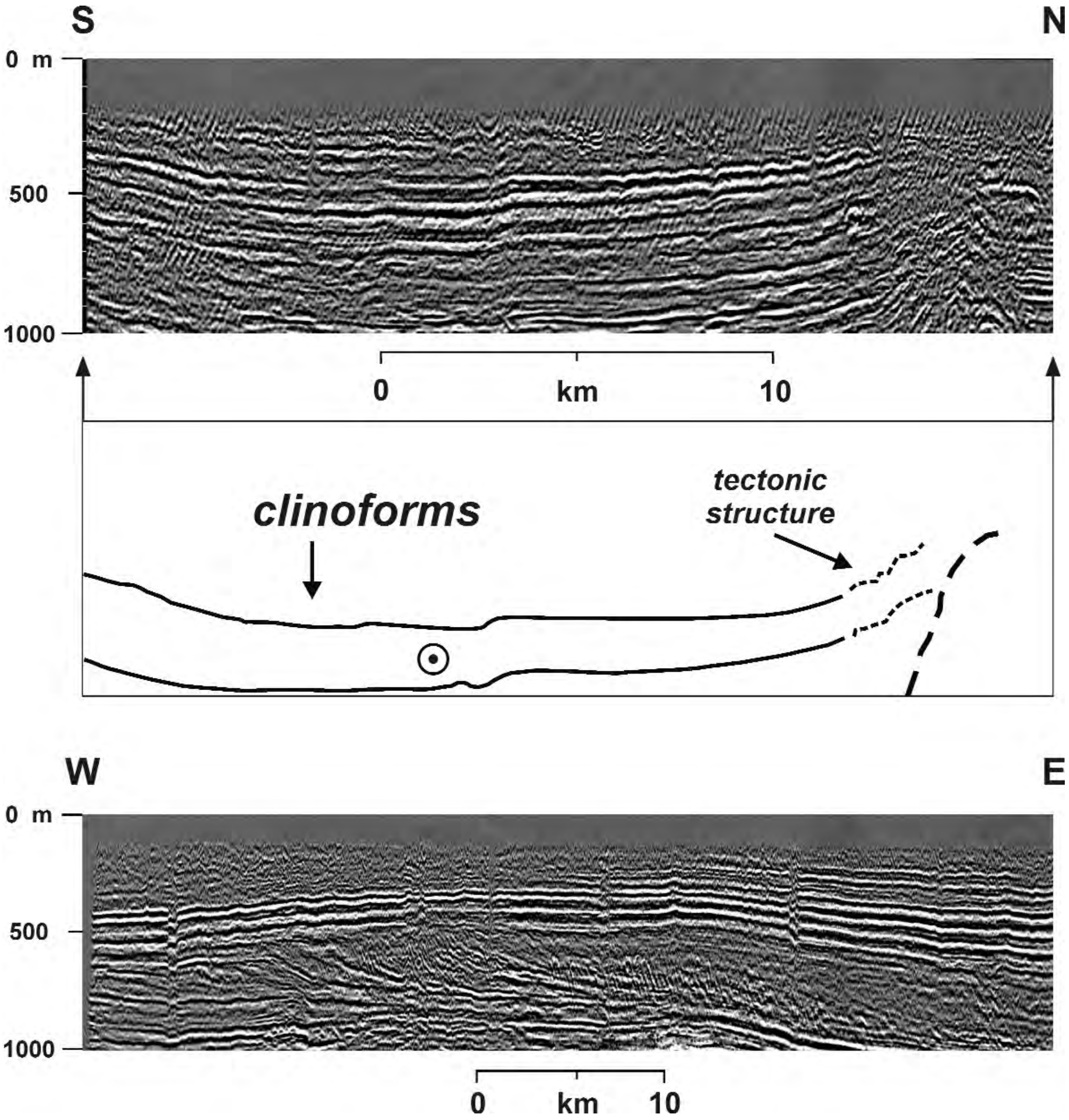

Fig. 3 – Two seismic sections in Bologna alluvial plain (courtesy of ENI) showing Middle and Upper Pleistocene foreland basin sedimentary deposits. The clino-stratified lithosome is clearly recognizable in the lowermost section, while in the upper one, where clinoforms are parallel to the section trace, the clinoform interval is indicated in the square mask of the intermediate scheme of the figure (the progradation verse is shown by the central circle). The seismic section (upper part of the figure) displays a prominent flexure in the depocentral zone of the wide Bologna Syncline. The section (lower point of the figure) line shows a family of vertical deformations originating from the core of the clinoforms lithosome or underneath.

(Grisanti, 2005), public aqueduct (legal threshold: 400 μS/cm; often: 500-700), sea shore (ca. 57,000 μS/cm), thermomineral springs along the Romagna Apennines [14,000-31,000: Benzi (2005)] and Parma foothills [199,000 at Salsomaggiore: Nanni and Zuppi, (1986)], Pliocenic

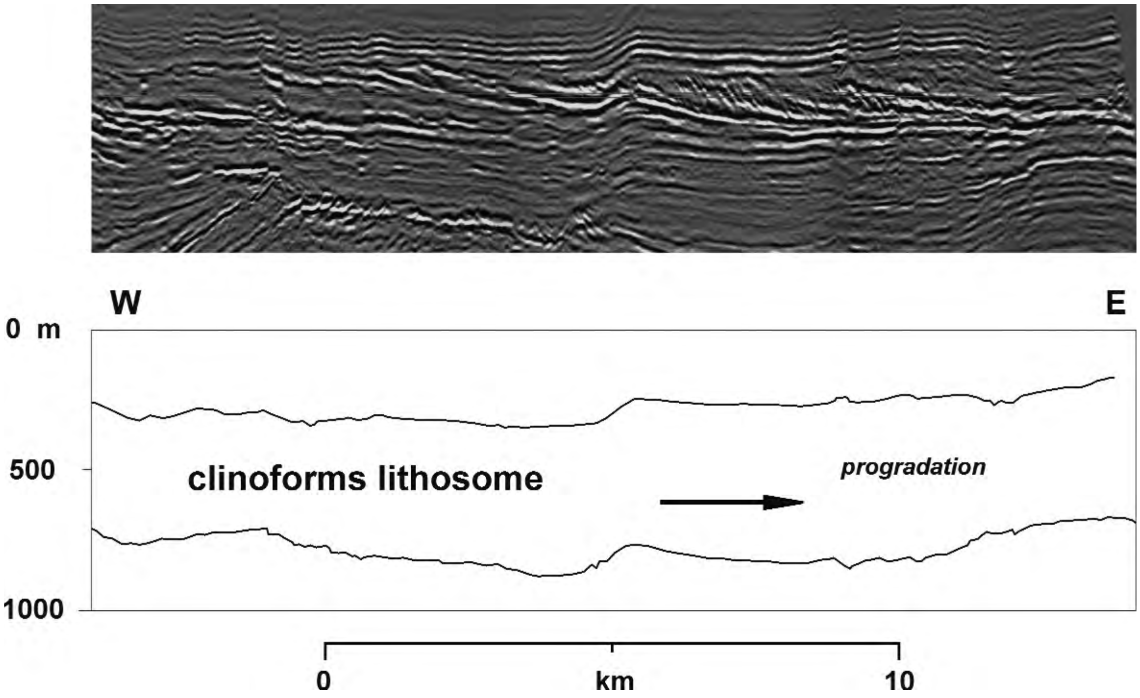

Fig. 4 – An axial seismic section (courtesy of ENI) near the top of the buried Apenninic thrust front shows deformations postdating the Quaternary succession.

brines up to the Piedmont area [41,500: ENEL, (1984)] and some Modena mud-volcanoes [14,000-27,000 µS/cm: Capozzi and Picotti, (2002)]. In a plain area, freshwater Ec ranging from 900 to 1500-2000 µS/cm can be considered usual from a statistical point of view (Cardelli, 2003 with references).

3.1 . Water concentration, temperature changes and setting of aquifers

As Ec depends directly on the whole water ionic concentration, the basic characteristics of the unsatured (phreatic) aquifers behaviour in the studied zones will be briefly summarized in a preliminary, general way.

A) *Strong and sudden water Ec variability according to an impulsive mechanism, synchronous or penecontemporary over areas of some square kilometers that can be related to fluids uprising.* These differences (5000-6000 µS/cm increase) must be interpreted as fluid uprisings. They involve both the brackish areas (big rising plumes) time-persistent and a peripheral crown, usually bearing freshwater. This indicates a water distribution model characterized by irregular concentric structures, thus indicating a prevailing vertical motion component (Cardelli, 2003): in fact, no geometrical relationships appears to exist between the brackish water uprising pattern and the local geomorphological setting (Cremonini, 2003). In the case of Zone 4 (Fig. 5), in particular, it must be stressed that these waters are not surficial rising freshwaters, because they are very different from the surrounding ones; furthermore,

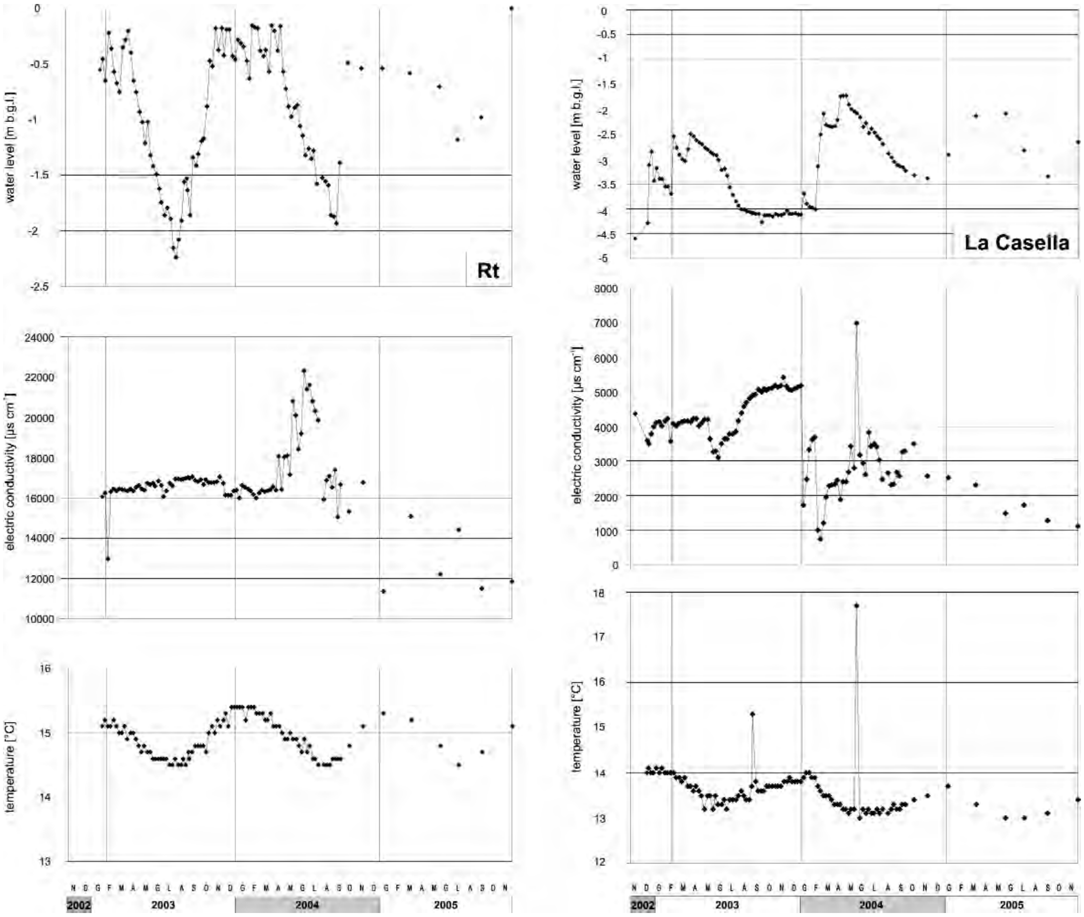

Fig. 5 – Data from two selected piezometers (Rt and La Casella, about 8 m deep) in Zone 4 during a three-year monitoring period: the two sites lie 5 km apart each other. The local ground level lies at 9 m a.s.l. See the temperature and electric conductivity values: to be noted the 2004 temperature spike.

they are down in the lower alluvial plain, very far from the alluvial fan toe where the resurgent freshwaters usually have their outlet belt (Cremonini, 2003). The survey lasted more than five years (1998-2003) in Zone 2 (Zappellone point). Here, very strong and fast water Ec variations (from 250 to 5000 µS/cm and *viceversa*) were recorded all along the entire water column (at least 20 m); such variations occurred in a very short time span (probably less than 24 hours), starting from a period of very low Ec stability condition (250 µS/cm). Moreover, stable Ec differences were recorded even in the case of short distances between water wells (30-40 m).

B) *Strong and negative anomalies of water Ec (reaching 3000-4000 µS/cm), lasting less than a week, asystematic (with a possible return interval of more than a year, but difficult to evaluate) and not depending on an usual, horizontal aquifer recharge mechanism*. Such

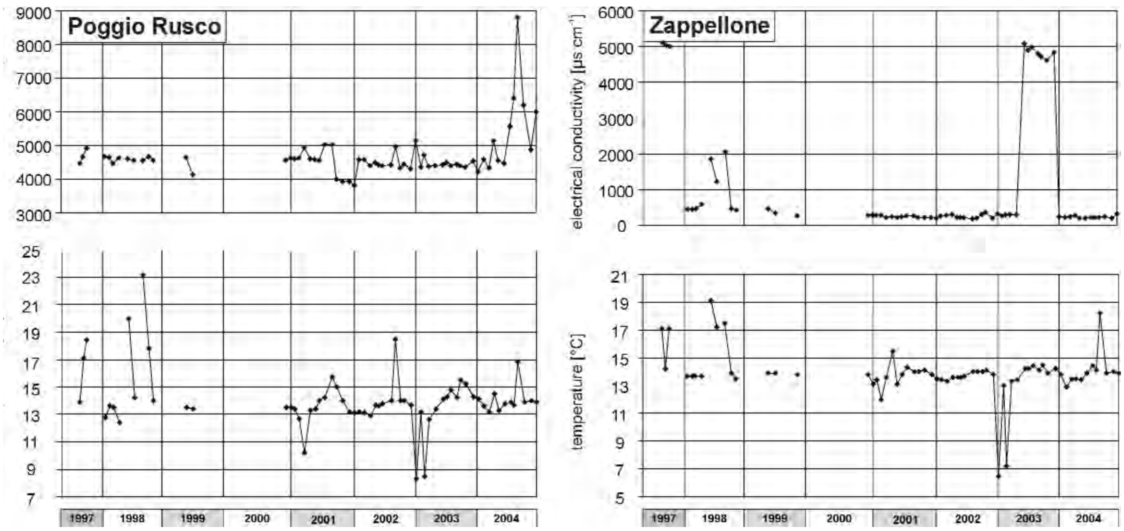

Fig. 6 – Electric conductivity and temperature in two selected artesian water wells of Zone 2 (Poggio Rusco and Zappellone, 40 and 30 m deep respectively), 600 m apart, during a seven-year monitoring period. The local ground level lies at 10 m a.s.l.

anomalies were recorded in Zone 4 (Fig. 5: Rt, February 2003) and immediately northwards (Stortoni, 2000). They are synchronous over medium sized areas (at least 1-10 km^2) and could be interpreted as particular dilutions operated over vertical brackish uprisings.

C) *Lack of evident aquifer water level variations during the major Ec pulses of the brackish uprings.* Only in a few cases (as in Zone 4) did the phreatimetric monitoring record local strong and fast local lowerings of the water table.

D) *Anomalies in the general aquifer setting, i.e. existence of areas characterized by local, permanent layering inversions of the water salinity*. In Zone 2, according to AGIP (1972), a particular hydrostratigraphic succession similar to the Ravenna one (AGIP, 1994) is recorded over a pronounced ramp anticlyne. This succession shows brackish waters at the bottom, then, upward, 100 m of (methane bearing ?) freshwaters and, finally, once again brackish waters at the top (140 m) up to the ground level (Ecchia, 2005).

E) *Occasional and sudden temperature anomalies of the underground waters*. They can be positive (i.e. T sudden increase) or relatively negative (i.e. T sudden decrease, never under 0°C). Positive temperature anomalies were recorded in natural conditions, free from anthropogenic influences, and they are relatively frequent. They range between 1.5 °C (Grisanti, 2005) and 5-8°C (Ecchia, 2005) above the mean annual temperature of the local bottom water and they match perfectly with the strongest piston-flow episodes (Zones 4 and 2). Negative temperature anomalies are very rare. In Zone 3 (Fig. 7, point P1) a temperature of 7.4°C lower than the mean annual one (14°C at 12 m under the ground level, in a 40 mm diameter piezometer) was recorded. In the same point, an Mps was generated some months later. Furthermore, in this point the water column was already very fresh [270 μS/cm: Martelli, (2005)] 3 months before the anomalous temperature decrease. Moreover, Ec values were

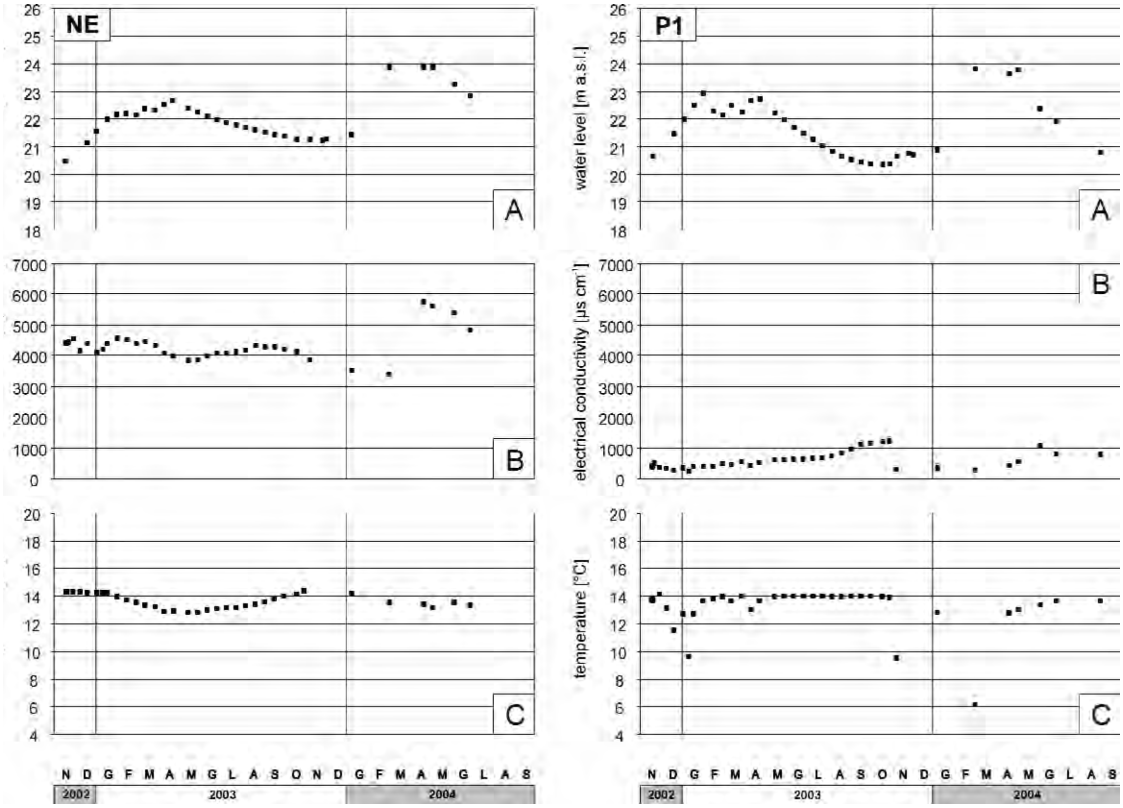

Fig. 7 – Piezometric data from two selected sites (“NE”, about 7 m deep, and P1, about 14 m deep), in Zone 3 during a two-year monitoring period: the two sites lie 270 m apart. The local ground level lies at 24.5 m a.s.l.. to be noted the evident temperature drop in P1.

completely different if compared to those of the previous period and to the ones recorded in the nearest points.

3.2 . Aquifers chemistry outlines

The main hydrochemical facies recorded will be shown briefly, bearing in mind the waters regional distribution models (R.ER. and ENI-AGIP, 1998) and the comparative Shoeller diagrams concerning the fossil, marine, phreatic and riverbed waters of the Po Plain (IRSA and CNR, 1982; Pellegrini *et al.*, 1982).

In Zone 3 (Fig. 1) fifteen piezometers scattered over a 900x300 m^2 area recorded HCO_3-CaMg water. Only one piezometer showed sulphate-CaMg water with a mean Ec, four times higher than the others (Fig. 7, point NE). A prominent Ec increase (not consistent with the water table rising) was recorded at the end of April 2004: in the deepest and freshest piezometer (P1), such Ec increase was about five times higher and, at the end of the year, Ec became similar to that of the other gauging-points (2020 µS/cm: out of Fig. 7). In every case, this increase did not appear to be related to a change in hydrochemical facies.

In Zone 4 (Fig. 1), a wide natural outcroping of Na-Cl waters was found, generating diluition or even change in its chemistry (Cl-CaMg or SO_4-Na), depending on the hydrostatic equilibrium with the surficial freshwaters: the peripheral crown waters of the outcrop area were Na-Cl or SO_4-Na. Furthermore, Cl-Na waters can be repeatedly replaced in time by sulphate-sodic compositions in the same point. In each point of this zone, an anomalous dilution episode (without a parallel facies change) was recorded on February 26, 2003, whereas a severe water Ec increase occurred from the end of April 2004, subsequently reaching the maximum values (June 1-30, 2004). All along the 25 km transect intersecting Zone 4, HCO_3-Ca waters were usually found, whereas the presence of the HCO_3-Cl ones was limited to the local structural highs (Bacchi, 1999).

In Zone 2 (Fig. 1) HCO_3-Cl -Na waters (or HCO_3-Na), with a high NaCl concentration, were present. Ec values were stable for such waters, ranging between 5000 and 11000 μS/cm up to September 2004: at that time a sudden NaCl lowering and a synchronuos HCO_3 increase were recorded. In all these cases, waters were originally marine as confirmed by the various ionic ratios usually calculated (Ecchia, 2005) such as $Na+K+Cl+SO_4/Ca+Mg+HCO_3$, Na+K/Cl, Ca+Mg/Na+K and SO_4/Cl. However, in the core of this last zone, a stable, straight (N to S directed), hydrochemical anomaly persists, bearing a very fresh (200-250 μS/cm) HCO_3-CaMg water rarely modified and replaced by local, brackish waters.

4 . Gas emissions

In the Po Plain basin, it is impossible to treat water circulation separately from the intense and widespread gas component existence. Natural, continuous gas seepage from the sedimentary cover (Scicli, 1937) is widely known both at a popular level (*jack-o'-lanterns*, *earth-lights*) and scientifically (Barilli Filopanti, 1841; A.N. Lincei and ENI, 1959; Roversi, 1966). These gas seeps have been exploited since the end of the Thirties (Veggiani, 1990). From a chemical point of view they are gaseous hydrocarbon mixtures with a prevailing methane content up to 80-99% (AGIP, 1938). The performed field observations were qualitative (sparkling, bubbling). At Corpo Reno, halfway between Zones 1 and 3, the seepage is still now continuous and intense. In Zone 3, a seismic section (Fig. 8) performed throughout the area which is characterized by Mps and Mpd, clearly shows the presence of gas saturation volumes in the upper 400 m of the sedimentary column. In Zone 2, the existence of inflammable gas is a common fact, particularly in the artesian waters. Isotopic analyses (CH_4 ‰^{13}C) performed on a degasing water sample gauged in a point located between Zone 1 and 3, suggested a gas origin depth of about 500-1000 m (Bonori *et al.*, 2000), i.e. surficial and biogenic. A local and modest thermogenic component cannot be excluded.

It is well known that surficial gaseous seeps are linked to mud and muddy fluid emissions (the Italian "salse" and "macalube") with surficial deposits of mud volcanoes. Till now, in the studied zones, direct recordings of fluid emissions and mud volcanoes are lacking. However, they must have been present, though sporadically, in the past as indicated by some place-names (Scicli, 1937), for instance Corte Vulcanello (Zone 2) or Casa Bollitore (Zone 1). In more recent times, starting from about 1990, the occurrence of peculiar surficial morphologies, such as Mps, Mpd (see Chapter 7), has been frequently reported. Nevertheless, they have already been known since the '70 (Pellegrini and Vezzani, 1978). Together with these forms, ground bulgings sometimes (Mdd and Mdc too) appeared, as local inhabitants still remember. For the Mps and Mpd origins

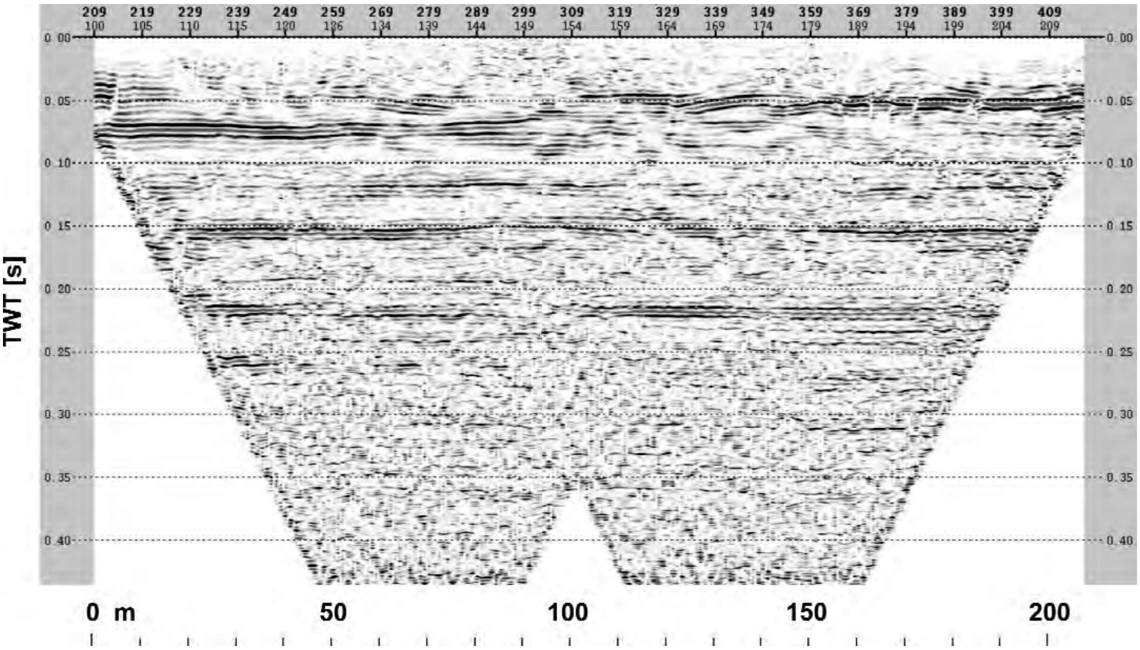

Fig. 8 – Seismic reflection section surveyed in Zone 3 across the piezometer field (courtesy of Consorzio di Bonifica Reno-Palata, Bologna). The original figure is in the Consorzio di Bonifica Reno-Palata (2005).

see later.

Depending on the attitude and stratigraphic conditions of the Po Plain Pleistocene deposits, we think that favourable conditions for gaseous hydrocarbon genesis probably existed in more anoxic levels of the fine prodelta muds inside the clinostratified lithosome. Interesting correlations between methane concentration and organic matter-bearing sediments have been observed in the sedimentary holocenic wedge near Ravenna (Curzi *et al.*, 1998) and in the Adriatic Sea bottom (Colantoni *et al.*, 1978). Because of the aims of this study, we think it could be useful to recall the gas hydrate and peat decomposing conditions. For basic problems concerning methane and hydrocarbon genesis the reader should refer to specific treatises (cf. Mattavelli and Novelli, 1988).

4.1. Gas hydrates

Gas hydrate liquefaction leads to the generation of very cold freshwater (eventually together with brackish water spikes related to the old salt component segregation) and large gas volumes (Hesse and Harrison, 1981; Kastner *et al.*, 1998; Zhu *et al.*, 2003), originally closed inside the hydrate reticulated structure according to a 1/164 water/gas ratio (Max, 2000; Collett, 2002). This gas could win the local lithostatic and hydrostatic confining pressure by triggering the fluid column motion (Mciver, 1982; Clennel, 1998). The methane bacterial production in the first surficial centimeters thickness beneath the marine basin water/sediment interface can lead to gas hydrate genesis only at particular T and P conditions (Henriet and Mienert, 1998). These conditions exist today in the continental slope of the high latitude marine basins in the first 500

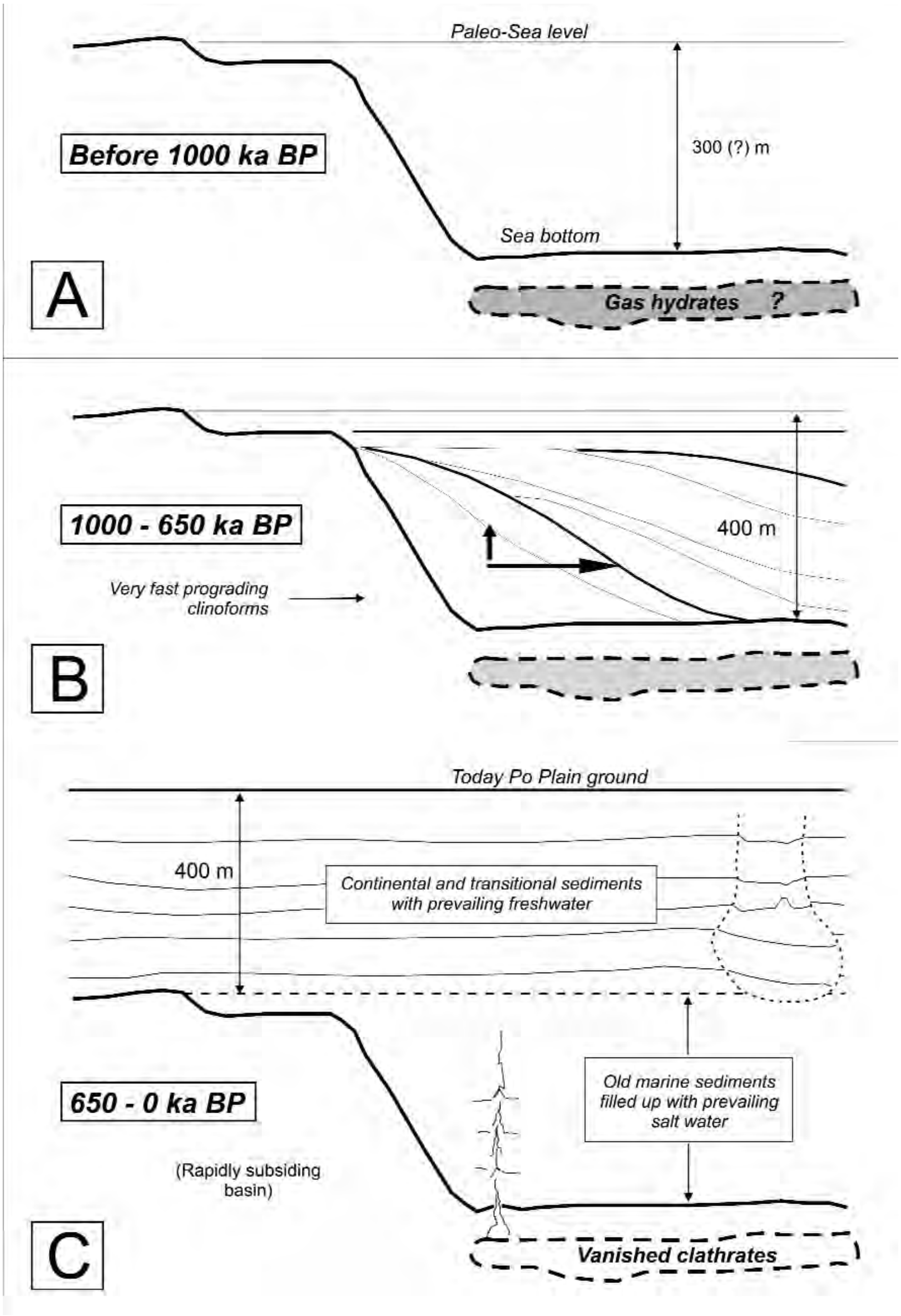

Fig. 9 – Three time intervals (A,B,C) of the Quaternary evolution of the Po Plain sedimentary basin. A) Inferred marine basin condition in the “preglacial” Quaternary. B) At the Lower to Middle Pleistocene boundary the Clinoforms Lithosome changes from deep sea to shallow marine/transitional conditions; this time interval is compatible with gas-hydrate generation. C) In the Middle and Upper Pleistocene natural subsidence continues controlling marine and further continental deposition. In the upper right corner of the figure an apparent collapsed big “pit-shaped” form is drawn.

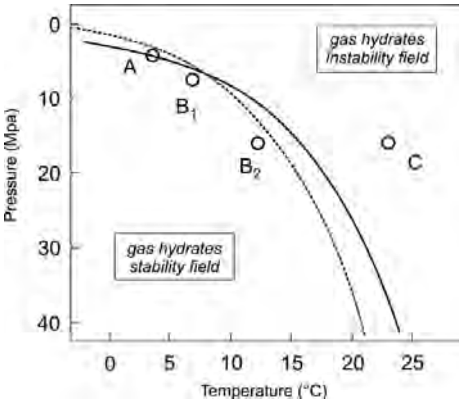

Fig. 10 – Possible evolution of the stability conditions for gas hydrates in the Po Plain basin during the Quaternary. The solid curve is redrawn from Peltzer and Brewer (2000). The dotted curve is the most reliable one for gas mixtures. We assume that the aquifer stratigraphic column has been laid over an aquiclude interval. Evolution is indicated by the sequence A-B2 , following the sedimentary trends of Fig. 9 (A-C). Today the real P/T conditions correspond to point C.

m sediments beneath the sea bottom, depending on the local geothermal gradient (USDE, 1998). Another possible stability field is represented by the subaereal periglacial environment with permafrost conditions. Shallow water (350-500 m) (Henriet and Mienert, 1998) and deeper (850-1200 m) clathrates are known, but gas hydrates are generating along fault planes too (Wood and Gettrust, 1998). Clathrates generated during the past Quaternary cold periods (Nisbet, 1990) are now partially decomposing, generating gas uprising and mud volcanoes, pockmarks, fractures, etc. (Mienert and Weaver, 2003). In postglacial times the clathrates decomposition is widely known (Ruppel, 1997; Suess *et al.*, 1999; Buffett, 2000; De Batist *et al.*, 2002; Pecher, 2002; Wood *et al.*, 2002; Poort *et al.*, 2005).

The climate and eustatic variations, that occurred during the Pleistocene could have created depositional conditions suitable for the clathrates' generation. Before emerging the study area of the central northern Po Plain was a medium depth marine basin (some hundreds of meters deep), elongated and enclosed between the Alpine and the Apenninic chains (R.L. and ENI-AGIP, 2002). At about 1000 ka BP (Fig. 9), a high sedimentation rate is reported by the clinoforms lithosome progradation and at 870 ka BP the first pronounced glaciation in the basin is recorded (Muttoni *et al.*, 2003). This could have led to favourable conditions for the development of gas hydrates inside the marine basinal area of the prodelta and delta deposits of the clinoforme lithosome. Subsequently, these deposits were covered by a high thickness of transitional and continental deposits, notably increasing the loading on the marine paleobottom (Figs. 9B and 9C). In physical terms, the evolutionary path of the clathrate masses could have proceeded as resumed in Fig. 10. In the figure, the A-B_1-B_2 parametric conditions correspond to the A-B-C evolution phases of the Po basin shown in Fig. 9.

It must be, however, stressed that thermal conditions of these deposits today are exclusively related to the local geothermal gradient mentioned above, which now maintain the Clinoforms at about 24°C. Such temperature implies a strong disequilibrium condition for a possible stability of gas hydrates (Fig. 10, point C) and for this reason their existence has to be excluded.

Furthermore, during the Middle and Upper Pleistocene anaglacial periods (*low stands*) wide emergence events of the Adriatic Sea bottom must be admitted. A 130 m sea level lowering (Vai and Cantelli, 2004), inducing deep river channel incisions and a severe draining action in the connected plain areas, surely caused difficult to define loading changes inside the Quaternary succession. Moreover, severe temperature lowerings during the anaglacial periods also took place. Both these conditions, developing into numerous events during the Middle-Upper Pleistocene glacial ages, may have multiplyed T and P conditions for clathrate generation, which are also very difficult to recognize.

4.2. Peats

A part of the gas emissions can be increased by the methane originating from swamp peat decomposition and possibly also lignite. A complex microbial (bacteria) action transforms the peat leading to CO_2 e H_2O, involving volume loss and gas release, mainly CH_4 coming from the anoxic intervals. The most famous surficial examples of the subsidence due to these kind of processes are recorded today in the Valli di Comacchio (GEMINA, 1963) reclaimed 40 years ago. In the studied zones, on the contrary, thick surficial peat layers are missing but their existence at various depths (also deeply buried) must be taken into account even if unknown today (AGIP, 1972). From peats and lignite with variable fine sediment content big amounts of normal Ec freshwater can thus originate (but not as low as 200 µS/cm). Therefore we think that, at place, the peats cannot be excluded as contributor of the methane generation.

5 . Low salinity waters and temperature variations

According to the above mentioned remarks, the most probable origin for the highly brackish NaCl waters seems to be their rising from the Middle Pleistocene Clinoforms: this lithosome in fact is still saltwater saturated (AGIP, 1972); moreover, only freshwater aquifers are present in the overlying sediments of the region (R.ER and ENI-AGIP, 1998). Chemical analysis concerning these saltwaters are missing in the literature, but 120,000-240,000 µS/cm Ec values are reported for the porewater of the Holocene transitional sedimentary wedge near Ravenna (AGIP, 1994; Curzi *et al.*, 1998) very similar to the clinoform interval environment.

The origin of the low concentration (250-270 µS/cm Ec) of freshwater (sometimes showing drops in temperature values as in Zone 3) can be explained by the following hypotheses:

1) direct vertical infiltration of the rainfall;

2) artesian freshwaters rising up to the ground;

3) methane oxidation processes not yet well known, such as the reaction $CH_4+SO_4 > HCO_3+ HS + H_2O$, mediated by the activity of a microbial consortium of *archaea* and sulphate-reducing bacteria (Judd, 2001), also generating new water;

4) water deriving from the compaction of fine sediments (clays and muds);

5) water deriving from peat and lignite consolidation;

6) connate saltwaters trapped at depth which then underwent a reverse osmosis process, bearing in mind that also the types of waters 1 to 5 may have undergone such of process, thus leading to various degrees of desalting.

While the positive temperature anomalies recorded in the previous paragraphs can be coherent with the local geothermic gradient (1°C/100 m) as suggested by Gorgoni *et al.* (1982), the rare cases of anomalous low water temperature are more difficult to explain. A severe cooling of gas due to a sudden volume expansion (Joule-Thomson effect) related to a lowering of the local confining pressure (e.g. induced by the genesis of fractures in the sedimentary cover) could be an explanation. But this effect is not easily admitted in the study areas, so it is still under evaluation.

Uprising fluids and gas are trapped inside the porous media of the stratigraphic column and they are released only when discontinuities or other causes affect their reservoirs.

6 . Uprising mechanisms, fluid mobility and seismicity

As indicated by the hydrochemical facies variations, salt waters are affected by mixing processes with underground freshwater (from the surficial or from artesian aquifer). The normal density layering of the underground waters (i.e. brackish/freshwater) can be modified due to excess in withdrawal or to fractures and faulting. The rapidity in these changes is not coherent with an ionic diffusion process, i.e. a very slow mixing process (Appelo and Postma, 1994): they can be explained by turbulent mixing due to a piston-flow mechanism.

As to the rise of fluid mixtures, their upward motions may be generated by a diapiric mechanism. Similar processes can be determined by the loading differential exerted by the sedimentary columns on unconsolidated mobile deposits or by the tectonic deformations on similar deposits of previous structures.

The diapiric bodies at the surface are marked by small mud volcanos metric to decametric in size, formed during continuous emissions (“Salse” and “Macalube”) or also episodical, in some cases, with violent sprays and upthrows of liquid mud some 10 m high or more with emission of gas (CO_2 and CH_4) (Sicli,1937; Cantelli, 1994). Similar conditions occurred and are typical of the Po plain–Adriatic border of the Northern Apennine up to the foot hills and of the Emilian adjacient plain (Nirano, S. Clemente); in other cases the emissions contain thermogenic methane and also oil (Salsomaggiore, Rio del Petrolio) (Capozzi *et al.*, 1994; Capozzi and Picotti 2002). It is to be noted that, in the last decades, these occurrences, not to be excluded in the future, were not observed in the study area, excepting for those of the far past as suggested above.

The rise of the emissions may be enhanced by the internal pressure of fluids, whose buoyancy determines an upward push and may lead the fluids to pass through the overlaying cover of sediments. In the study area, during the last decades, gas emissions were low energy events which took place without strong dins or rumble. No wet sediment and mud was conveyed, during the emissions, to the surface, where external edifices around the emission spots are totally missing. Moreover, the swells interposed between collapses, can be interpreted as zones not involved by the collapsing processes rather than reliefs or dome structures sustained by gas chambers.

Seismic sections show structures of up to 400-500 m wide, produced by active mechanisms as recognized at some 800-1200 m in depth. Their 2D geometry indicates vertical contacts between the peripheral, outer undisturbed sedimentary column and the bent, displaced beds inside a pit shaped, apparently collapsed zone (see the upper right-hand side of the Fig. 9C).

"Weakness" zones, a few meters beneath the surface have also been observed. In Zone 3, vertical bands 3-4 m wide, within the last 4 m of the ground have been recognized by GPR surveying (Vettore *et al.*, 2004). Similar results were further obtained in zones affected by collapse structures (Mps: see below) (Bonori *et al.,* 2000). Moreover, seismic and electric tomographies detected feature of similar geometry affecting the alluvial deposits up to 10-15 m from the ground (Martelli, 2005).

Vertical risings of the fluids are also the key to explaining the thermal anomalies of the underground water. Positive thermal anomalies were detected in the Plain (Bologna and Forlì provinces) with magnitude of + 4-5.3°C at a 95-150 m depth on artesian waterwells, which were referred to the drilling effects in the well (Gorgoni *et al.,* 1982). Inside the study area, these results were confirmed on natural water samples close to the ground. The positive temperature anomalies (T values up to 4.5°C higher than the average annual water temperature) can be referred to rapid rising of the waters from other domains, 300-400 m deeper, at least. In fact, the local thermal gradient of 1°C/100 m (constrained to an average annual temperature $T_{ya} = +13.5°C$ (Gorgoni *et al.*, 1982) is coherent with a similar depth of the source which may be considered located in the upper part of the clinoforme lithosome (Fig. 9).

Tectonic activity in the frontal buried and emerged structures of the Northern Apennines is coherent with historical seismic documentation and with records of the events of the last decades (//www.ingv.it/~roma/reti/rms/bollettino). Uprises of salt fluids were recognized both in the structural high zones of the buried thrust belt (Calvino, 1965; R.ER. and CNR, 1982) and in the undeformed buried sector of the Po Plain (Mantua lower alluvial plain) (Baraldi and Pellegrini, 1976). At present, similar uprisings are known also above the syncline zone of the buried belt, in Zone 3 of this paper.

In the Bologna province, thermal co-seismic anomalies are recorded for the year 1779 (Boschi and Guidoboni, 2003) and, in the Ferrara district, in the year 1624 (ING and SGA, 1995). In Zone 2, during the seismic cycle of 1997 and 1998 an appreciable increase of occurrences of fluid temperature spikes was detected (Fig. 6). In Zone 4, the highest Ec value, joined by thermal anomaly (Fig. 5), was recorded on June 1, 2004, predating the seismic crisis affecting the area of Monghidoro village (June 24, 2004) by some 20 days, in the core of the N-Apennine frontal sector.

Previously, a modest thermal anomaly, postdating one similar event by 2 days, occurred in the same area (September 15, 2003). The Ec anomaly of 2004 started at the end of April; its value can be correlated with identical records in Zones 1 and 3, some 40 and 30 km from Zone 4 (Martelli, 2005). Moreover, in September 2004 very strong spikes in Ec values occurred in Zone 2; they were almost synchronous (August-September) with the seismic events affecting the area in the Modena and Mantova provinces (////www.ingv.it/~roma/reti/rms/bollettino). This link between the underground waters Ec and the tectonic tensional field and seismicity, across wide distances, was also suggested in previous studies (Bonori *et al.*, 2000).

It is consequently recognized and confirmed that most of the anomalies of the study area are controlled by the active frontal zone of the Northern Apennines.

7. Surficial ground-collapses (Mps, Mpd)

In the last two decades, a series of particular morphological structures, mesoscopical in size (from m to dam), developed in various places in the Emilia-Romagna plain as well as in Zones

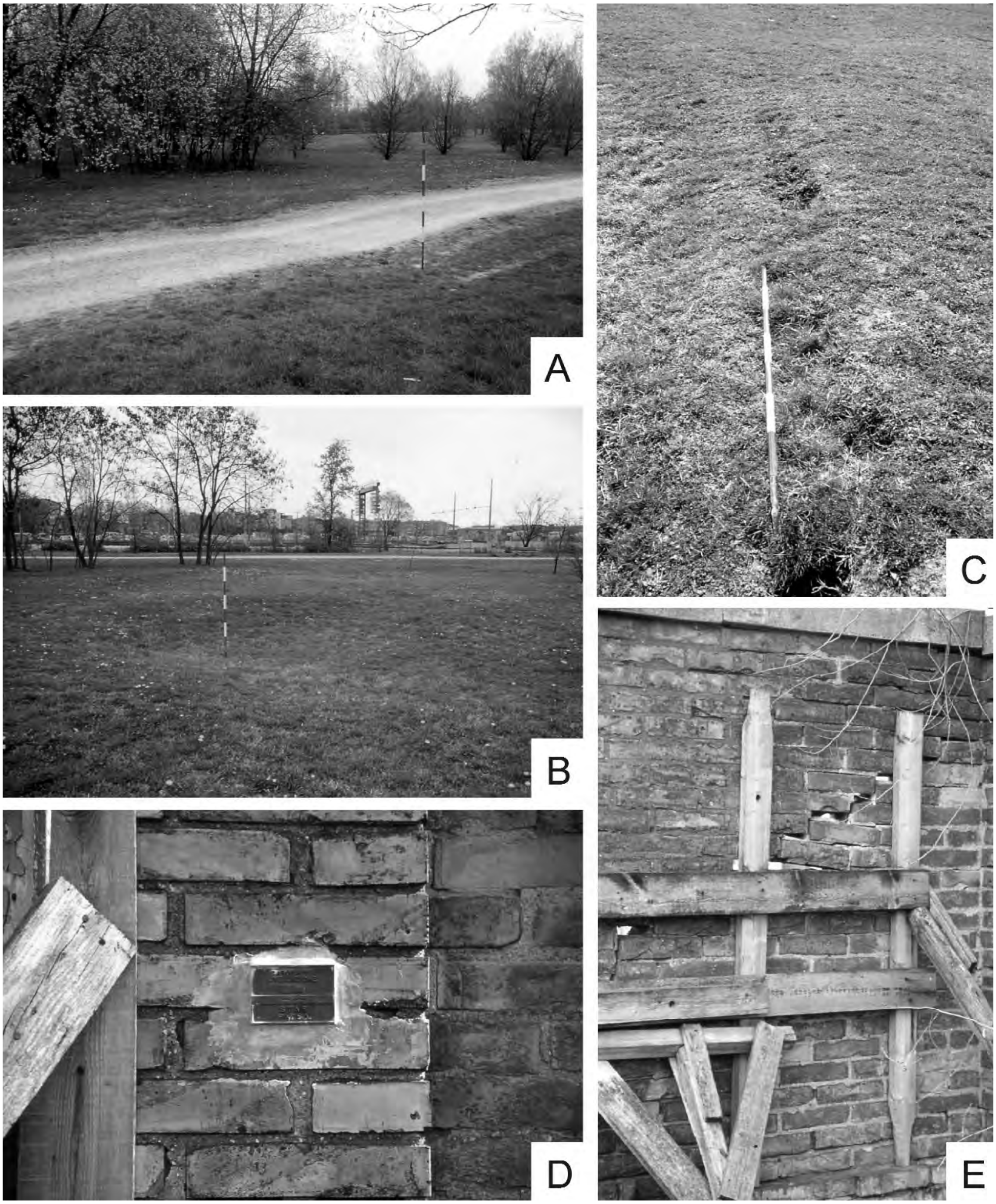

Fig. 11 – Small meso-pseudo-doline (Mpd) (B), meso-pseudo-ditch (Mpc) (A) and an Earth- fissure (C) bordering a form like that of B. These examples are taken from a group of about 80 surficial forms developed in a Bologna public park (Villa Angeletti). E shows the damage in a brick wall caused by the evolution of an Mpd. D: levelling benchmark on the same wall showed in E.

1, 3 and 4 (with minor occurrences) of this study. Here, they are named “meso-pseudo-dolines” (Mpd) and collapses or “meso-pseudo-sinkholes” (Mps), as stated by Martelli (2005), meso-pseudo-domes (Mdd) and meso-pseudo-ditch (Mdc). The “Earth-fissur*e*” (Carpenter, 1999) has been recognized only in one case, near Bologna, a small structure connected to a regular depression (Mpd) (Fig. 11).

As a rule, the Mps (Fig. 12) appear as small (decimeters-meters) depressions in the ground, indicating the existence of an empty underground chamber already developing beneath the plowed-layer (Fig. 13). This chamber seems to increase its volume by means of repeated wall-falls developing from fracture systems existing inside the surficial layer: sometimes the chambers resemble wide linear fractures. It is likely that beyond a certain volume threshold, the chamber roof collapses: according to our data, perhaps it takes only one year, and the colluvial Earth collects and remains at the bottom of the previous chamber at a depth of about 1-1.8 m. The chambers do not show any trace of faunal activity. They contain exclusively gravity-laid sediments and do not seem to host active water flows (Fig. 14). More chambers often seem to be aligned along short branches of different directions (Febo, 1999).

Mps can be associated to a subsiding subcircular, elliptical or poligonal Mpd (Fig. 11), having a 40 m major diameter, a 10-20 cm or little more central depth and a 100 mm/a maximum central subsidence rate (Bonori *et al.*, 2000). By our data, they never correspond to bomb craters of World War II. They are often recorded in orchards, where the soil is not seasonally disturbed by agricultural work. They have often been observed to drain huge amounts of rain water stored in the agrarian ditches rapidly. Over a decennial period at least, the Mps occurrences affect the same areas, without a clear areal spreading trend; furthermore, they continue to slowly develop (with grassing of the enclosed soil) if not filled up artificially. It is interesting to note that, at least in one case, they were already known during the last world war, i.e. before the strong underground water withdrawal and riverbed erosion dating from the Fifties (Cremonini, 2004). The greater part of Mps lay at a certain distance from the riverbeds (up to 200-750 m) in loamy, clayey-loamy or sandy-loamy soils: sometimes they develop even in the central part of the interfluvial low alluvial basins without any possible relation to the river talwegs. Furthermore, when the Mps are located near the river embankments (as Reno, Panaro, Po Rivers), during our surveys they never revealed a direct hydraulic connection with the river channel during the bankful stages. In the zones illustrated in this study, they develop in areas located either on buried structural highs or in syncline areas. Moreover, they are present both in areas affected both by low and by high artificial subsidence rate (ARPA, 2001). In particular, in Zones 1 and 3 the Mps seem to be generated in the lower limbs of flexures or faults (even if not completely defined) as predicted by the theoretical models (Mandl, 1988).

The set of morphological characters and the impossibility of defining a real underground horizontal drainage network allows us to hypothesize a prevailing vertical setting for the hole assemblages. Such a system may be related to continental pockmarks, generated by gas seepage recorded in the seismic surveys performed in Zone 3 (Martelli, 2005). Similar fossil structures are known in the Apennine foothills (Curzi *et al.*, 1987). There are no good reasons to suppose a different genesis and behaviour for today’s subaerial Po Plain with respect to the actually submerged Adriatic paleoalluvial plain. The pockmarks development are well known today in the Adriatic bottom (Curzi and Veggiani, 1985; Curzi, 1996). The different morphology and

Fig. 12 - Examples of ground collapses, ie. meso-pseudo-sinkholes (Mps), in the flat alluvial plain of Bologna and Modena, NW of Zone 3. The single elements of the levelling rod are 0.5 m long (each single mark of the rod is 1 cm wide).

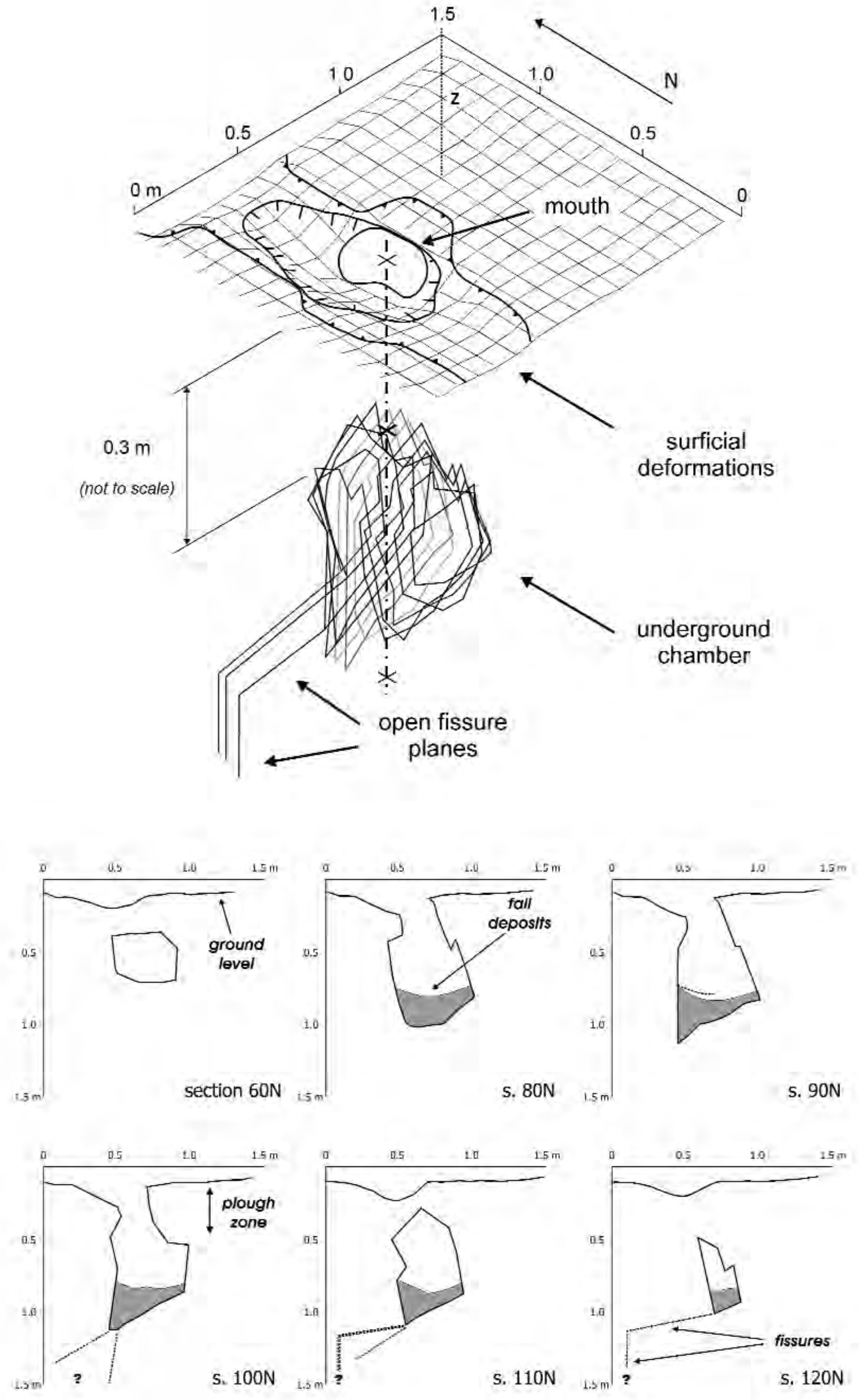

Fig. 13 – 3D development reconstruction of the underground chamber related to a small little surficial collapse (Mps) such as that of Fig. 12 (upper right-hand corner). In the lower scheme of the figure six selected sections across the chamber are indicated.

behaviour of the recorded mesoforms in these two domains could simply depend on the different environmental conditions and on the related geomechanical reactions: unsatured and more cohesive materials at the soil/atmosphere interface in the continental domain versus saturated and prevailing non-cohesive sediments at the sea bottom.

The ground-collapses (Mps) of the Emilia-Romagna plain discussed above hardly or only partly refer to regional subsidence. The subsidence, in fact, can cause only widespread and regular ground lowerings as documented in the whole Po Plain area (from Pieri and Groppi , 1981 onward; Carminati and Di Donato, 1999; Carminati and Martinelli, 2002). The recorded structures need localized volume losses completely independent from regional control instead.

Another theoretical possibility for this phenomenon are the fine sediments and peat compaction according to their spatial distribution. Among the various theoretical possibilities for the collapses we must consider: 1) the sediments or rocks chemical dissolution (ie. karstification) induced by the aquifer water circulation; 2) the underground mechanical water erosion as suffosion (piping, tunnelling), ie. rainfall vertical infiltration; 3) the direct piping (i.e. “embankment underseepage”, that is the river pressured water uprising during a bankful stage, or “fontanazzo”, as an Italian popular word), generated along the main water courses in their plain reaches; 4) the gas-hydrates (clathrates) decomposing involving relevant volume loss at depth (10-13%) and a methane plus water release.

In our opinion, the karstic processes cannot be invoked here because the buried, thick Neogenic successions are not characterized by any sort of carbonatic (limestone) or sulphate (gypsum) rocks. Furthermore, in these almost horizontal plain areas the hydraulic gradients and the sediments permability only allow a slow and moderate underground water circulation. The horizontal suffosion can also be excluded for the same reasons, due to the low energy of the underground water motion that is incompatible with erosion and transportation of sediments. Moreover, it is also difficult to explain the existence and generation of empty spaces at depth, able to accomodate the eroded sediments. Furthermore, they are also inconsistent with the surficial ground setting which appears strongly collapsed. Finally, the embankment underseepage can not be invoked because the Mps never allowed water uprisings during or after the bankful stages of the rivers (Febo, 1999; Martelli, 2005) and furthermore the Mps have been recorded in areas very far from the river courses.

Finally, loss in volume and lowering of the ground can not be derived from the deep clathrate decomposition, because their existence can be admitted only during the remote past (Pleistocene) and it is not active today.

8 . Origin of collapses and their meanings: a discussion

Alternative interpretations of the collapsed zones are the following.

1) *Over-pressured gas amasses in chambers inside the upper subsoil sustaining the plowed layer.*

This interpretation is consistent with the high volumes in methane released by the ground, but it is denied by the absence of violent events pre-dating the collapses. In fact, the surface is totally lacking blast-deriving deposits or other accreting products due to rising flows to the surface; moreover, gas chambers should be marked by positive structures such as reliefs or dome

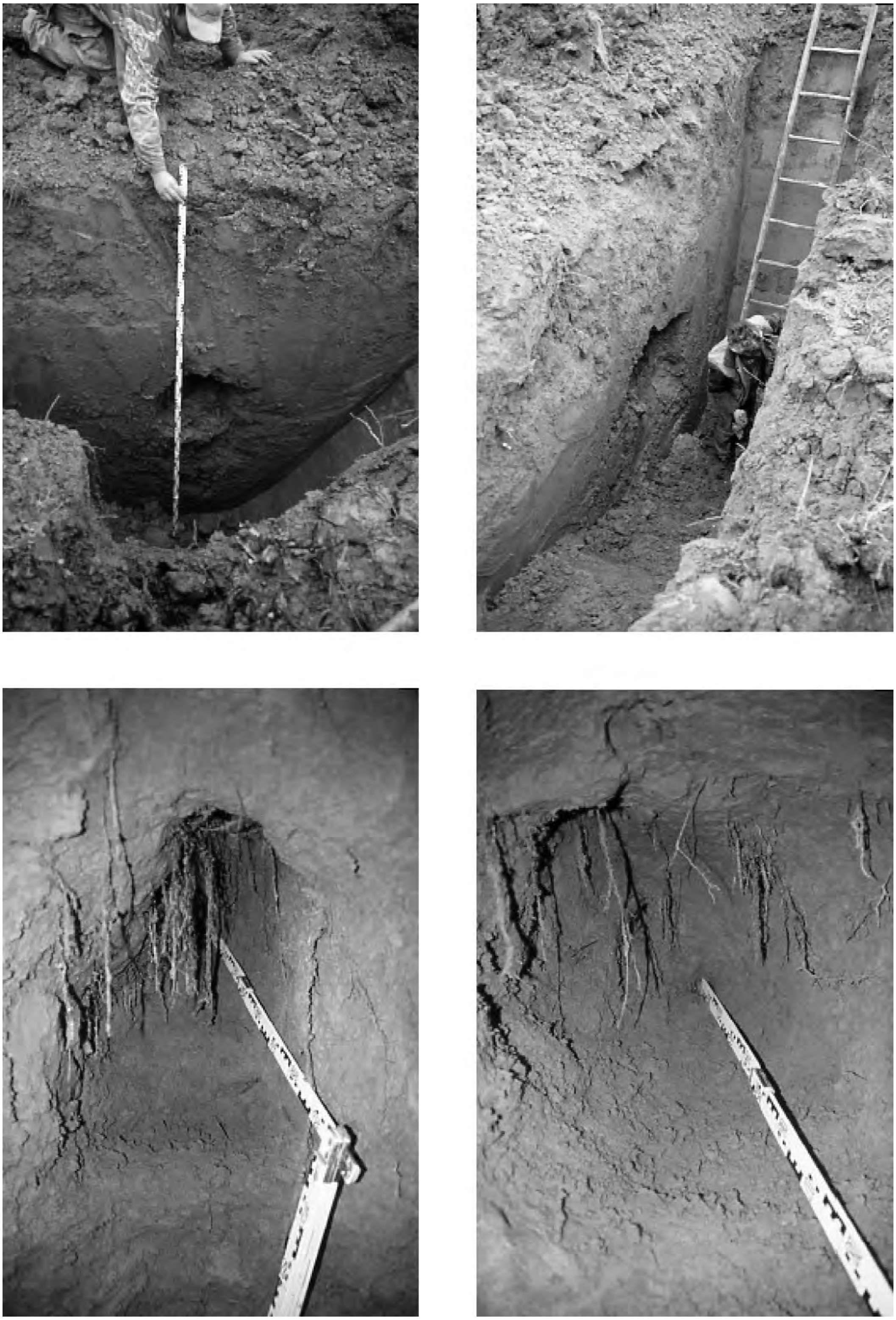

Fig. 14 – Examples of deep underground chambers. Note the original lateral closure of the chamber (indicated by the tip of the levelling rod) and the well-preserved tree roots at its roof.

structures. In the study zone, similar occurrences have never been observed in spite of the very recent origin of several collapses, some of which were recorded during their rapid evolution. It is to be noted that a discharged gas chamber could not produce any depression of the ground at the surface which is, on the contrary, affected by holes and pits, up to some cubic metres in size. These conditions could be explained only by underground erosion or similar processes which cannot be admitted (see previous paragraph).

2) *Blind detachment of the cover at the surface, opening holes underneath the ground which hung over the void chambers.* The static equilibrium is established by the collapsing of the hanging ground.

This proposal is coherent with the conditions observed in this paper. In fact, if the source zone of the collapses (Mps, Mpd), originated by loss of volume, should be located several tens to some hundreds of metres in depth, the holes at the surface should be very gentle and not remarkable because of the confining pressure produced by the sediment load. On the contrary, the holes are very prominent at ground level. Consequently, the source zone of the collapses have to be located close to the surface (at some meters in depth); moreover, the loss in volume and the collapses have to be developed at the surface in a short time span, as documented by their rapid evolution. It is supposed here that similar processes were triggered at depth due to the packing of loose sediments (inside silty mud deposits and organic and vegetable-matter bearing sediments). Due to unconformities and not to homogeneous behaviour, the uppermost part of the sediment succession detached itself from the underlying lowered one, producing unstable chambers close to the surface. Their stability settings were attained by the collapse of the hanging ground, producing holes and pits (Mps, Mpd) at the surface as previously defined. This last evolution, intensified soil fragmentation, porosity and permeability in the soil, fluid and gas upward mobility.

9. Conclusions

The central eastern Po Plain sector includes the severe structures of the buried Northern Apennine thrust belt containing Pliocene-Pleistocene basinal successions mostly forming kilometric sintectonic prismsatic wedges. The Pleistocene units display mostly post-tectonic tabular setting, and are both marine and continental. Marine successions are composed of silt and sand clinoform deposits related to Lower-Middle Pleistocene encompassing an interval between about 1000 and 600 ka BP. In spite of its prevailing tabular geometry this succession is locally affected by fault and gentle folds at place involving the continental deposits of the overlying interval. These units enclose important water resources. Waters of the surficial aquifer and, in part of deeper domains (artesian aquifer) have been analysed. Ec and T water monitoring was performed directly on the agricultural (surficial) wells and on piezometers of selected sites. Samplings and analyses, occurring every month or week, were developed over a time span of 2-7 years.

The principal results of the study are as it follows.

a) A water Ec wide range from 22.000 μS/cm (brackisch waters) and 200 μS/cm (freshwaters) was detected in the whole studied area. Local severe Ec variations, inside the same acquifer were observed (Zones 4 and 2, Figs. 5 to 7).

b) Changes in water temperature up to 5°-7°C, over or below the mean annual values (in few cases, within 24 hours) have been observed (Figs. 5 to 7).

c) Water risings are often combined with gas emissions (mostly methane). Nowadays and in the past decades, similar emanations, were never associated to mud volcanoes nor to other kinds of deposits emplaced around the emission centres which, on the contrary were affected by ground collapses, hampering the agricultural work with the risk of damaging the farm buildings.

d) Methane is considered as coming up to the surface from biogenic sources such as anoxic deposits: marine (organic matter bearing sediments) or continental intervals (enclosing peats and lignites). Methane coming from liquefaction of clathrates cannot be considered because the origin of clathrates was possible mainly during the anaglacial events of the Lower to Middle Pleistocene (onset at about 870 ka BP) in connection with the marine deposits of the Clinoform Lithosome (Fig. 9). It is to be noted that gas emissions can enclose old methane of previous Pleistocene clathrates. Modest component in thermogenic methane can not be totally excluded.

e) The collapses of the ground (Mps, Mpd) (Figs. 11 to 14), are the expression of loss in volume occurring vertically underneath the surface, due to packing of loose sediments. These holes were not originated by the collapses of gas chambers, nor by underground excavations and /or erosion processes as documented by the data collected today. The loss in volume occurred at depth and was transmitted to the surface. Detachments of the uppermost part of the sediment succession from the underlying lowered one may explain the origin of the unstable chambers close to the surface. The detachment levels can be related to non homogeneous behaviour and to unconformities inside the deposits; or to other causes still unknown. The stability settings of the field were attained by the collapse of the hanging ground, producing holes and pits at the surface (Mps, Mpd) as described in this paper.

f) Hydrochemical and thermal anomalies in the underground water are nearly synchronous or penecontemporaneous across distances as wide as 30-40 km. There is an evident connection with the seismic activities of the Po Plain and of the adjoining frontal Apennine Chain. They could potentially be precursory markers of major seismic shocks.

g) The results of the investigations presented in this paper, support and confirm the strong tectonic control exerted by the active dynamics of the Apennine frontal zone in the study area. They involve a great part of the observed anomalies.

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