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GEOCHEMICAL AND GEOPHYSICAL MONITORING IN TECTONICALLY ACTIVE AREAS OF THE PO VALLEY (NORTHERN ITALY). CASE HISTORIES LINKED TO GAS EMISSION STRUCTURES

ABSTRACT: BONORI O., CIABATTI M., CREMONINI S., DI GIOVAMBATTISTA R., MARTINELLI G., MAURIZZI S., QUADRI G., RABBI E., RIGHI P.V., TINTI S. & ZANTEDESCHI E., *Geochemical and geophysical monitoring in tectonically active areas of the Po Valley (Northern Italy). Case histories linked to gas emission structures.* (IT ISSN 0391-9838, 2000).

In some tectonically active areas of the Po river plain the ground surface is locally affected by collapse phenomena linked to gas escapes. In order to better identify these «pockmarks-featured» structures whose occurence seems to be proof of an eruptive seepage at a high flow rate, between 1996 and 1998 the main geochemical trends in 15 selected water-wells were investigated and geophysical prospections and levelling surveys were performed. In the wells, whose depths range from about 5 to 70 m, some geochemical anomalies have been detected suggesting mixing phenomena among fresh shallow waters and brackish deep-seated waters. Refraction seismic data and seismic tomography highligted the first 50 m and revealed possibly tectonic disturbance at a depth of about 30-35 m. Topographic survey allowed to recognize ground deformations consisting of some steps generated along straight lines. Data collected about local earthquakes occurred in the study area should indicate a relation between seismic events and the anomalous behaviour observed in the geochemical parameters detected in the monitored wells. Thus a possible relation between all the observed phenomena and geodynamic factors, probably linked to actual evolution of the apenninic chain structural arc, can be inferred.

KEY WORDS: Po plain, Neotectonics, Seismicity, Groundwater geochemistry, Groundwater uprising, Gas emission structures.

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Nella pianura emiliana, in alcune zone a sud del Po, si vanno da tempo manifestando episodici e localizzati affossamenti della superficie del suolo a forma di cavità, larghi e profondi al massimo qualche metro. L'area rientra in una parte della Pianura ritenuta tettonicamente attiva come risulta dalla presenza di alcune faglie, rilevabili in superficie, già note in letteratura.

Per giungere alla conoscenza delle cause che stanno all'origine di questi fenomeni e dei meccanismi con cui si producono, negli anni 1996-1998 sono state effettuate ricerche variamente orientate con l'intento di potere 1) meglio conoscere i caratteri litologici, geotecnici e strutturali del sottosuolo nelle aree interessate, 2) scoprire la presenza di eventuali anomalie del piano di campagna significative di movimenti tettonici in atto, 3) precisare i caratteri chimici e geochimici delle acque di falda e studiarne il comportamento nel tempo. Inoltre sono stati raccolti dati sugli eventi sismici che hanno interessato la zona e quelle contermini nel triennio considerato.

Una rete di monitoraggio topografico di elevata precisione ha consentito di accertare che a partire dal 1997, dopo il terremoto del 15 ottobre 1996 verificatosi nell'area di Reggio Emilia, in almeno tre località sono comparse significative alterazioni nella morfologia del suolo manifestatesi nel primo caso con un gradino orientato N-S lungo una cinquantina di metri e dell'altezza di circa 5-15 cm, nel secondo con un piccolo cratere ed infine nel terzo con una frattura lunga 42 m ad andamento O-SO/E-NE.

Sulla base dei dati reperibili in letteratura e di ricerche dirette, condotte mediante trivellazioni e indagini geofisiche, si è potuta accertare la

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presenza nei primi 50 m di materiali per la quasi totalità fini (argille e limi) mentre al di sotto, a varie profondità, si ritrovano anche sedimenti sabbiosi e consistenti livelli torbosi.

Le sezioni ottenute con sismica a riflessione hanno messo chiaramente in evidenza delle zone nel sottosuolo, che si sviluppano su assi verticali, ove il segnale è disturbato con anomalie tipiche interpretabili come risalita di gas mentre nella sismica a rifrazione si sono individuate in profondità delle inversioni nei valori delle velocità significative di fenomeni dislocativi (con tutta probabilità piccole faglie o fratture). Tramite geofisica, con metodologia del tipo radar, infine si sono potute riconoscere numerose cavità subsuperficiali, non visibili all'esterno, interpretabili come potenziali luoghi di sprofondamento del terreno.

Osservazioni periodiche condotte, anche con cadenza settimanale, su 15 pozzi, consistenti in misurazioni della temperatura, del pH, Eh, conducibilità elettrica e in analisi della composizione delle acque, hanno mostrato che la quasi totalità delle acque di falda sono salmastre e che la loro composizione varia nel tempo così come sono state individuate brusche variazioni nei valori della conducibilità. Si è potuto dimostrare che tali modificazioni sono per lo più imputabili a intrusioni di acque salate che risalgono dal basso. Tali intrusioni sono state finora segnalate soltanto nei confronti di falde profonde artesiane mentre la presente ricerca ha dimostrato che questi fenomeni possono riguardare anche acque freatiche molto più superficiali e ciò rappresenta un'ulteriore conferma della esistenza nella copertura alluvionale di superfici di discontinuità prossime al piano di campagna. In quanto ai fattori in grado di innescare o agevolare la risalita di gas e acque salate, in alcuni casi sono state individuate possibili relazioni con l'attività sismica cui sono strettamente legate le deformazioni e l'evoluzione del fronte sepolto dell'arco appenninico.

Il gas che fuoriesce dalla superficie di campagna o che gorgoglia nelle acque di alcuni pozzi è risultato metano di origine sicuramente biogenica verosimilmente prodotto dagli orizzonti torbosi riconosciuti nel sottosuolo. In considerazione del carattere episodico ed esplosivo dell'attività esalante, si deve avanzare l'ipotesi che il gas salga lungo fratture o piccole faglie che si approssimano al piano campagna e che il gas fuoriesca solo dopo avere indebolito e vinto la resistenza del «cappello» formato dai terreni di natura pelitica sovrastanti. La presenza di crateri sta ad indicare che la pressione ed il flusso del gas sono elevati come è stato dimostrato per strutture analoghe riscontrate sui fondi marini e note col termine di «pockmarks».

PAROLE CHIAVE: Pianura Padana, Neotettonica, Sismicità, Geochimica delle acque sotterranee, Risalita di acque sotterranee, Strutture da emissioni di gas.

INTRODUCTION

Several Authors have reported on the neotectonic activity in the Po Valley (Gasperi & Pellegrini, 1968; Pellegrini & Vezzani,1978; Castaldini & *alii,* 1980). In particular, previous papers have reported evidence of possible surface faulting on the basis of stratigraphical correlations and height variations occurring along levelling lines. The purpose of our paper is to corroborate the previous findings by means of geochemical and geophysical data. In particular, geochemical and high resolution seismic prospections have been performed. The recorded data have been compared with local seismic activity and local meteorological data. Collapse phenomena observed in the ground have allowed us to focus our attention on some areas of the Po Valley (figs. 1, 2). In some of these, a gas outflow was episodically observed coinciding precisely with the ground-collapse points.

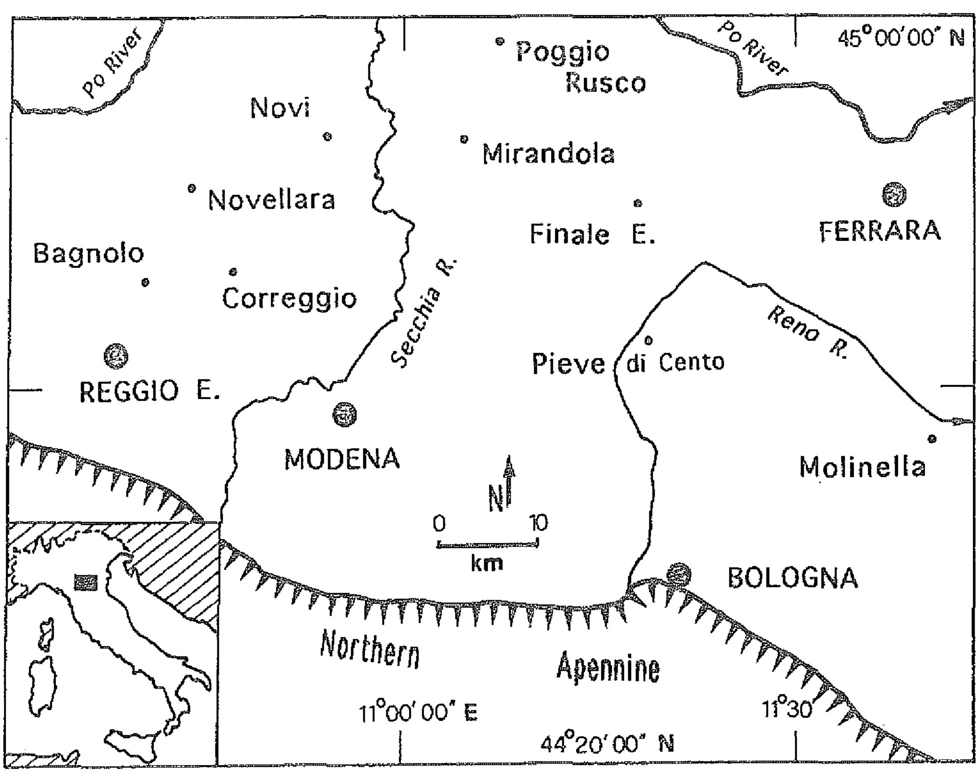
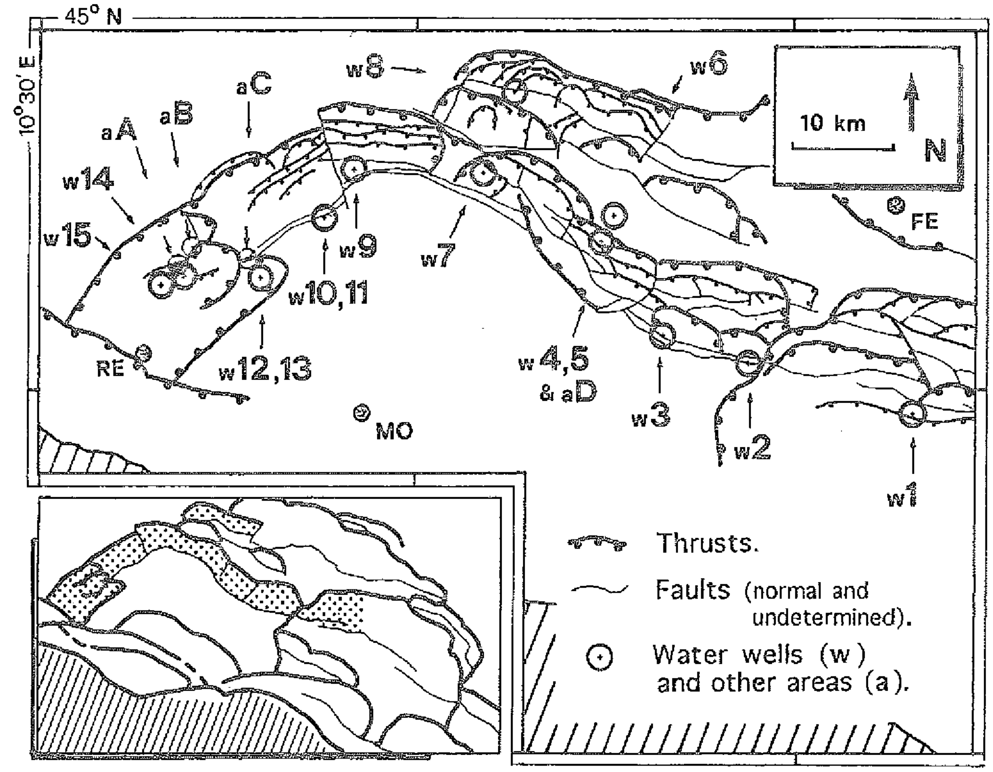


FIG. 1 - Location of the study area.

FIG. 2 - Structural sketch of the buried Apenninic external front (*Dorsale Ferrarese*) and location of the monitored water wells (w) and areas (a) selected for geophysical and topographycal surveys.



GEOLOGICAL SETTING

The explored area is located in the Emilia-Romagna Region occupying the southernmost part of the Po Valley and is bounded by the Northern Apennines to the south and the Adriatic Sea to the east. The Po Valley was a subsident basin during the Neogene and is still subsiding. The uppermost part of the Quaternary sediments belong to a continental environment in which gravels correspond to the Apenninic alluvial fans and sandy-clay layers were generated by the interaction among the Po river sediments and the Apenninic derived ones. All these terrains lie on a pre-Holocene substratum consisting of gently folded and faulted impermeable marine formations, of Calabrian-Pliocene age, which covers Oligo-Miocene sandstones and Mesozoic limestones belonging to the «Tuscan» nappe (E.N.I., 1959).

The subsurface Pliocene and older sequences in the Po Valley evidence three main folded arcs from west to east: the Monferrato, the Emilia arc and the Ferrara-Romagna arc. The Ferrara folds represent the outermost part of the arc and consist of the structural unit known as «Dorsale Ferrarese» which was involved in a strong tectonic phase during late Pliocene and Pleistocene. Structures very similar to the Ferrara one are located at Cavone and Bagnolo in Piano (Pieri & Groppi, 1981; Castellarin & *alii*, 1985; CNR, 1990). A compressive regional style was recognized (Frepoli & Amato, 1997; Montone & *alii*, 1997, 1999). Signs of neotectonic activity are visible at the top of the mentioned buried structural heights and in particular in the hinterlands of Reggio Emilia, Modena and Ferrara (Gasperi & Pellegrini, 1981).

The large-scale clay-sandy alternances of the Po Valley are believed to be due to alternated climatic conditions (RER & ENI-AGIP, 1998), while local alternances are attributable, as mentioned before, to the role of fluvial sedimentation.

EXPERIMENTAL DATA

Geochemical sampling strategy

Thirteen wells characterized by depths up to 15 m were selected in the outlying areas of Reggio Emilia, Modena and Ferrara affected by neotectonic processes. Further checks were carried out in two wells (W8, W11) characterized by depths of 25 and 70 m respectively (tab.1). W7 and W8 were characterized by methane bubbling. All the wells are located in areas where the Quaternary terrains overlay the tectonic heights belonging to the previously described folded arcs whose tops are buried in the depth range of 100-500 m from field surface.

An average distance between the various wells is about 10 Km and they are distributed as depicted in fig. 2.

TABLE 1

Wells	*Name*	*Depth (m)*
W 1	Alberino	7.86
W 2	Cenacchio	5.46
W 3	Pieve di Cento	13.92
W 4	Natali	10.97
W 5	Bregoli	11.40
W 6	Accorsi	5.95
W 7	Mirandola	10.62
W 8	Falconiera	25
W 9	Novi	7.25
W10	Fossoli	7.12
W11	Fossoli artesiano	70
W12	Correggio 4 vie	7.59
W13	Correggio Astrologo	10.51
W14	Pieve Rossa	5.69
W15	Bagnolo	3.1

Weekly sampling was carried out in all the wells to monitor temperature, pH, Eh and electrical conductivity. Weekly sampling and chemical analysis were carried out in W3 and W6. The water sampled in W2, W7, W8, W9, W10, W11, W12, W13, W14, W15 was analyzed three times in the period 1997-1998. Water sampled in W1 was analyzed five times in the period 1997-1998. Water sampled in W4 and W5 was analyzed eight times in the period 1997-1998. A multiparametric station was placed in W4.

The depth of the water table ranged from 2 to 7 m below ground level.

Analytical methods

Temperature, pH, Eh and electrical conductivity (at 25°C) were measured in the field at all the sampling points. Total chemical analysis was carried out at a different rate in the wells studied. Ca and Mg were determined by EDTA titration. Na and K were determined by AASF. Anions were determined by titration.

Electrical conductivity was about 1500-3500 µS/cm, but some detected spikes or high constant trends reached the value of 6000 µS/cm. In W8 electrical conductivity maintained nearly 10800 µS/cm. Water temperatures were in the 12-15°C range.

Geochemical characterization of sampled waters

Water chemical data were plotted on a Piper plot (fig. 3). Three main families were identified, while mixed derived groundwaters have also been recognized. In particular, samples from W2, W11, W12, W15 belong to the Ca-HCO_3 family, while sample from W8 belongs to the Na-Cl family and samples W3, W6, W9, W13 to the Ca-Mg-SO_4, while the other samples can be considered a result of different degrees of mixing.

Shoeller plots (fig. 4) show the chemical composition trend during the monitoring time.

Sharp increases in electric conductivity (fig. 5) suggest a possible uprising of brackish waters followed by mixing phenomena. Mixing processes in many cases probably develop in non-conservative conditions as occurs in fine-grained sediments which act as exchange media during the water-rock interactions. In fact, particularly in W1, W4, W5, W7, W8 and W12, a reduction in Na concentration and at the same time an increase in Ca content were recorded as shown in fig. 6, where the differences (DNa and DCa) between theoretical and actual Na and Ca concentrations assume negative and positive values respectively, whereas zero indicates conservative conditions (Appelo & Postma, 1994).

Isotopic carbon patterns in CH_4 (delta C13 = −78) and in CO_2 (delta C13 = −15; −24) bubbling gases (as determined by mass-spectrometry evaluations) indicate a low equilibrium temperature (Giggenbach, 1982) consistent with an original gas depth of 500-1000 m. Escaping gas may compel the brackish water to reach more surficial levels.

Possible anomalies detected in groundwater chemical behaviour vs. time at some wells cannot be attributed to meteorologically-induced changes in recharge conditions as no relations between meteoclimatic parameters and chemical anomalies were unambiguously evidenced upon inspecting all the available data sets (fig. 7). Furthermore analysis performed on the data set recorded by the multiparametric station at W4 did not highlight any possible relations between water withdrawal and electrical conductivity changes, excluding human-induced causes. Thus, geodynamic causes could be responsible for some geochemical anomalies possibly linked to the neotectonic phenomena observed on the ground surface.

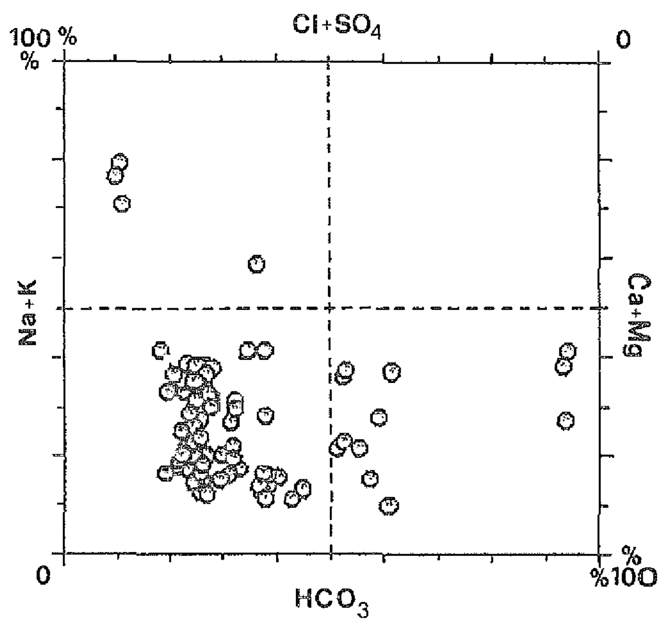
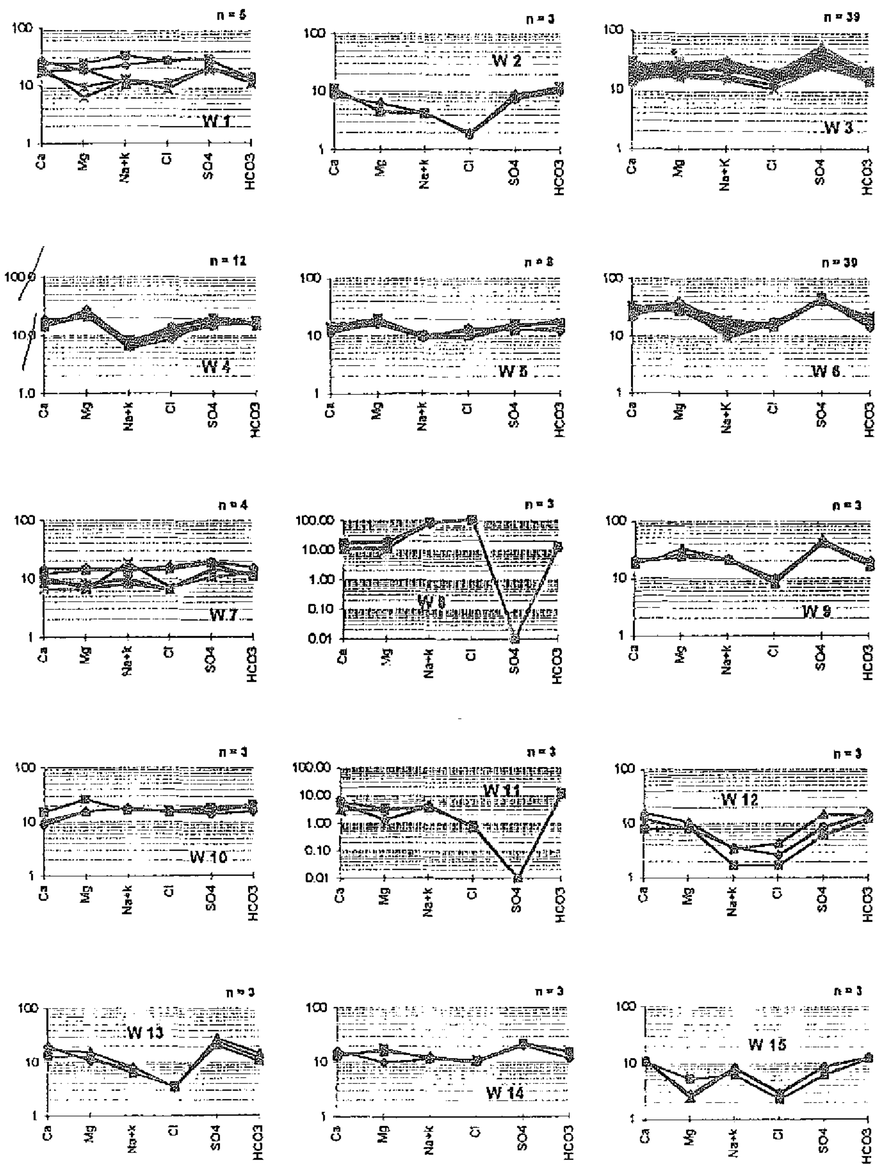


FIG. 3 - Square Piper plot.

FIG. 4 - Shoeller plots showing chemical composition of all water wells (n = sampling number during monitoring time).



Geophysical survey

Ground collapse phenomena were detectable close to W4 (figs. 8, 9), where more than 100 pockmark depressions (5 to 120 cm in diameter and in the 1-5 m range in depth) were observed. In many cases their features show a reverse funnel, bell or fissure-shaped morphology. A rough orientation of pockmarks along a SW-NE axis is also slightly recognizable. The hollows particularly appear in fruit-tree growing areas (and rarely in the ploughed terrains) and are phreatic-water free. Their position is locally slightly changeable over a few years but the area of appearance is always the same over a decade or longer.

A high-resolution seismic survey was carried out (fig. 10) in order to better constrain the geologic and seismotectonic causes of these phenomena. Seismic survey data were compared with the data from a GPR survey and a geoelectrical survey.

Data obtained from locally available stratigraphic logs and a short borehole effected using a hand-tool and a stat-

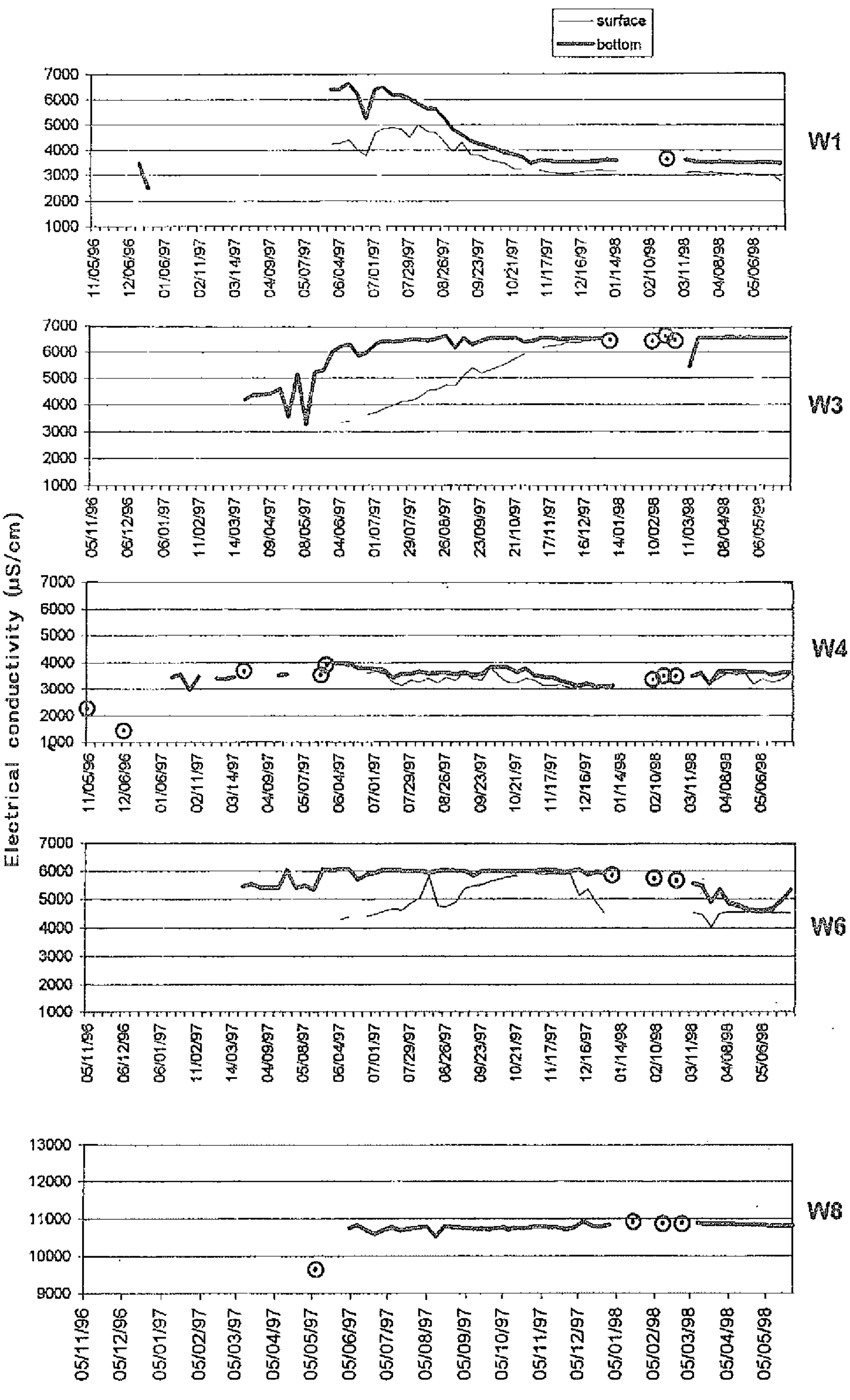


FIG. 5 - Variations in the electric conductivity of surface and bottom waters registered at some selected wells (W1,W3,W4,W6,W8). Single, isolated values are marked by circles.

ic penetration test both located near some ground-collapse points and the W4 well were also utilized. The stratigraphic log from the borehole highlighted the following terrain succession: locally sandy, silty clays (0.00-2.00 m); silty clays and blue clays (2.00-3.90 m); alternated clays and silty grey-blue clays (3.90-4.65 m); clays and grey silty clays (4.65-5.30); grey-blue and blackish clays (5.30-7.45). The penetration diagram is reported in fig.11.

The data obtained by the geoelectrical survey indicate the presence of silty clays and locally sandy clays up to a

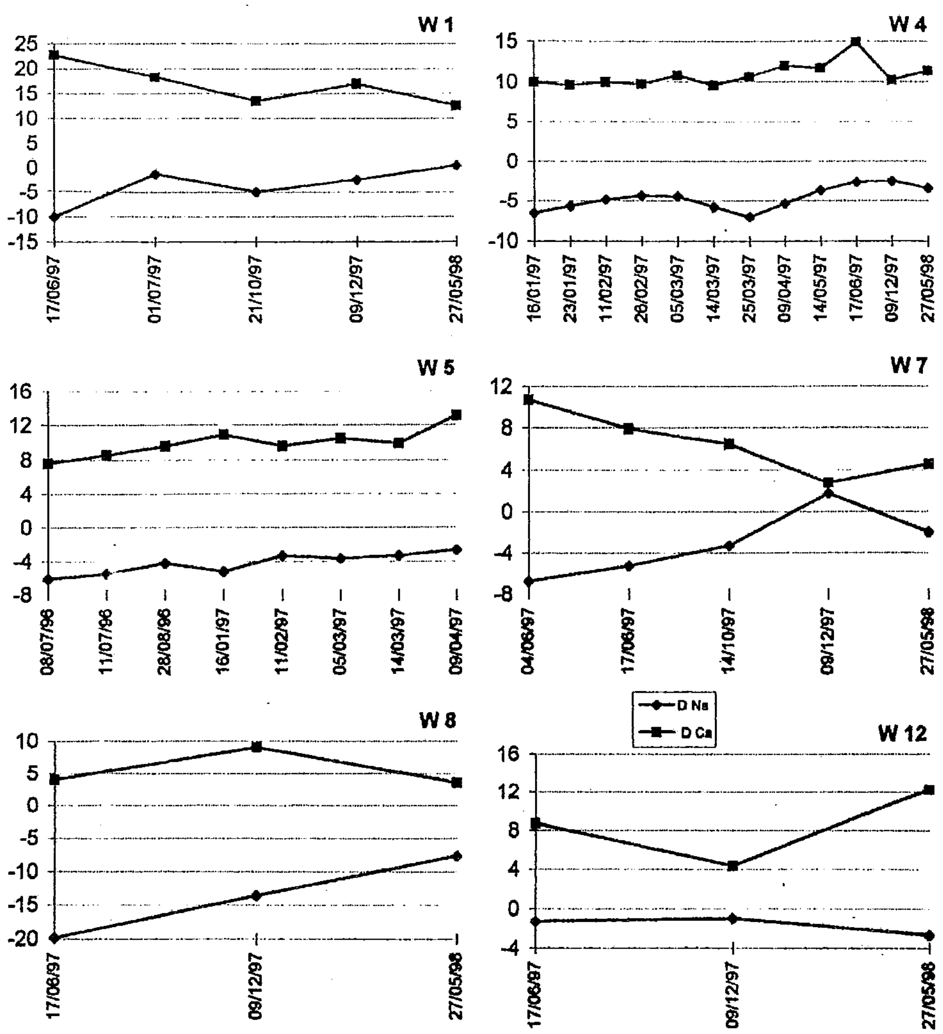


FIG. 6 - Negative and positive values of the differences between theoretical and actual concentrations of Na (DNa) and Ca (DCa) respectively, showing a non-conservative mixture between uprising brackish waters and fresh shallow waters (wells: W1,W4, W5,W7,W8,W12).

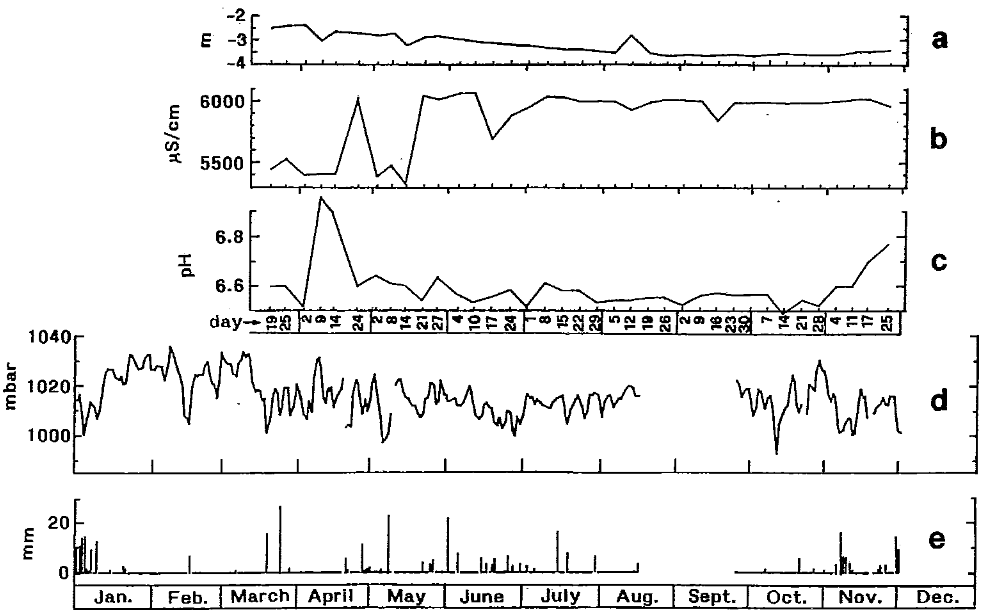


FIG. 7 - Trend of water table level (a), electric conductivity (b) and pH (c) in well W6 compared to atmospheric pressure (d) and rainfall (e) (Finale Emilia meteorological station). No correlations are observed between meteoclimatic parameters and the behaviour of the water well.

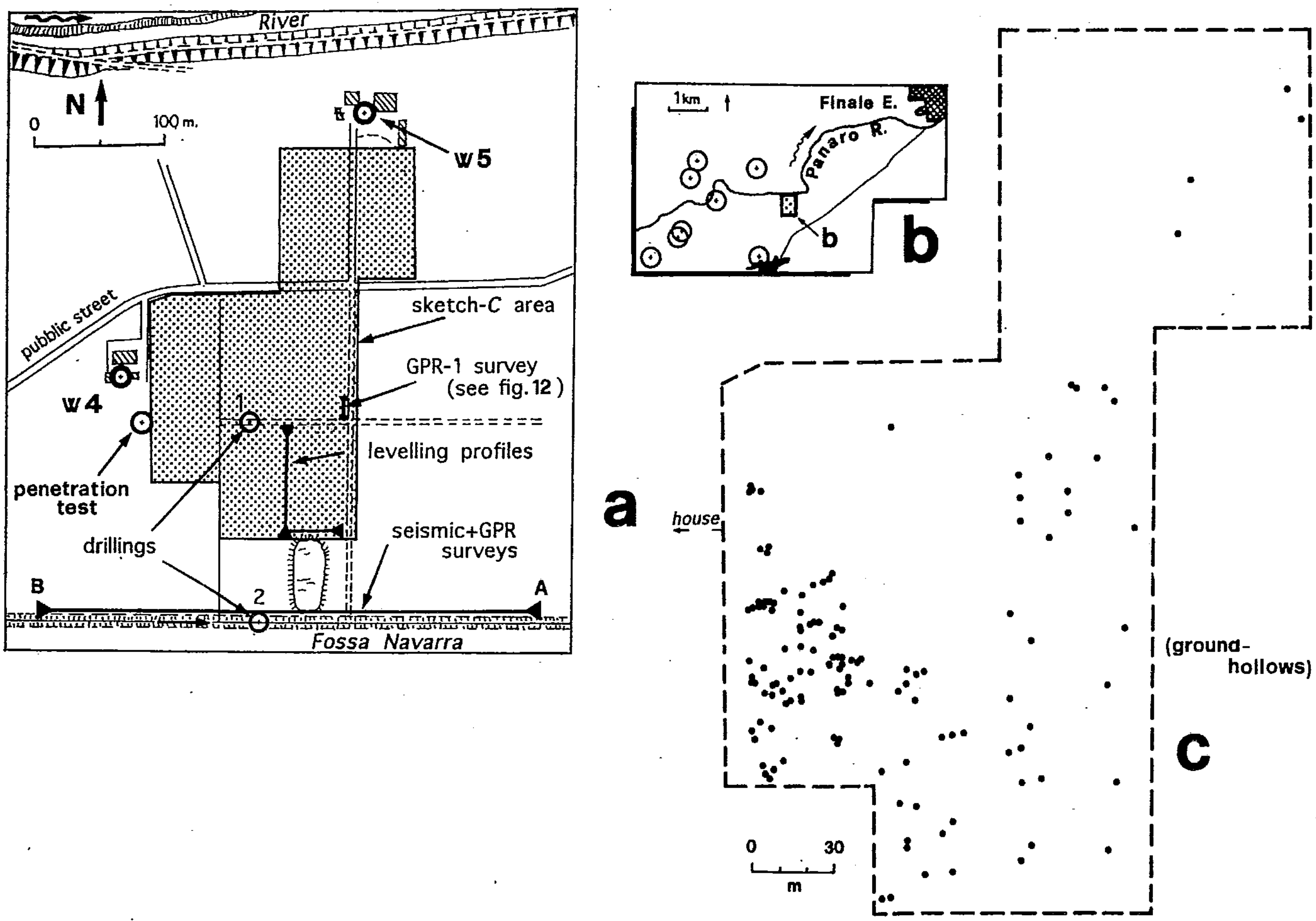


FIG. 8 - Various kinds of performed surveys (a). Areas near Finale Emilia characterized by clusters of ground-collapse points (b) and their scattering in the W4,W5 subarea (c).

depth more than 150 m with sand and gravels in the 96 m-150 m range.

Reflection seismic data were acquired by an ES-240, EG&G seismometer equipped with 12 vertical geophones characterized by a proper frequency of 14 Hz. Energy sources were a hammer and an explosive source (mini-bang). Data were processed by mean of the SEISTRIX 3, Interpex Limited Gold software (Quadri, 1997-98). This data set evidences the existence of a prevailing clayey-sandy sequence up to 140-160 m. Layers located in the 160 m-300 m depth-range are characterized by a wider spatial regularity than the upper ones. Seismic signals appear to be disturbed in the proximity of some vertical axes (fig. 10) probably related to gas uprisings. Indeed, a marked peat occurrence at a depth of 150 m-200 m and gas pockets detected at about 300 m in depth were already known of (AGIP, 1994: well Bevilacqua 1).

GPR soundings revealed the phreatic water table at a 3.5 m in depth and the existence of further hollows not visible at ground surface (fig. 12).

Refraction seismic data and seismic tomography highligted the first 50 m and revealed the existence of inversions in the normal sequence of velocity values showing possibly tectonic disturbances at a depth of about 30 m-35 m (fig. 13). Such tectonic disturbances could be considered responsible for the gas expulsion phenomena observed in the hole-affected area and in some local groundwaters. Their features allow us to tentatively interpret the ground-observed phenomena as pockmarks (Curzi & Veggiani, 1985; Hovland & Judd, 1988).

Topographic survey

The studied area is affected by a subsidence rate of 2.5-3.0 mm/year (IDROSER, 1978; Arca & Beretta, 1985). Subsidence, typical of the great natural basins (Ronayi, 1965; Arca & Beretta 1985; Bondesan & *alii,* 1997; Carminati & Di Donato, 1999), is due to natural causes and to some possibly artificial ones like groundwater withdrawal, gas and oil extraction, etc.

FIG. 9 - Some different kinds of ground-collapse points near Finale Emilia. The example in the upper right hand side is located in the area of fig. 8c.

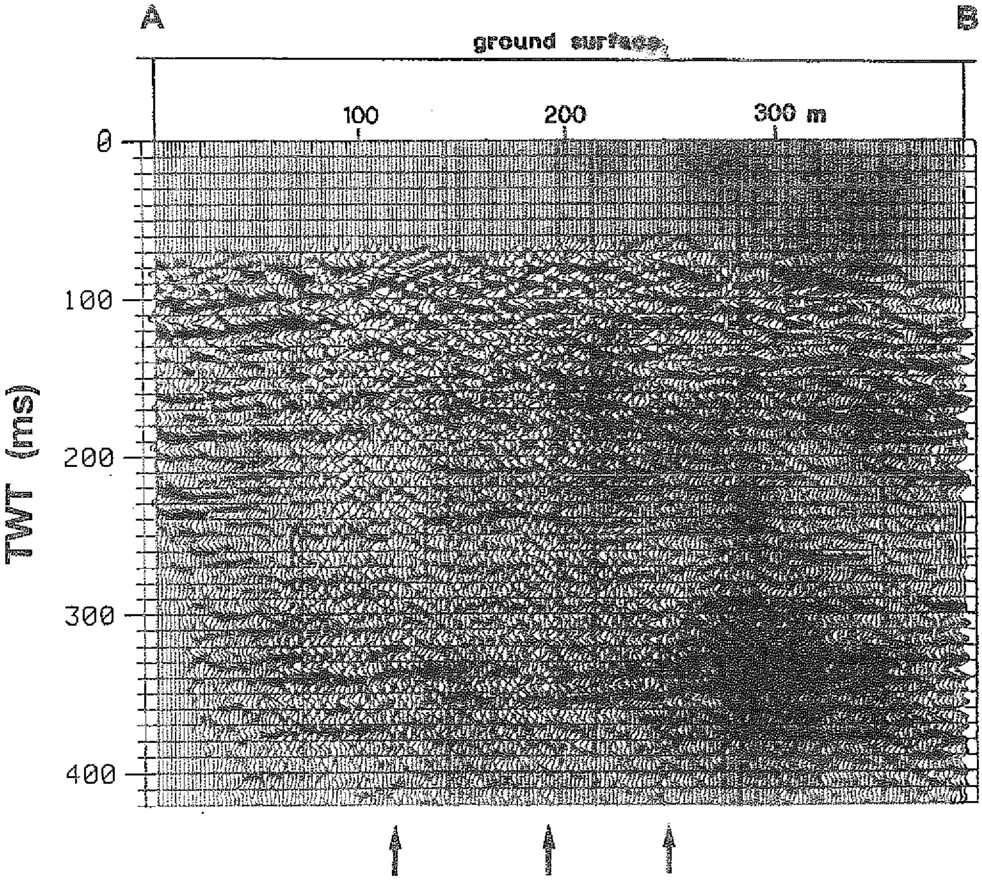


FIG. 10 - Reflection seismic profile (E-W) near W4 (location in fig. 8). Arrows indicate columnar disturbance of seismic reflections typical of upward gas migration.

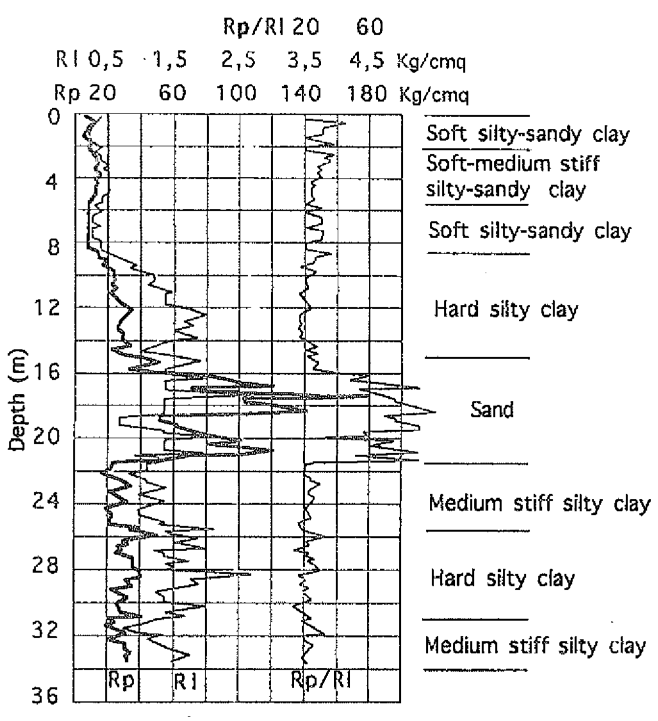


FIG. 11 - Penetration diagram (near W4, location in fig. 8) and soil classification, according to Searle, based on Rp/Rl ratio.

In some selected areas (fig. 2: aA, aB, aC, aD), indicated by local inhabitants as being highly subsiding ones, four distinct topographic surveys were carried out. Topographic transects were identified and surveyed in each of those test-areas. Recorded data are shown in figs. 14-18. The measurements highlighted rates of 50-100 mm/year in small areas characterized by local central subsidence. These morphological elements are almost cup-shaped (up to about 40 m in diameter) or fissure-shaped and are surrounded by disjunctive phenomena (circular, elliptical as in fig. 9) visible in the ground all around. In particular, in the area aC ground deformation consists of a 5-15 cm high step generated along a straight line S-N directed (fig. 15) with a lowering of the western limb, while in aA a 42 m long open fracture (fig. 17) shows a changeable width of up to 81 mm.

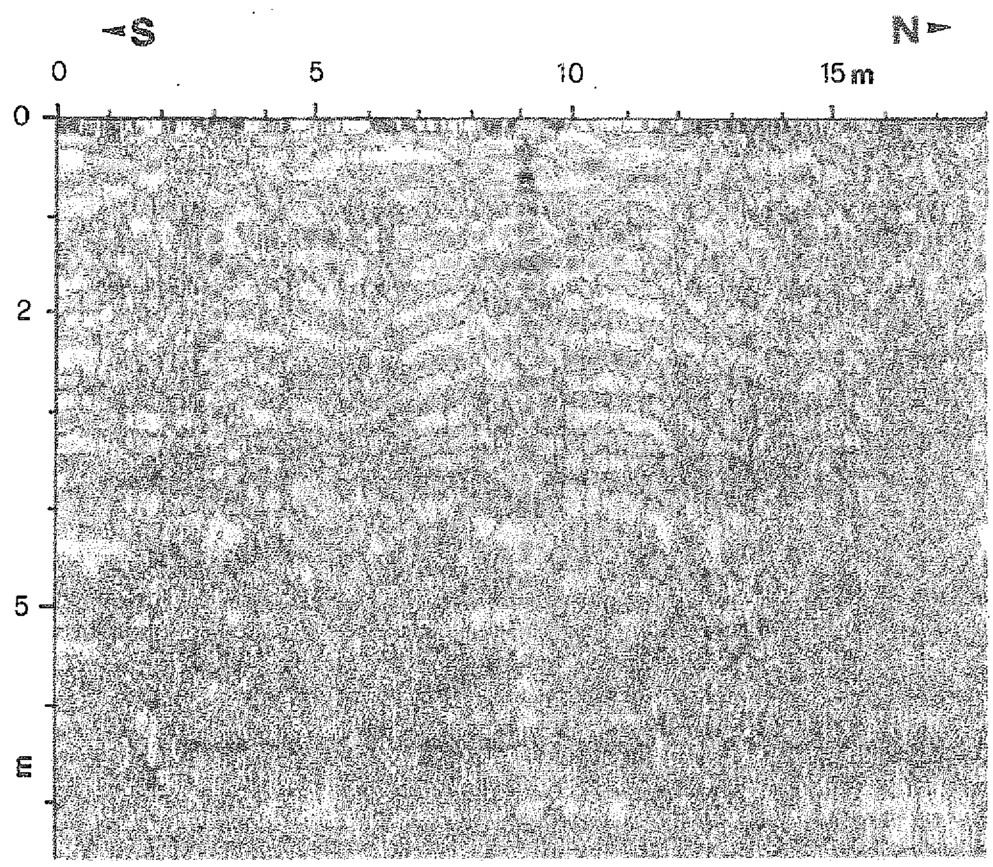
A possible correlation between these phenomena and local seismic event frequency is suggested by fig. 19.

DATA ANALYSIS

Active faulting and pockmarks

Active faulting has been widely observed in other alluvial plains of the world (e.g.: Ronay, 1965). Methane escape phenomena in the Po Valley have been widely report-

FIG. 12 - GPR cross-section near well W4 and ground-collapse points (location in fig. 8). The vertical disturbances located at 3 m, 9 m and 18 m along the distance axis, suggest the presence of subsurface hollows able to generate ground-collapses.



ed in the past (Pantanelli, 1910; Scicli, 1937). In spite of the ample literature available on hydrocarbon occurrence in the Po Valley, no definitive or unambiguous proofs had been obtained about possible correlations with active tectonic and gas escape phenomena. Nevertheless, some inferences can be made.

In fact, preferential pathways for gas escape have been recognized in marine environments like the North Sea, the Adriatic Sea, etc. (Hovland & Judd, 1988; Curzi & Judd, 1998). Such gas escapes are interpreted as pockmarks in the Adriatic Sea (Curzi & Veggiani, 1985). Granted that the Po Valley, characterized by a low compaction degree,

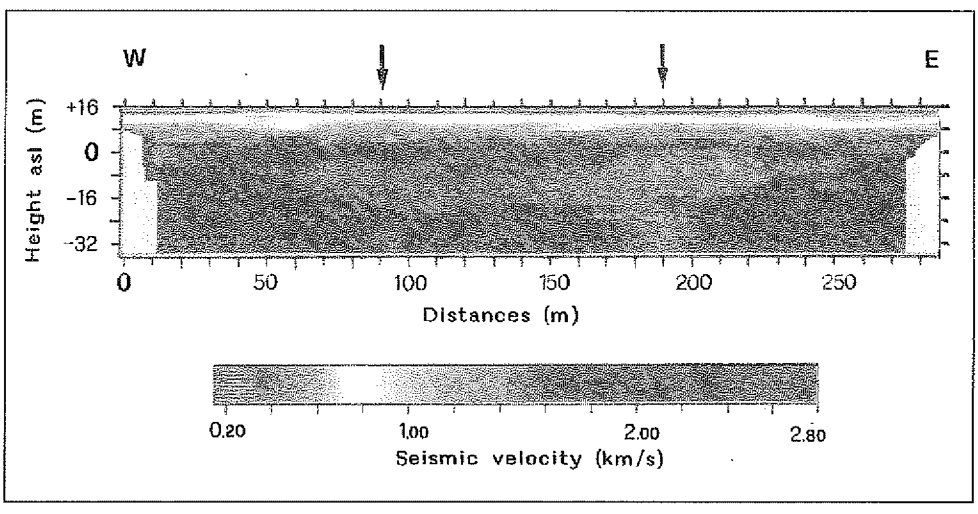


FIG. 13 - Refraction seismostratigrafic section near W4 (location in fig. 8). The velocity anomalies that appear in the range 80 - 100 m and 180-200 m along the distance axis can be ascribed to tectonic disturbances.

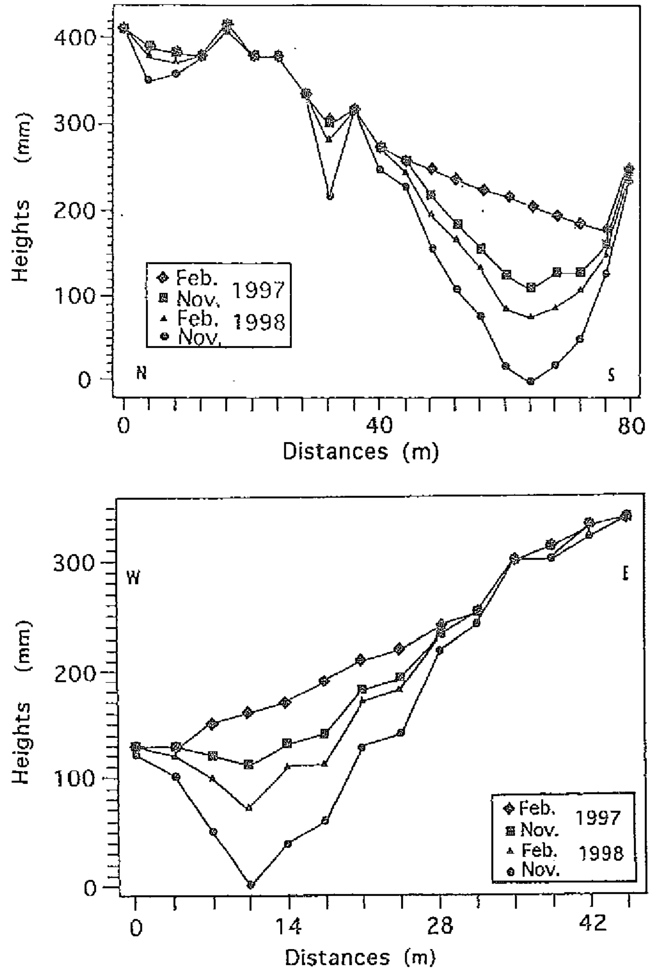


FIG. 14 - Levelling profiles in the area aD (Finale Emilia, location in fig. 8).

is not affected by significant geological differences when compared to the Adriatic Sea, then the existence of subaerial pockmark-featured structures can also be justified in the Po Valley. Furthermore, Stefanon & *alii,* (1981) inferred a possible link between seismicity and pockmarks. Obviously, during gas escapes groundwater mixing phenomena can also occur.

Geophysical and geochemical prospections, carried out in the selected area of the Po Valley studied here, evidenced tectonic disturbances capable of allowing gas escaping. Their evidence is not yet complete since the geophysical data only allow for a preliminary description of the observed phenomena. The observed gas escapes and the existence of brackish waters grazing the ground surface allow us to interpret these phenomena as ground effects of the pockmark-featured structures. This model is not in contrast with the alternative one which considers the existence and action of active faults alone. Since ground effects seem to follow a SW-NE and NW-SE orientation (fig. 8) the existence of a faulted pockmark-generating area can be surmised.

Local seismicity and geochemically recorded signals

In 1997 (i.e. the longest monitoring period) about 100 local earthquakes (85 % of which clustered in the Bagnolo area, close to W14) occurred in the study area (fig. 20). The data used in this study are the results of an integration of arrival times recorded by the Italian Telemetered Seismic Network (Barba & *alii,* 1995) and a local network maintained by the Italian Petroleum Agency (AGIP).

Since magnitudes (M) are in the 1-3.0 range, only seismic events occurring at a distance <15 km from the monitored wells can be considered as potential anomaly-generators of geochemical parameters (Dobrovolsky & *alii,* 1979). In particular, a small cluster of low-magnitude seis-

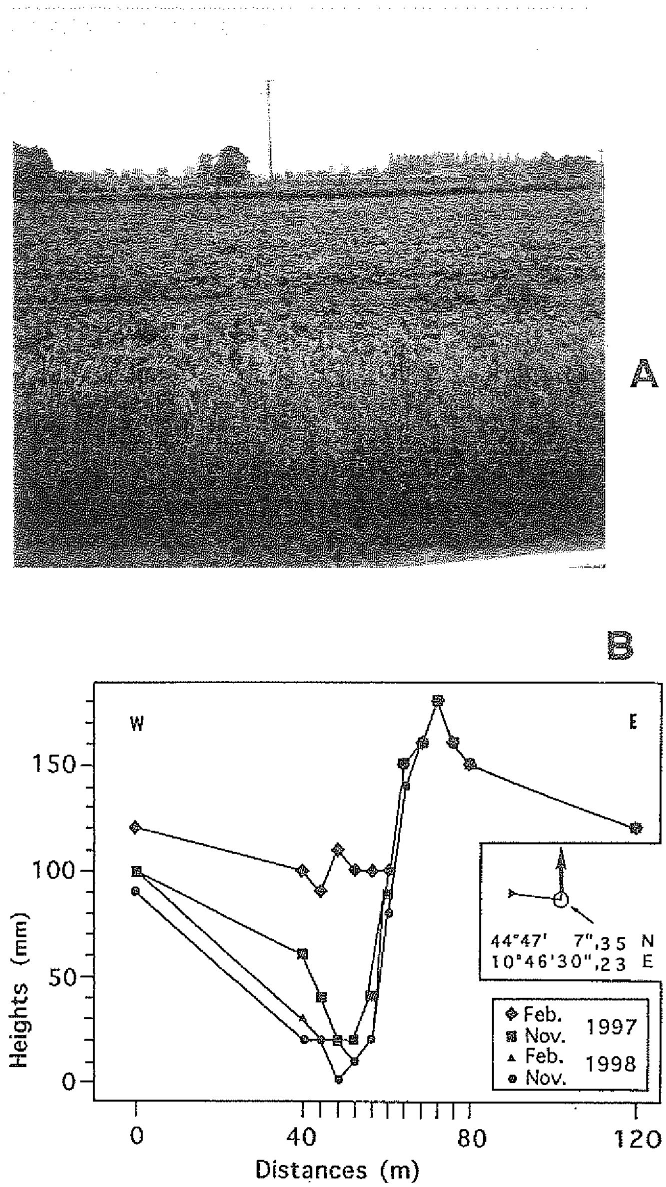


FIG. 15 - View of the ground step oriented along a S-N straight line in the area aC near Correggio (A) with the western side lowered compared to the eastern one as in the levelling profile (B).

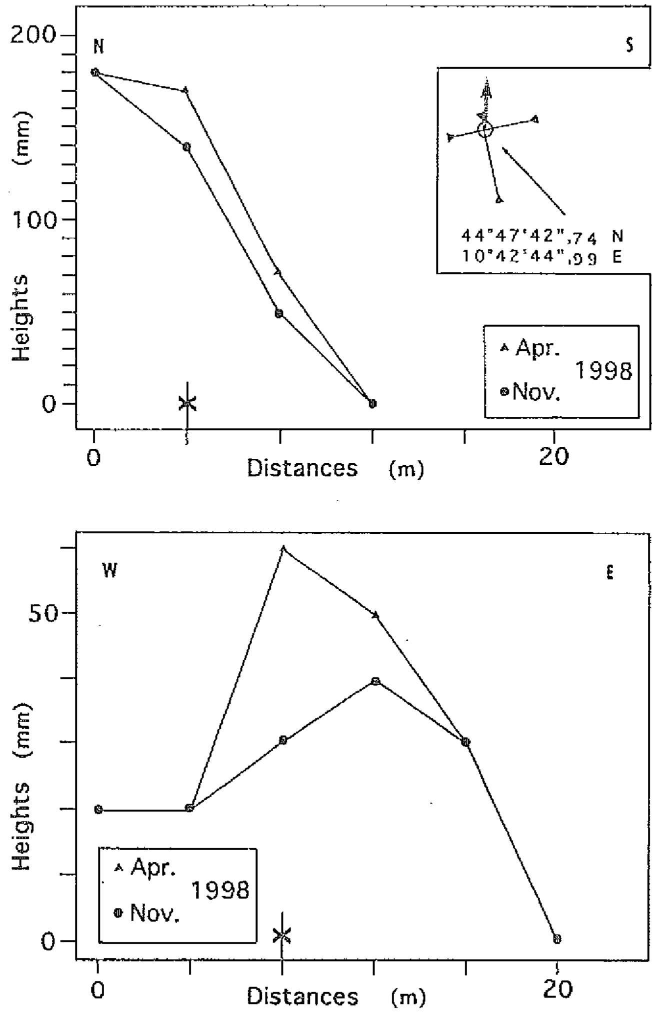


FIG. 16 - Right-angle levelling profiles across a subsiding, circumscribed area near Novellara (aB).

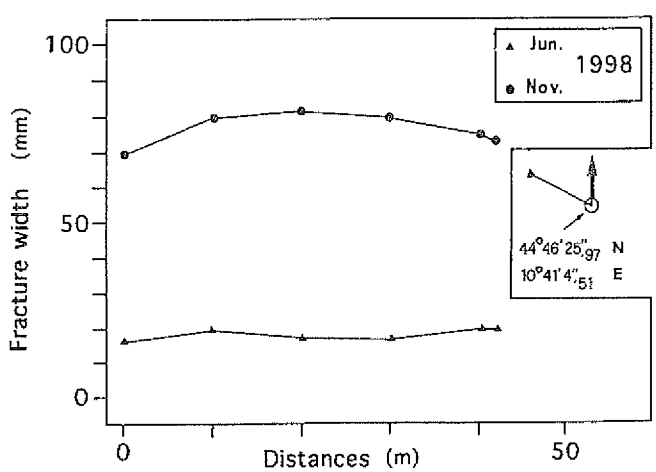


FIG. 17 - Progressive widening of the open ground-fracture in the area aA near Bagnolo (see fig. 18).

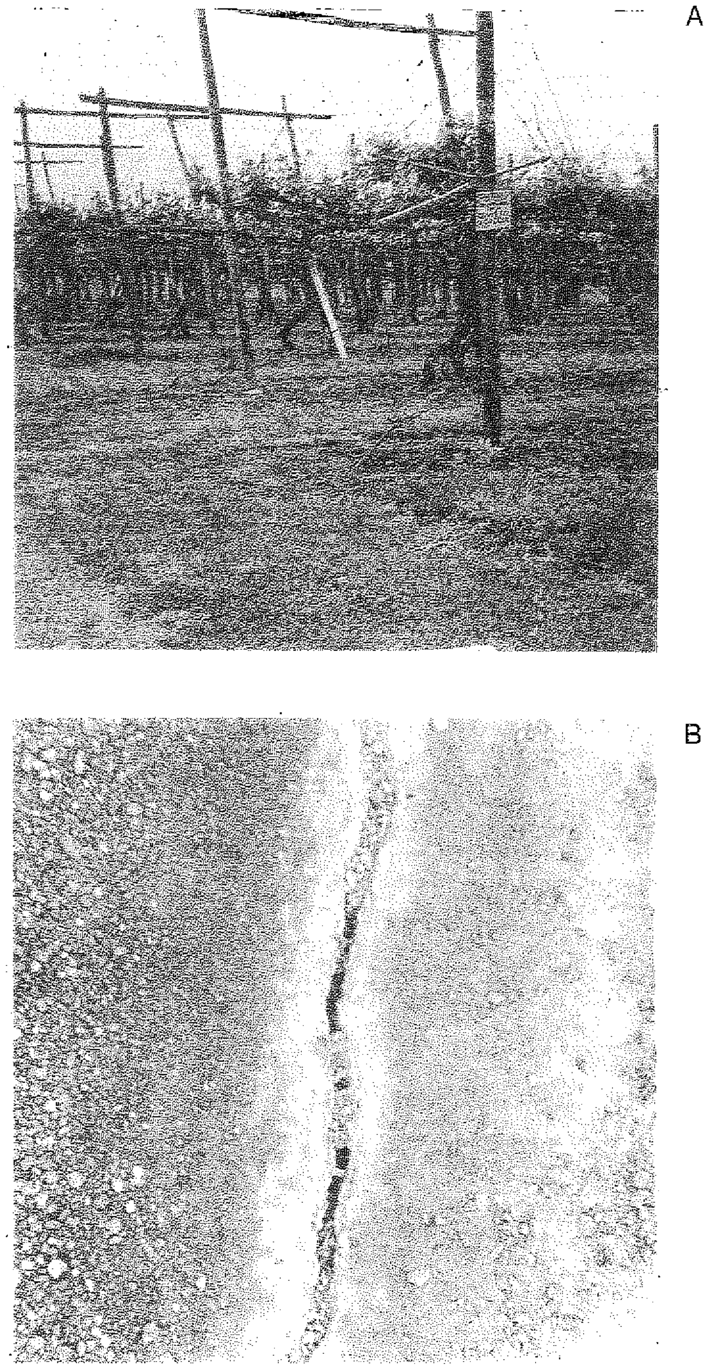


FIG. 18 - A: view of the subsiding area near Novellara surveyed as in fig. 16. B: detail of the ground-fracture in the area aA, Bagnolo.

mic events occurring 8-12 km north of W6 (event 1: August 15, 8 km NNE, M = 2.5, depth = 9.7 km; event 2: August 15, 11 km NNW, M = 2.5, depth = 8.5 km; event 3: August 19, 12 km N, M = 3, depth = 5 km) could be linked to an increasing water concentration recorded in this well. Here a total ion concentration spike of 176 meq/l was detected on August 19 vs. a mean value of about 160

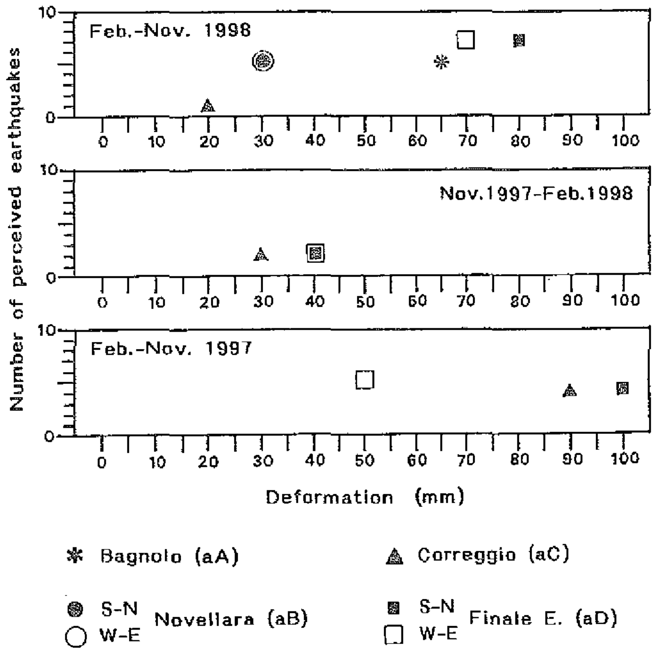


FIG. 19 - Quakes not only monitored but also clearly noticed by the inhabitants in the areas aA, aB, aC and aD with indications of the two components (S-N, W-E) when measured. In the horizontal axis are reported the values of the ground-surface deformations described in figs. 14-18.

meq/l (fig. 21). Indeed, tectonic pumping phenomena could be easily induced by local stress field changes (Sibson,1981). Furthermore, the above-mentioned seismic event cluster could be responsible for an increase in the total number of ground hollows in the field near W4.

Di Giovambattista and Tyupkin (1996, submitted) have identified stress-field migration phenomena in the Apennine belt. In particular, fig. 20 shows that earthquakes occurring in the mountain area are followed by ones occurring in the plain area, northern of Correggio, thus identifying a zone of possible stress-transfer (Montone & *alii*,1997) highly suspected of affecting the behaviour of the monitored belt-line. While fluctuations in the local seismic rate have been recognized to strongly affect the piezometric levels in deep wells of the Po plain (Albarello & Martinelli,1994), none of the listed seismic events seems capable of potentially affecting the observed well water levels due to the small size of the associated crustal deformation radius (Dobrovolsky & *alii*,1979). Nevertheless during the period September 16-December 16, 1997 a water-table lowering was observed at W7 (fig. 22) and at W13 of about 2 m and 0.40 m, respectively.

W3 and W6 showed contemporaneous long-term geochemical behaviours in the period April 9-June 10 1997 (fig. 21) characterized by an electrical conductivity increase and short-term transient phenomena, i.e. sharp and synchronous electrical conductivity decreases also recorded in W1, W14 (fig. 5) and others. W3 and W6 are about 14 km apart and catch phreatic waters from different superficial acquifers (Castaldini & Raimondi, 1985; Cremonini, 1987, 1989). The observed anomalies should indicate mixing phenomena among fresh shallow waters and brackish deep-seated waters. Spike-like anomalies recorded in the pH values (fig. 23) could indicate the existence of bubbling gases rising upwards, as local inhabitants have often directly observed.

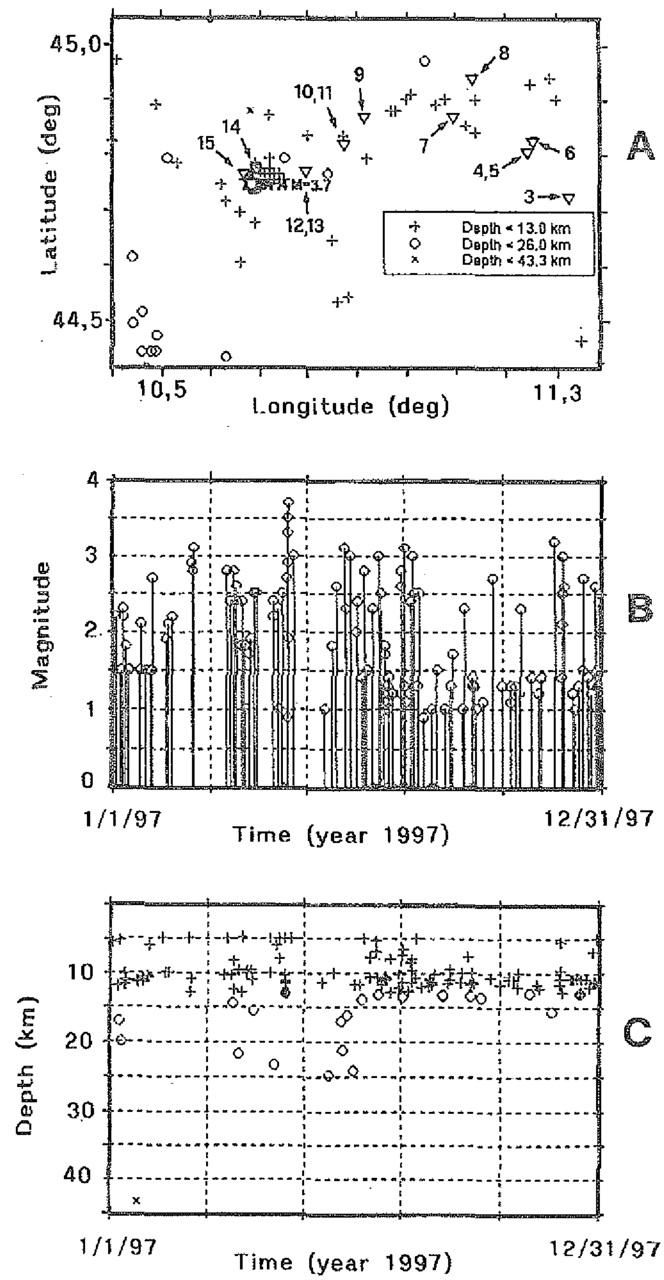


FIG. 20 - A: map showing the locations of the epicenters (circles) and the locations of the monitored water-wells (black triangles); B: the plot of the magnitude distribution as a function of time; C: the plot of the depth distribution as a function of time.

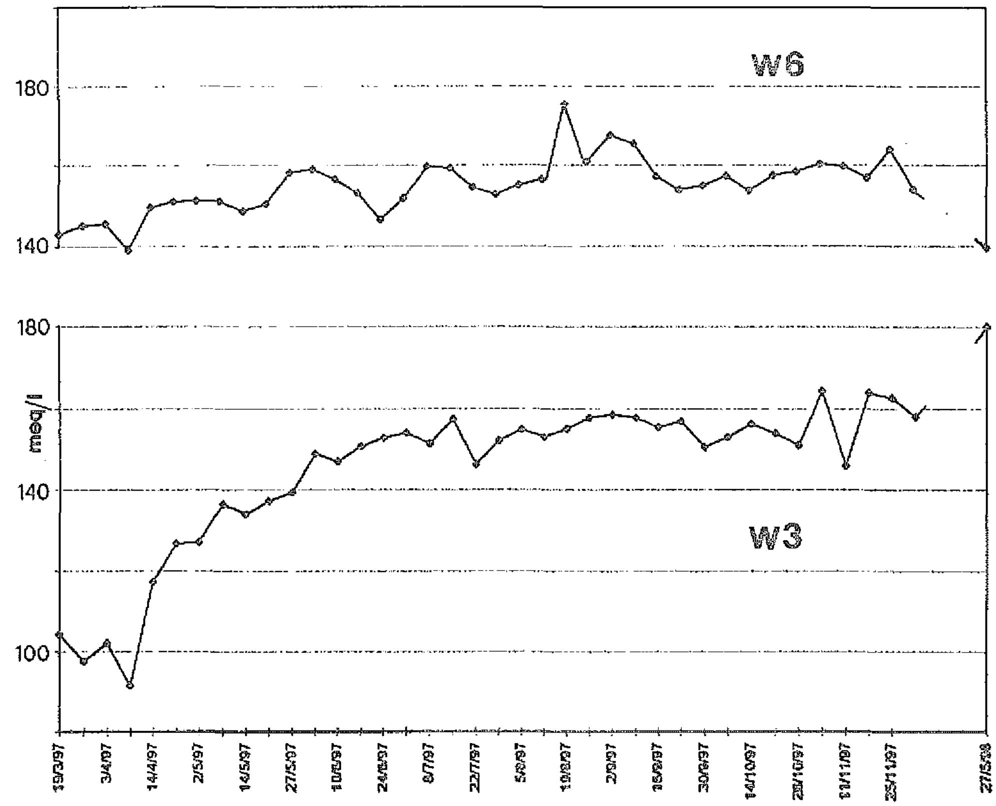


FIG. 21 - Total ionic concentration increases recorded at wells W6 and W3 (ions: Ca, Mg, Na, K, Cl, SO_4, HCO_3).

Since the contemporaneous behaviour of the parameters monitored in both these wells (figs. 21-23) cannot be related to meteorological causes (fig. 7), other factors can be considered to account for the observed phenomena. In particular, anthropic noise can be ruled out due to the low local withdrawal of waters for industrial and agricultural purposes (IDROSER, 1978). Thus a geodynamic origin can only be inferred for the observed signals.

During the observed period the seismic frequency in the broad area of fig. 20 (including the Apenninic core) was relatively constant: about 10 seismic events/month ($M < 3$) with a maximum up to 17-20 evs./month in July-

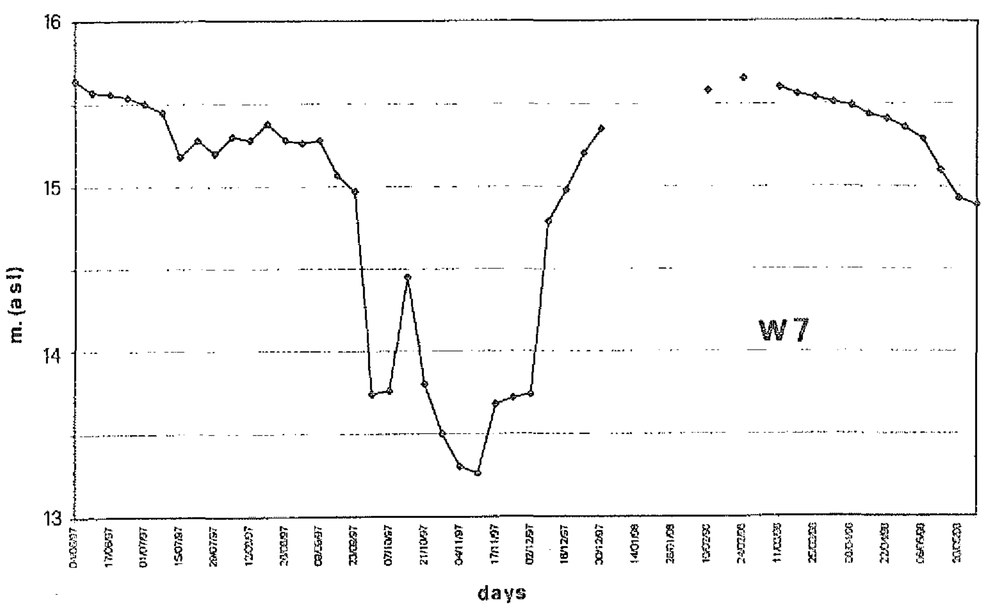
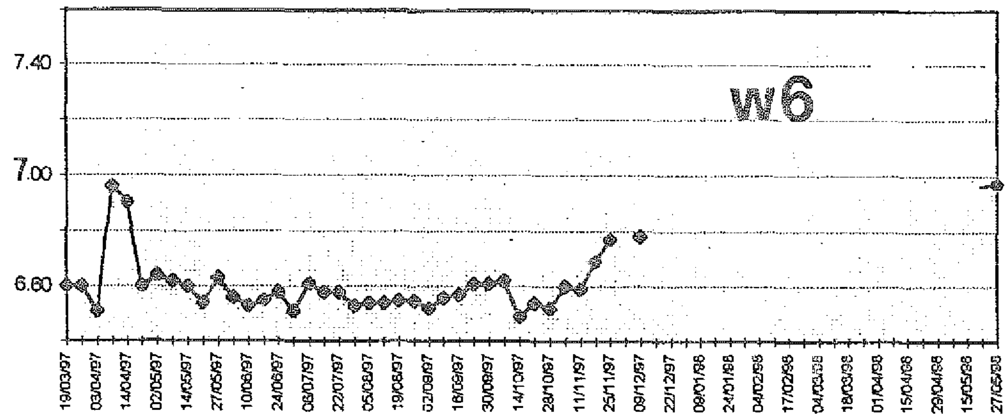


FIG. 22 - Water-table lowering observed at well W7 (Mirandola) about between September 16 and December 16, 1997. Heights in meters above sea-level.



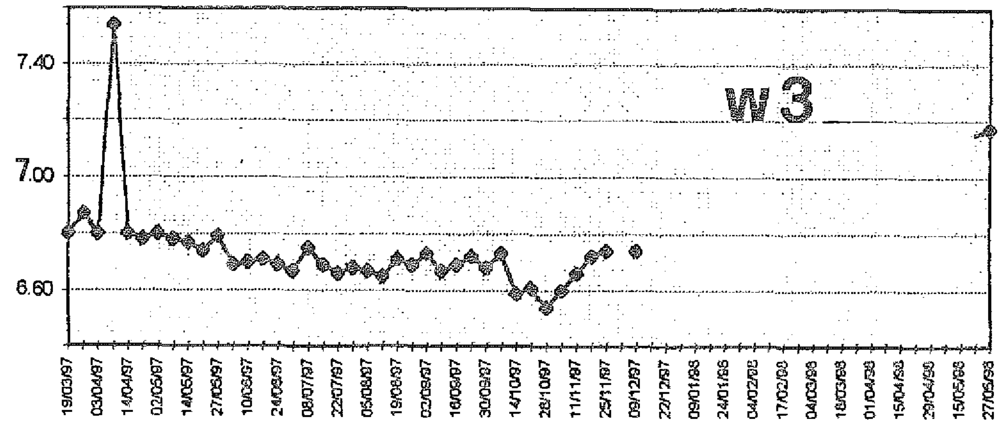


FIG. 23 - Anomalous spike in the value of pH in April,1997 probably indicating upward migration of bubbling gases. Note the similarity in the value trend in the W3 and W6 wells.

August 1997. In the meanwhile, a deepening of the hypocentral depth of some earthquakes was observed in the period April- June. In the subsequent period June-December 1997 the shallowest and deepest earthquakes disappeared and seismic activity was concentrated in the intermediate layer located at 9-13 km in depth. Ranalli & Murphy (1987) reviewed some rheological stratification processes occurring in the lithospere. Hypocentral layering can be tentatively ascribed to the Earth's rheological layering properties observed at the plate boundaries. Thus, the anomalous behaviour observed in the geochemical parameters detected in the monitored wells can be related to the observed fluctuations of the ductile/brittle boundary recorded in the monitored area by seismic event plotting. Connate waters occurring in the northern apenninic belt have been recognized in recent past as being sensitive to local seismic events (Martinelli & *alii,* 1995). Thus, local tectonic activity can possibly be thought of as responsible for the observed geochemical phenomena.

In a compressive tectonic setting like that of the buried Apenninic Front (Dorsale Ferrarese) (Montone & Mariucci, 1999), probably spatially unchanging risings of highly concentrated water («salt water-spots») are allowed along weakness lines or near structural surface intersections (Febo, 1999; Bacchi, 1999). Also, minor decreases (up to 500-1500 μS/cm) in temporal electrical conductivity trends (fig. 5) often appeared to be synchronous over long distances along the tectonic arc and sometimes seemed to be substantially synchronous with local seismic events of very low magnitude ($M < 3.0$). In such cases, the brief lowering in water well conductivity could be explained by the «dilatancy diffusion model» in a compressive regime (Scholz, 1990; Sibson, 1994; Wood, 1994; Keller & Pinter, 1996), also capable of explaining the great ground-fractures and deformations observed in the Correggio-Bagnolo-Novellara area (figs. 14-18).

CONCLUSIONS

The geochemical and geophysical prospections performed in a selected area of the Po Valley have allowed us to better identify, among others, a group of pockmark-featured structures which have generated some ground collapse phenomena possibly linked to active faulting. In such areas, a variety of geochemical anomalies have been detected, some of which seem to be related to local seismic activity. The occurrence of pockmark-featured structures seems to be proof of an eruptive seepage at a high flow rate. The occurrence of pockmark-bearing areas corroborates the idea that locally geodynamic factors are responsible for gas outflow phenomena, contributing to inducing geochemical anomalies. On the other hand, the surficial cracking and ground deformations on the western side of the buried apenninic front are strictly related to local seismicity. All these phenomena, especially the strongly increasing trends in electrical water conductivity, are probably linked to a large-scale actual evolution in the apenninic chain structural arc.

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