Giornale di Geologia Applicata 1 (2005) 23 –32, doi: 10.1474/GGA.2005-01.0-03.0003

The Subsidence of Ravenna

Werter Bertoni[1], Carlo Elmi[2] & Francesco Marabini[3]

[1]Servizio Geologico, Comune di Ravenna
[2]Dipartimento di Scienze della Terra e Geologico Ambientali, Università di Bologna, Via Zamboni 67, 40127 Bologna, e-mail elmi@geomin.unibo.it
[3]ISMAR, CNR, Bologna

ABSTRACT. The Ravenna area is subject to a high natural subsidence, near to the maximum values of the eastern Po river plain, active from at least the Lower Pliocene. The subsidence rate can be inferred by the thickness of the sedimentary sequence: the velocities are quite constant in time, ranging between 0 and about 2 mm/y. In the second half of the last century, the town and its surroundings have been affected by a severe artificial subsidence of up to fifty times the natural rate, chiefly due to water and gas extraction. The total subsidence reached values of about one meter. The reduction in the last two decades of underground water use brought the subsidence close to natural rates, but the gas extraction from the offshore gas pools still have effect and threaten the coast belt with rapid coastal erosion, higher storm surges and river floods.

Key terms: Subsidence, Piezometric decline, Coast erosion, Ravenna, Po Plain.

Introduction

The town of Ravenna lies on the southeastern edge of the Po River Plain, 10 km from the present shoreline, on a wide beach ridge formed by deposits of an ancient Po River delta. Its elevation is between 9 and 3 m a.s.l. The area is highly urbanized, with residential, economic and industrial settlements, including one of the most important harbors of the Mediterranean. It is subject to a high regional natural subsidence, near to the maximum values of all the Po plain, active from at least the Pliocene and during all the Quaternary. In the last decades, Ravenna and its surroundings have been affected by man-induced subsidence of up to fifty times the natural rate, mainly due to water pumping for civic usage and then to the extraction of methane. Since the 1960's the progressive expansion of land sinking has influenced the whole historical center and the new industrial zones, as well as the coastline, a few kilometers from the city center. The subsidence reached peaks of high risk and the related effects of these became critical. The progressive reduction in the last two decades of underground water use brought the subsidence close to natural rates, but the negative consequences of elevation loss in the near future, due to coastal erosion, higher storm surges and the risk of river floods, still remain.

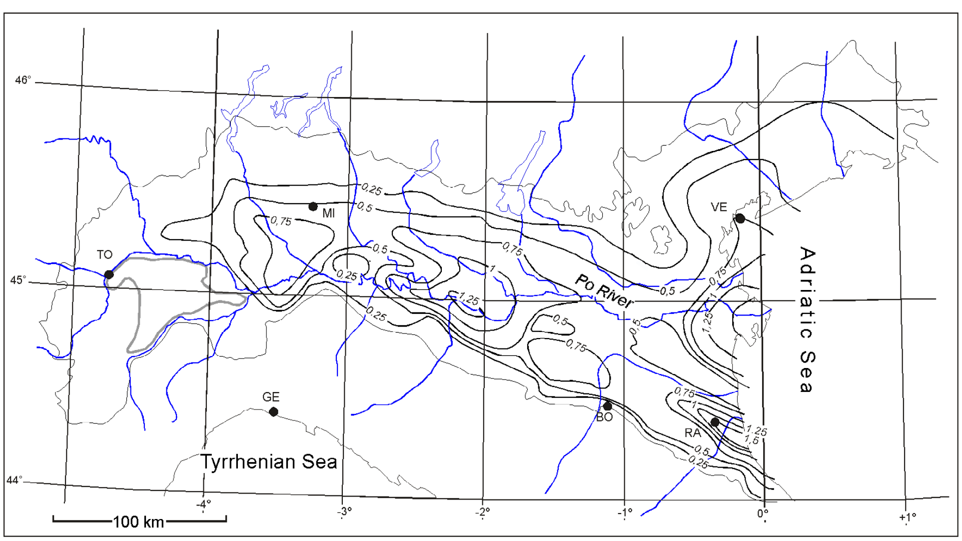

Fig.1 – Mean Quaternary (1.7 My) subsidence rate in mm/y in the eastern sector of the Po Plain (from ELMI ET ALII. 2003).

The natural Subsidence

The knowledge of the natural process and of its changes in space and over time may be useful for an understanding of the case history of Ravenna and for a comparison of natural and anthropogenic causes.

The Po plain forms a complex system where tectonic, depositional, climatic and man-induced factors act in ways that are different in intensity and velocity, with superimposed effects. The main framework of the Po "Valley" is clearly shaped by the tectonic activity, dating back at least to Lower Miocene. The tectonic effects of compressive deformations, subsidence and local uplift show high variability in space. The subsidence varies in small cells of 1 to 50 km in dimension. On the other hand, the deformation rates in the single cells are quite constant or have been slowly changing during the whole Quaternary at least.

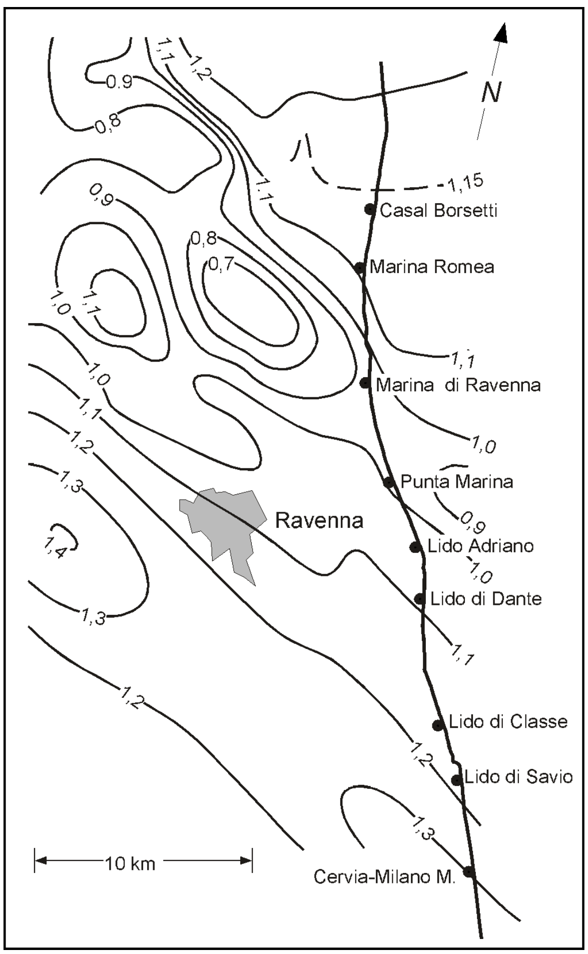

Fig. 2 - Mean Quaternary subsidence rate (mm/y) in the Ravenna area (ELMI ET ALII 2003, from data of SELLI & CIABATTI, 1977).

The sinking of the natural land is connected to a) crust deformations; b) sediment compaction; c) isostatic response to the variation of load, i.e. sediment and marine water load; d) eustatic sea level rise (relative subsidence) (BOSI ET ALII: 1996). If a continuous accumulation in a shallow marine basin similar to the present Adriatic Sea is assumed, the natural subsidence may be indirectly inferred by the sediment thickness. Tectonic subsidence causes sedimentation which in turn produces isostatic response, while sediment compaction generates further accommodation. In any case, whatever the origin and the mechanism of the subsidence, the result is always sediment thickness. In conclusion, if there is no need to know the uncompacted thickness of the various stratigraphic units, and "if we are satisfied with a global evaluation through geological periods, we can use the compacted thickness of the various formations, as they may be derived from the chronostratigraphic reconstruction" (GAMBOLATI & TEATINI: 1997).

Therefore, knowing the thickness, the time (duration) of deposition and the variation of deposition depth it is possible: a) to distinguish areas of different subsidence, and b) to obtain the approximate subsidence-sedimentation rates or velocity V. This is expressed by:

$$V = (S_{tot} - \Delta z)/T \neq 0 \qquad (1)$$

where S_{tot} is the total sediment thickness, or the sum of the effects mentioned above; i.e. S_t is tectonic sinking, S_c is sediment compaction and S_i is isostatic response, and Δz the algebraic sums of depth variations due to the basin filling or to eustatic oscillations; T is the age of the oldest sediments.

The thickness of Quaternary marine and continental sediments has been reconstructed from the geological data of gas and oil wells (PIERI & GROPPI, 1981) and their elaborations by various authors, (SELLI & CIABATTI: 1977, AGIP: 1994, FARABEGOLI ET ALII: 1997). These sediments are present in a continuous succession; therefore, during this period the Po Plain was always subsiding, at least in its middle and eastern sector. The isopach pattern shows several irregularities, with depressions and highs, marking variations in subsidence rate. The mean subsidence rate for the whole Quaternary has been calculated according to the (1) formula, with a time T = 1.7 My, (ELMI ET ALII: 2003). The velocity or "isosubsidence" contour lines in mm/y are reconstructed in Fig. 1.

Excluding the inner zones, the areas with highest sinking rates are the modern Po River Delta and the Romagna plain (Ravenna), where the maximum Pleistocene sediment accumulation took place (>2500 m thickness, 1.5 mm/y subsidence rate). The so-called "highs" are subsiding areas with less than one tenth of the maximum rate. Another relative depression with a rate of between 0.5 and 0.75 mm/y is the Venetian lagoon (see CARBOGNIN ET ALII, present volume).

The spatial variation of subsidence can be seen from the contour spacing and it changes rapidly in "cells" often smaller than 10 km in length. In the Ravenna area, where denser well logs are available, the velocity contour lines show variations of the subsidence even on a scale of about 1 km (Fig. 2).

The above values are mean values for the whole 1.7 My period. Where data (age and thickness) of more recent deposits are available, the reconstruction of the natural subsidence in shorter time spans from 750 to 10 ky, has been carried out. Three cases are described as follows:

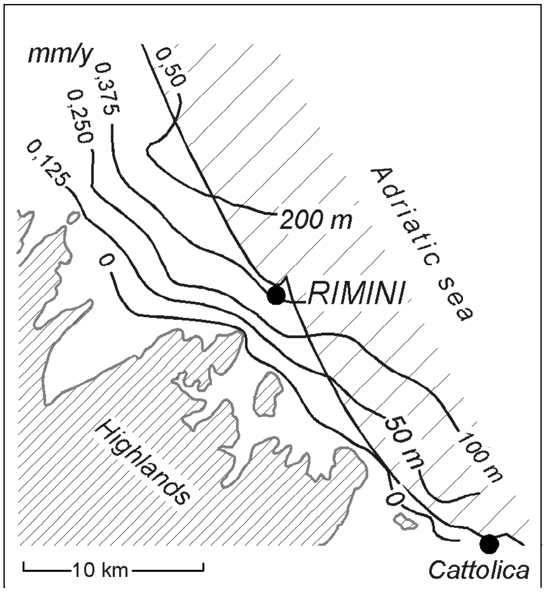

Fig. 3- Isopach in m of the Emilia-Romagna Supersynthem (age 400 ky) and relative subsidence rate in mm/y on the E margin of the Po Plain. See Fig. 1 contour lines, showing comparable values (from ELMI ET ALII, 2003)

a) In the Emilia-Romagna Supersynthem, age 450-350 ky, the rates are completely similar to the mean Quaternary (1.7 My) values (Fig. 3).

b) Ravenna and Ferrara Coast – The age of Quaternary sediments collected from gas wells on the outer margin of the Po Plain gives further indication of the trend of subsidence related to very short time intervals. The depth and the ^{18}O age of three wells are reported in Fig. 4 (GAMBOLATI: 1998, GAMBOLATI ET ALII: 1999). The derived sedimentation rates are constant and similar to those of the whole Quaternary, with limited exceptions due to a rapid decrease in the deposit bathymetry (GAMBOLATI & TEATINI: 1997).

c) Po Delta – The depth-age graph reconstructed on shallow (20 m) water wells shows rates ranging from 4.8 to 1.4 mm/y (Fig. 5). The deposits reflect a time interval of 10 ky. In this case the higher velocity between 10 and 6 ky must be related to the sum of the subsidence and the rise in sea level during the final stage of Flandrian transgression. Subtracting the relative subsidence, the velocity once more almost perfectly coincides with the average Quaternary value in this area.

In conclusion, in the Po River Plain the natural subsidence rates range between 0 and about 2 mm/y. Over space, the movements are very variable, with high gradients and noticeable differences on a scale of 10 or even 1 km. Over time, however, the velocities are quite constant, except in the case of rapid variation of deposition bathymetry, as during the Flandrian rise of the sea level.

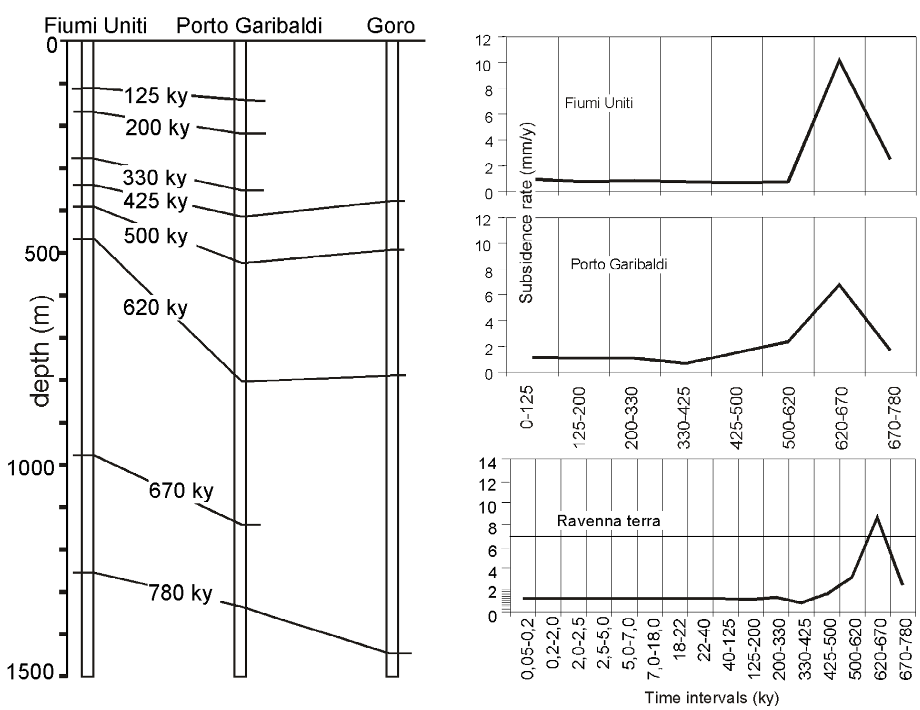

Fig. 4 – Left: (^{18}O) age in ky and depth of quaternary sediments on the Ravenna and Ferrara coast (redrawn from GAMBOLATI & TEATINI, 1997). Right: variations of the subsidence rates in the 0-780 ky B.P. time interval (calculated from data of GAMBOLATI & TEATINI, 1997).

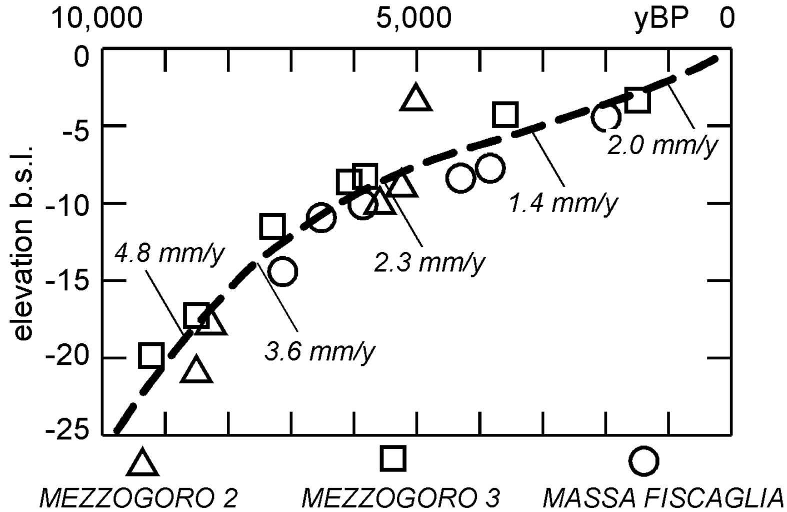

Fig. 5 – Elevation-age graph of Holocene sediments in the Po River Delta and reconstructed subsidence-sedimentation rates (redrawn from BONDESAN ET ALII , 1999).

Ravenna and its surroundings are located on highly subsiding areas, the highest on the southeastern fringe of the plain. Here the natural subsidence rates are the following (Table 1).

Those values are smaller than the rates calculated by other Authors, e.g. by GAMBOLATI & TEATINI, 1997 (2.5 mm/y) and by CARMINATI & DI DONATO 1999, BARNABA, 2000), probably due to the fact that a recent period with initial anthropogenic subsidence has been considered in the rates calculation.

Table 1 – Natural subsidence rates in the Ravenna area for different time intervals.

Time	Subsidence rate (mm/y)
Quaternary (1.7 My) general data	1.5
Quaternary (1.7 My) local data	1.0 – 1.4
U. Pleistocene (125 ky)	1.2
18-2 ky (U. Pleistocene-Holocene)	1.2

The Local Scale Geological Setting

The natural trend outlined above has been suddenly modified starting from about 1950 by the intense exploitation of the underground aquifers and, to a minor extent, by gas extraction in inland and in offshore wells. Locally the ground sinking reached its highest rates of up to fifty times the natural ones. The same phenomenon affected not only places with a high natural subsidence but also areas close to the Apennine border (Bologna, Modena).

For a better understanding of the man-induced land settlement, a detailed description of the main sedimentary units affected by the phenomenon is instructive. In the stratigraphic sequence, from the top, a unit of littoral, lagoon and alluvial deposits which is 0.4 km thick covers a marine substratum of Quaternary and Neogene age which is 4-5 km thick, and is progressively deformed by synsedimentary tectonic processes (Fig. 6a).

Ravenna lies on an ancient beach ridge of Etruscan age, (CIABATTI, 1967), followed by other large ridges of Roman and more modern ages towards the sea. These littoral chiefly sandy sediments, about 20 m thick (Fig. 6c), are linked to a depositional regression that followed the eustatic Flandrian (Holocene) transgression (SERVIZIO GEOLOGICO D'ITALIA, 1999). Below this unit, a continuous Pleistocene alluvial deposit, more than 400 m thick has developed. It is formed by at least nine sandy and loamy fresh water aquifers separated by silty and clayey aquitards or aquicludes. The aquifer/aquitard thickness ratio is about 1:1 (Fig. 6 c).

A continuous Plio-Pleistocene marine sequence, formed by alternating normally consolidated clay, silt and sand, lies under the continental units. The greatest depth (or thickness) of the Pleistocene sediments is found in the Ravenna area (Fig. 6a and 6b), indicating the high tectonic subsidence. Several gas reservoirs have been detected and exploited in this formation, with inland and offshore platforms at depths ranging between 1000 and 4500 m (Fig. 7).

Man-Induced Subsidence

The artificial subsidence in Ravenna began to show its effects in the middle of the last century immediately after the Second World War, either with effects evident in the historical buildings or with the progressive rise in the tide as well as the more frequent storm surges. A sharp increase in the subsidence rate was marked by tide measurements. The first analyses expressly focusing on the subsidence problems were initiated in 1970 by the CNR of Venice and the Municipality of Ravenna.

The topographic measurements carried out provided a good understanding of the overall occurrence.

The tide-gauge records at the harbor of Porto Corsini, 10 km east of Ravenna, show a sudden change around the 1950's (Fig. 8). The relative rise in the sea level between 1885 and 1950 indicates a rate of 3.25 mm/y, which is the sum of the eustatic rise (the average linear eustatic rate of 1.13 mm/y, CARBOGNIN ET ALII, present volume), and the natural subsidence. Values of the same order (2.8 mm/y) have been obtained by comparing the levels of the remains of sewage systems from Roman and Medieval periods in Ravenna (RONCUZZI: 1992).

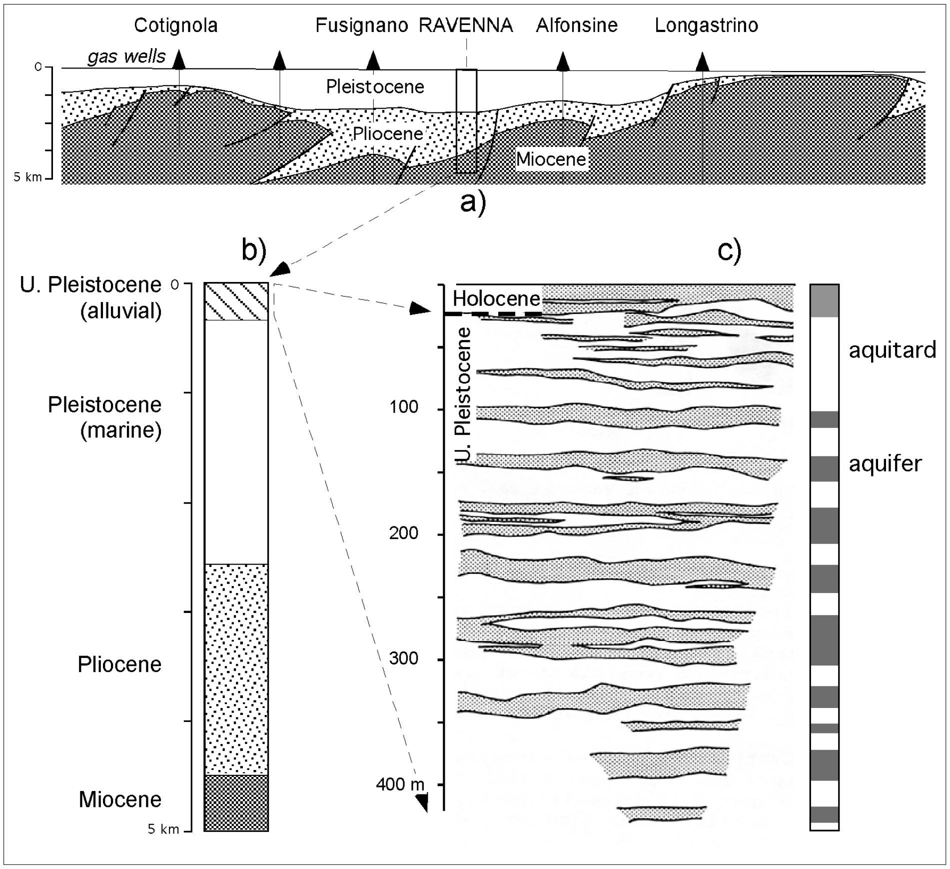

Fig. 6 – Geological setting of the eastern Po Plain. a) N-S cross section (redrawn from PIERI & GROPPI 1981); b) stratigraphic column (Ravenna area); c) the Ravenna aquifer system (from (CARBOGNIN ET ALII 1979). The man-induced subsidence is linked to water withdrawal from the alluvial Upper Pleistocene deposit c) and to gas extraction in the Plio-Pleistocene marine units b).

The difference between the tide-gauge (3.25) and the eustatic rise rate (1.13), i.e. land subsidence is slightly higher than the average long period rate (Table 1), and is probably due to either higher recent soil compaction or to the early of man-induced effects such as land reclamation or agricultural use of water in the first decade of the century. From the 1950's onward, the relative rise in the sea level from tide gauge records increased by up to about 17 mm/y.

Geodetic measurements in the Ravenna zone and along the coast line (IGM: 1950, 1970, 1977; Consorzio di Bonifica di Ravenna 1949, 1972; Comune di Ravenna: 1972, 1977; ENI-AGI: 1970 onward) revealed higher land settlement rates of up to 42 mm/y at Lido Adriano and 110 mm between 1972 and 1973 in the Ravenna industrial zone.

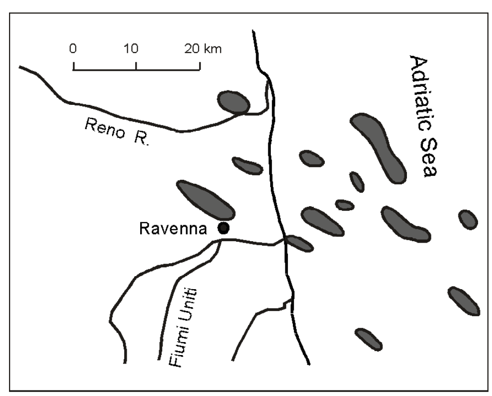

Fig. 7 – The gas reservoirs in the Ravenna and Upper Adriatic Sea sector (from AGIP, 1996).

It was quite clear that the causes of such rapid land sinking had to be ascribed to a *geotechnical* subsidence. At first, the main cause of local subsidence was ascribed to gas exploitation. This was probably suggested by the fact that a gas field is located a few km north of the historic center, and that in the nearby Po Delta a huge subsidence of up to 2.5 m caused by gas-bearing water extraction was recorded during the period between 1945 and 1960. However, the close correspondence of the shape of subsiding areas to the depression cone of the fresh water artesian aquifers clearly showed that the main cause was the groundwater withdrawal, (CARBOGNIN ET ALII: 1978), which was mainly concentrated in the rapidly expanding industrial district of Ravenna. The decline of the pore pressure along with the corresponding increase in effective stress in the aquifer sediments caused a rapid volume reduction of the normally consolidated alluvial sediments (Fig. 9).

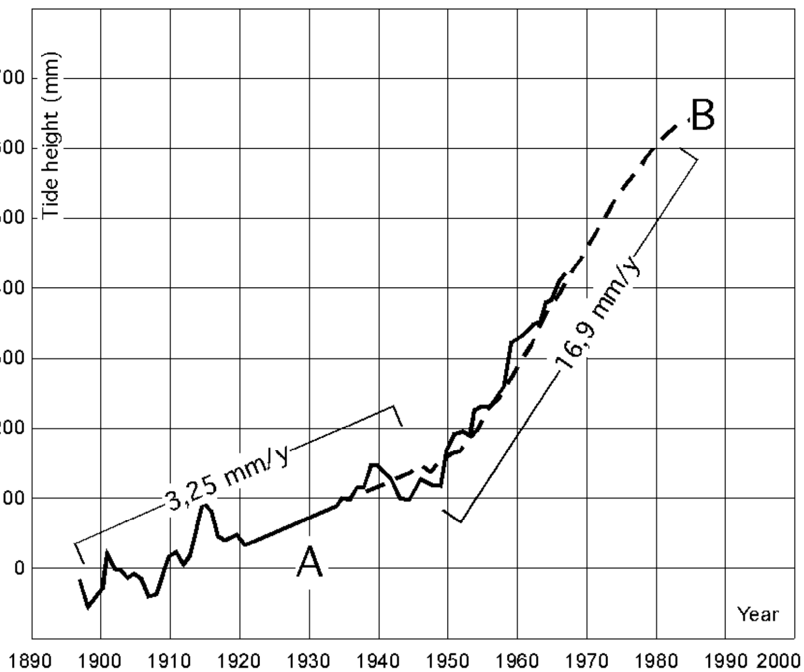

Fig. 8 – 1885-1988 tide gauge records at Ravenna, Porto Corsini (from BONDESAN ET ALII 1995), according to ANTONIAZZI 1976 (A) and SAPIR 1992 (B). Tide height referred to 0 IGM (Istituto Geografico Militare) of 1897.

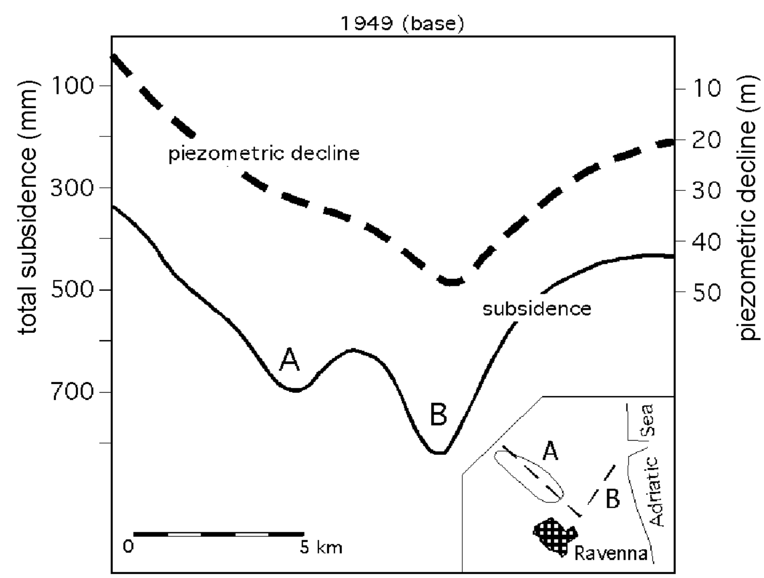

Fig. 9 – Total subsidence and average piezometric decline in the 1949-1972 period in the Ravenna area. Insert: index map and section line. (A) Ravenna Terra gas field; (B) Industrial zone (CARBOGNIN ET ALII, 1979).

There is no doubt that gas extraction from deeper reservoirs has contributed to an increase in land settlement. In fact by overlapping the 1949-1972 subsidence map with the Ravenna gas field a good correspondence between the elliptic shape and the orientation of the reservoir and the subsidence contour lines can be observed. A meaningful clue to the influence of gas exploitation can be supplied by the same figure: a secondary local bowl of subsidence can be noted in correspondence with the position of the gas reservoir (point A in Fig. 9). The contribution to the local 1949-1972 subsidence (70 cm) may be roughly estimated as 10 cm (14%).

In conclusion, all the land settlement phenomena of artificial origin are confined within the Upper Pleistocene alluvial deposits (water withdrawal) and, to a lesser extent, within the Plio-Pleistocene marine deposits (gas exploitation).

Table 2 – Subsidence rates since 1900 in Ravenna and its surroundings. Data: (1) from I.G.M. geodetic surveys, reconstructed by SALVIONI: 1957; (2) CONSORZIO DI BONIFICA DI RAVENNA; (3) CARBOGNIN ET ALII: 1984; (4) BERTONI: 2003.

Time interval	Subsidence rate (mm/y)		
	Ravenna	Ravenna industrial zone	Coast line (Punta Marina)
1900-1957 (1)	5.5	6	6.2
1949-1972 (2)	25	35	15
1972-1973 (3)	80	110	42 (Lido Adriano)
1972-1977 (4)	60	70	65
1977-1982 (4)	13	11	9
1982-1986 (4)	5	5	7
1986-1992 (4)	5	5	6
1992-1998 (4)	4.5	4.5	6
1998-2002 (4)	1.3	1.3	2.5

More recent geodetic surveys, up to the present century, are available, covering the whole urban and coastal area (BERTONI: 2003). The data set allows the calculation of the subsidence rates and their present trends from the beginning of the last century until 2002. In Table 2 the land settlements in three different locations are summarized.

It should be noted that in the first interval considered, from 1900 to 1957, the sinking velocity of 5.5 mm/y probably marks the early effects of fluid removal. The data show that a drop in subsidence rates, close to the natural ones or even lower, was occurring after the 1980's, due to the drastic reduction of the pumping of artesian water and to a correspondent recovery of piezometric head.

In terms of total land subsidence, the graph in Fig. 10 shows the values recorded at the benchmark of Porta Adriana, in the historic center. The total, natural and man-induced elevation loss, recorded over a wide area of about 30 km^2, are around 1.1 m during a century. A significant picture of past and present subsidence trends may be drawn.

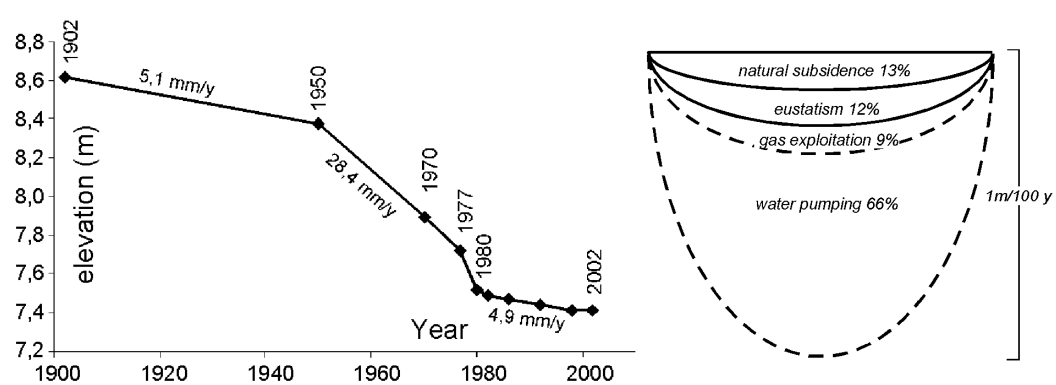

Fig.10 – Left: elevation of benchmark (not at ground level) of Porta Adriana (historic center) from 1902 to 2002 (1902-1980 data from CARBOGNIN ET ALII, 1984, updated with 1982-2002 data from BERTONI, 2003). Right: contribution to subsidence of the natural and artificial components.

Subsidence of the Ravenna Coast

The previous data relate to the urban and industrial area of Ravenna. A similar accelerated subsidence has been observed along the Adriatic coast, on a front of approximately 30 km (Fig. 11).

The Ravenna coast, between the Reno River mouth and the town of Cervia, as well as 70% of the Emilia Adriatic shore, is affected by the phenomena of rapid shoreline retreat, which has required massive defense works. The causes of this environmental degradation can be identified in the reduced river sediment supply, in the maritime constructions that have modified the long shore current pattern, and particularly in the man-induced subsidence once again linked to water pumping and gas reservoir exploitation.

The maximum subsidence in the 1949-2002 time span is recorded for Ravenna harbor, between Marina di Ravenna and Marina Romea (Fig. 11), with an elevation loss of 0 . 8-1 m. The total subsidence in the last century, calculated by adding the natural value of the 1900-1949 interval, shows a loss of an extra 0 . 15 m along the entire coastal strip.

The consequence is that floodwater phenomena occur frequently, together with episodes of storm surges (CARBOGNIN ET ALII: 1984, BONDESAN ET ALII: 1995). The port wharves have been raised with continuous walls and mobile bulkheads. A large part of the territory, behind the littoral ridge, is now below sea level. If the present trend continues, the residual man-induced subsidence will last until 2020 (BONDESAN ET AL: 1995). Severe risks of river flooding in the outer part of the territory and higher floodwater in towns and tourist facilities along the coastline are expected.

In the zone from Lido Adriano to Lido di Dante, values of 13 ÷ 25 mm/y were recorded in 1986, corresponding perhaps to the exploitation of offshore reservoirs.

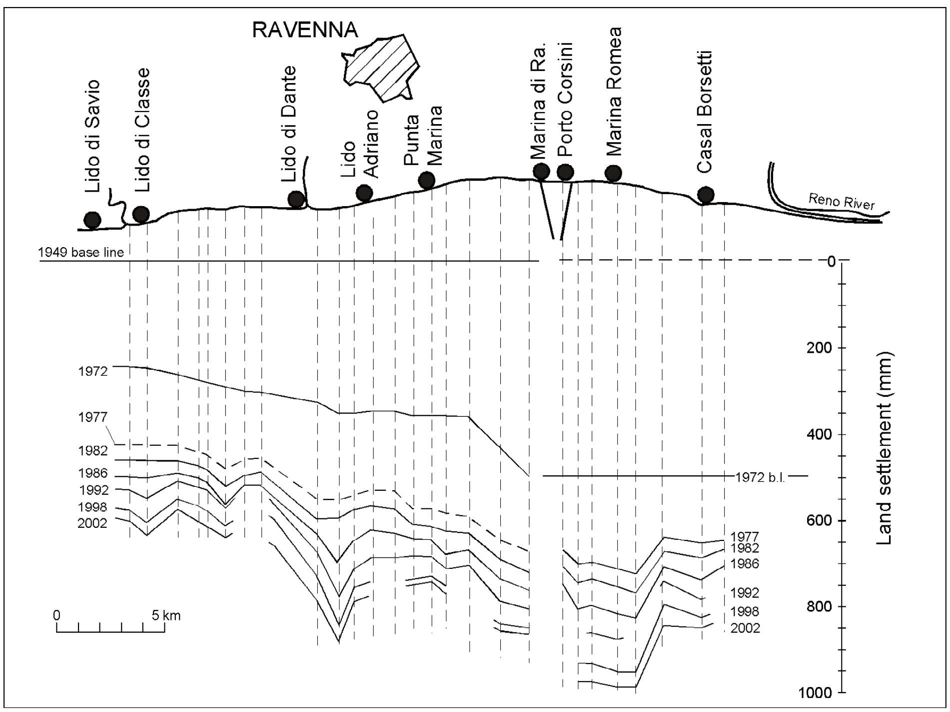

Fig. 11 – Elevation loss along the Ravenna shoreline between 1949 and 2002 (from COMUNE DI RAVENNA – C.N.R. 1993, redrawn and updated).

By overlaying the subsidence contour in the period between 1998 and 2002 and the reservoir position, a significant correspondence between still productive gas fields and the highest sinking velocity can be observed, and in particular with the Angela-Angelina and Dosso degli Angeli gas reservoirs (BERTONI ET ALII: 1995). The first is made up of 47 pools at depths of between 3000 and 4000 m. Its margins intersect the coast profile (Fig. 12). According to the simulations carried out by GAMBOLATI ET ALII: 1997, the pore pressure decline, both in the productive levels and in the aquifers surrounding the gas fields, can cause a total settlement of about 40 cm, reduced to 25 cm corresponding to the overlying coastline.

The modeling approach, developed for the prediction of the Upper Adriatic morphodynamics for the present century (GAMBOLATI ET ALII: 1997), indicate that the Romagna coastline and in particular the Ravenna shore area “is very sensitive to land/sea elevation changes”. At the end of the 21st century, "a large part of the present lowlands will be potentially flooded by meteomarine events with a 1 year return period".

Such a subsidence rate in the whole coastal area is greatly contributing to environmental and geomorphologic deterioration (BONDESAN ET ALII: 1978, 1995; CARBOGNIN ET ALII: 1984), which in relation to the expected rise in sea level, has the following principal themes:

a) a retreating shoreline only partially lessened by remedial works such as breakwaters. The main causes have not changed; for example, the reduced river sediment supply, the urban impact as well as the deterioration of the beach and the dune ridge. In particular, in correspondence with the highest sinking values of Lido Adriano a large shoreline retreat can be observed. Instead, at Porto Corsini the high subsidence effect has been halted as a result of deposits from the long shore currents (in a South-North direction) against the harbor piers.

b) A continuous sequence of dense pine forest (dating back to the Middle Ages), marshes, lagoons ("pialasse"), behind the dune ridge, endangered by increasing salinity of the phreatic nappe. The marshes and the lagoons show traces of a changed superficial water exchange with the sea, caused by the dismantling of the tideway network. The "pialasse" in particular now show a high risk of flooding. Some areas of the industrial facilities close to the Ravenna harbor are protected from the water floods by long bulkheads.

c) Backlands near or below the present sea level and protected only by a narrow dune and beach ridge. A dense net of surface channels and of water-pumping plants is draining the entire area. The interruption of the mechanical drainage would change the backlands into a wide marshy area with difficult run-off or permanent waters.

d) Due to the widespread land reclamation and to the continuous rise of the artificial levees, the river channels are somewhat higher than the surrounding areas and there are no more deposits of sediments balancing the floodplain subsidence. Furthermore, the riverbeds, which have become narrow, are no longer capable of carrying the largest secular floods.Therefore, the main effects of a marked rise in the sea level in the near future will most likely lead to a deterioration of the existing imbalance, along with other important phenomena which are still unclear, such as the brackish water rise, the building stability, etc. These effects could reach critical values long before the end of the 21st century, if the rates observed remain at peak values. In fact, if a eustatic rise reaches the 1992 maximum (+25 cm, WIGLEY & RAPER: 1992), as stated by the Intergovernmental Panel of Climate Change (IPCC) and the subsidence rates are the same as those recorded in the period 1986-1992, a total rise in sea level of 35-40 cm will occur in the study area before 2025. On the other hand, slightly higher values of about 60-70 cm would occur by 2100 if subsidence rates were close to the natural value and of a medium IPCC 1992 eustatic rise (+48 cm).

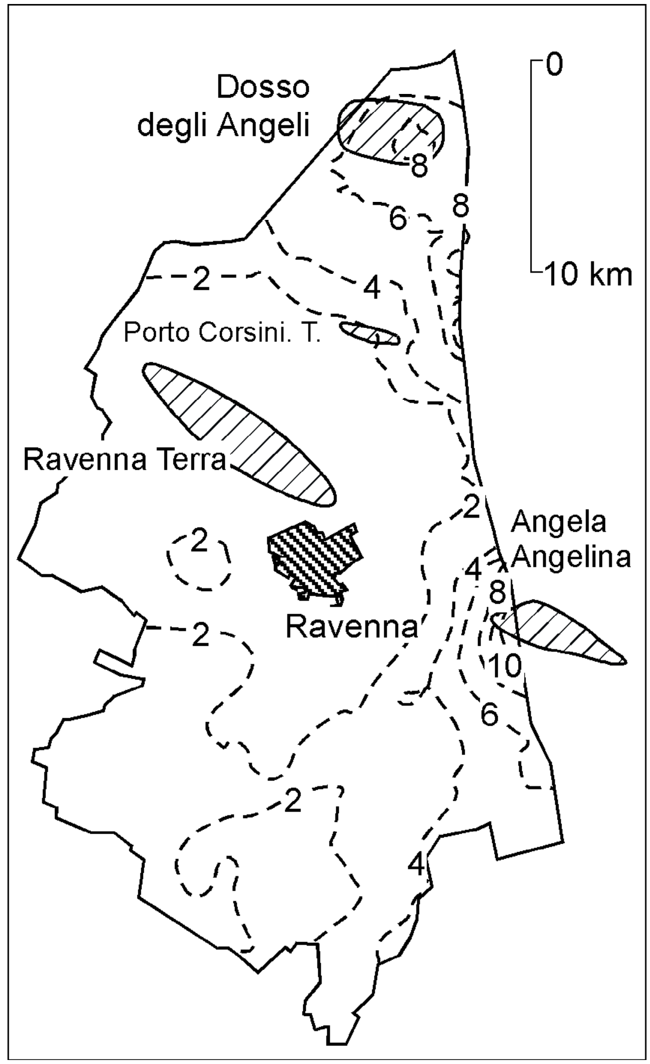

Fig. 12 – Subsidence rate contour lines (mm/y, dashed) and gas reservoirs in the Ravenna area. (Redrawn from BERTONI, 2003).

In both cases, the shoreline erosion will continue to follow the same trend, resulting in a 50-70 m retreat of the beach, due to a reshaping of the profile. In some zones, (Lido Adriano to Punta Marina), the beach erosion will be even greater (up to 100 m or more) and very close to, or just inside the tourist facilities. Most coastal areas will probably have to be abandoned to the sea or else continuous defenses will have to be constructed all along the shoreline, in order to maintain industrial and tourist activities in what is becoming increasingly an "Italian Netherlands" (BONDESAN ET ALII: 1995).

Acnowledgement

Grants supported by University of Bologna, funds ex 60% 2002-2003, scientific resp. Carlo Elmi.

References

AGIP (1994) – *Acque dolci sotterranee*. Graf 3, Roma, 515 pag..

AGIP (1996) – *Alto Adriatico, Rapporto di sintesi*. Technical report. AGIP S.p.A., Milano

ANTONIAZZI A. (1976) - *L 'erosione marina nel litorale fra Cervia e Pesaro.* Boll. C.C.I.A.A., Forlì.

BERTONI W. (2003) - *La subsidenza di Ravenna: lo stato attuale in relazione alla coltivazione dei giacimenti a gas.* Comune di Ravenna, Servizio Geologico e Protezione civile. Int. Report

BERTONI W., BRIGHENTI G., GAMBOLATI G., RICCERI G. & VUILLERMIN F. 1995 – *Land subsidence due to gas production in the on- and off-shore natural gas fields of the Ravenna area, Italy.* Proc. Fifth Int. Symp. on Land Subsidence, The Hague, IAHS publ. n. 234, 13-20

BONDESAN M., CASTIGLIONI G.B., ELMI C., GABBIANELLI G., MAROCCO R., PIRAZZOLI P.A., TOMASIN A. (1995) – *Coastal areas at risk from storm surges and sea level rise in Northeastern Italy.* Journal of Coastal research , 11, 4, 1354-1379

BONDESAN M., CALDERONI G. CATTANI L. FERRARI M., FURINI A.L., SERANDREI BARBERO R. & STEFANI M. (1999) – *Nuovi dati stratigrafici, paleoambientali e di cronologia radiometrica sul ciclo trasgressivo-regressivo olocenico nell'area deltizia padana.* Ann. Univ. Ferrara, 8, 1, 1-34.

BONDESAN M., CALDERONI G., DOLCINI R. (1978) - *Il litorale della provincia di Ferrara e Ravenna (Alto Adriatico). Evoluzione morfologica e distribuzione dei sedimenti*. Boll. Soc. Geol. It., 97, 247-287.

BOSI C., CAROBENE L. & SPOSATO A. (1996) - *Il ruolo dell'eustatismo nell'evoluzione geologica dell'area mediterranea.* Mem. Soc. Geol. It., 51, 363-382.

CARBOGNIN L., GATTO P., & MARABINI F. (1984) - *Guidebook of the eastern Po Plain (Italy).A short illustration about environment and land subsidence.* Third Int. Symp. on land subsidence, Venice, 1984.

CARBOGNIN L., GATTO P., MOZZI G. & GAMBOLATI G., 1979 - *Land subsidence of Ravenna and its similarities with the Venice case*. Proc. of the Engineering Found. Conf. on Evaluation and prediction of subsidence, ASCE, pp. 254-266.

CARBOGNIN L., GATTO P., MOZZI G. ZAMBONI G. & BERTONI W, 1978 – *Cause ed effetti della subsidenza in atto a Ravenna.* Atti Conf. su: I problemi della subsidenza nella politica del territorio e della difesa del suolo. Pisa 1978.

CARMINATI E. & DI DONATO G. (1999) - *Separating natural and anthropogenic vertical movements in fast subsiding areas: the Po plain (N. Italy) case*, Geoph. Research Letters, 26, 2291-2294.

CIABATTI M. 1967 – Ricerche sull'evoluzione del Delta Padano. Giornale di Geologia, 2, 34, 26 pp.

COMUNE DI RAVENNA - C.N.R. (1993) – *Influenza della subsidenza sul trend evolutivo della fascia costiera Ravennate*. Int. Report, Ravenna.

ELMI C., FORTI P., NESCI O. & SAVELLI D. (2003) - *La risposta dei processi geomorfologici alle variazioni ambientali nella pianura padana e veneto-friulana, nelle pianure minori e sulle coste nord e centro-adriatiche.* In: Biancotti, A., Motta, M, eds., MIUR – Risposta dei processi geomorfologici alle variazioni ambientali. Atti Conv. Bologna 10-11 Febbraio 2000, 225-260, Brigati G., Genova.

FARABEGOLI E., ONOREVOLI G., RUFFINO C. & COSTANTINI B. (1997) – *Struttura del sottosuolo quaternario della Pianura Padana meridionale (Provincia di Ravenna – Italia).* Università di Bologna-AGIP, S.El.Ca., Firenze.

GAMBOLATI & TEATINI, 1997, *Numerical analysis of landl subsidence due to natural compaction of the Upper Adriatic Sea Basin.* CENAS - Study on the coastline evolution of the Eastern Po Plain due to Sealevel Change caused by climatic variation and to natural and anthropic subsidence. Dip. Metodi e Modelli Matematici per le Scienze applicate, Padova, 105-134.

GAMBOLATI G. (ed.), 1998 - CENAS, *Coastline Evolution of the Upper Adriatic Sea due to Sea Level Rise and Natural and Anthropogenic Land Subsidence*. Kluwer Academic Publ., Series Water Science & Technology Library, n.28, 344 pp.,

GAMBOLATI G., TEATINI P., TOMASI L. & GONELLA M., 1999 - *Coastline regression of the Romagna region, Italy, due to sea level rise and natural and anthropogenic land subsidence.* Water Resources Research, 35(1), 163-184,.

PIERI M. & GROPPI G. (1981) – *Subsurface geological structure of the Po Plain.* C.N.R. Progetto finalizzato Geodinamica, Sottoprogetto Modello strutturale, pubbl. 414

RONCUZZI A., 1992- Topografia di Ravenna antica: le mura. Boll. Camera di CCARB, XXXIX, 691-742.

SALVIONI G., 1957 – *I movimenti del suolo nell'Italia centro-settentrionale.* Boll. Geodesia e Sc. affini, 16, 3.

SAPIR (1992) - *Relazione sugli aspetti idraulici per il progetto esecutivo del Molo Nord in sinistra Candiano, Ravenna*. Unpublised Report.

SELLI R. & CIABATTI M. (1977) - *L'abbassamento del suolo della zona litoranea Ravennate.* Giorn. Geol., 42, 1-47.

SERVIZIO GEOLOGICO D'ITALIA (1999) - *Note Illustrative della carta geologica d'Italia alla scala 1:50.000, F° 223 Ravenna.*

WIGLEY T.M.L. & RAPER S.C.B., 1992 – *Implications for climate and sea level of revised IPCC emissions scenarios.* Nature, 357, 709-719.