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## THE NATURAL AND MAN-INDUCED SUBSIDENCE OF THE RAVENNA AREA (Po Plain)

**ABSTRACT:** ELMI C., BERTONI W. & MARABINI F., *The natural and man-induced subsidence of the Ravenna area, Po Plain.* (IT ISSN 1724-4757, 2005).

The Ravenna area (south-east rim of the Po Plain, Italy) is subject to a high regional natural subsidence, near to the maximum values of all the Po Plain, active from at least the Lower Pliocene and during all the Quaternary. In the last decades Ravenna and its surroundings have been affected by a man-induced subsidence of up to fifty times the natural rate, mainly due to water pumping and to the extraction of methane. Since the 1960's the progressively widening of the land sinking has influenced the whole historical centre and the new industrial zones, as well as the coastline, few kilometers from the city centre. The subsidence reached peaks of high risk and the related effects 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.

**KEY WORDS:** Subsidence, Piezometric decline, Coast erosion, Ravenna, Po Plain (Italy).

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L'area di Ravenna è soggetta ad una elevata subsidenza naturale prossima ai massimi valori registrati in tutta la Pianura Padana, attiva a partire almeno dal Pliocene inferiore e perdurante per tutto il Quaternario. Negli ultimi decenni, Ravenna e i suoi dintorni sono stati interessati da subsidenza artificiale con tassi fino a cinquanta volte quelli naturali, dovuti a pompaggio di acque dolci superficiali e in minore misura a estrazione di metano da *reservoirs* più profondi. A partire dal 1960 il progressivo ampliamento del fenomeno ha coinvolto l'intero centro storico e la vicina zona industriale, e così pure la fascia costiera, a pochi km dalla città, con punte di elevato rischio. La progressiva riduzione dei pompaggi dagli acquiferi superficiali ha portato la velocità di subsidenza a valori prossimi a quelli naturali, ma restano le conseguenze negative della perdita di quota, prossima a circa 1 m, ossia erosione costiera, ingresso di acque alte e rischio di esondazioni dei corsi d'acqua.

**TERMINI CHIAVE:** Subsidenza, Idrogeologia, Erosione costiera, Ravenna, Pianura Padana.

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### INTRODUCTION: THE NATURAL SUBSIDENCE

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 so called «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 slowly changing during the whole Quaternary at least.

The causes of the natural subsidence are: 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 & 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. 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:

$$V = (S_{tot} - \Delta_z)/T \neq 0 \quad (1)$$

where

$S_{tot}$  = total subsidence (defined by sediment thickness), due to tectonic sinking, to sediment compaction and to isostatic response;

$\Delta_z$  = algebraic sum of depth variations due to the basin filling or to eustatic oscillations;

$T$  = 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 different authors, (Selli & Ciabatti, 1977; AGIP, 1994; Farabegoli & 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 depressions and highs, marking variations in subsidence velocity. The mean subsidence rate for the whole Quaternary has been calculated according to the (1) formula, with a time of  $T = 1.7$  My (Elmi & alii, 2003). The velocity or «isobasins» contour lines in mm/y are reconstructed in fig. 1.

Excluding the inner zones, the areas with higher sinking rates are the modern Po River Delta and the Romagna plain (Ravenna), where the maximum Pleistocene sediment accumulation took place (>2,500 m thickness, 1.5 mm/y subsidence rate). The so-called «high» are subsiding areas with less than one tenth of the maximum rate. Another relative depression with a rate of between 0.5 e 0.75 mm/y is the Venetian lagoon.

The 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.

The above values are mean values for the whole 1.7 My period. Where data (age and thickness) of more recent de-

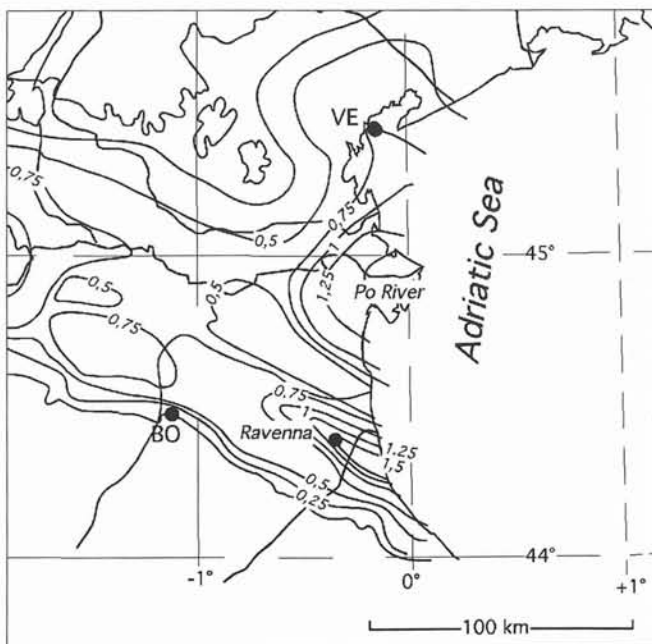


FIG. 1 - Mean Quaternary (1.7 My) subsidence rate in mm/y in the Eastern sector of the Po Plain (from Elmi & alii, 2003).

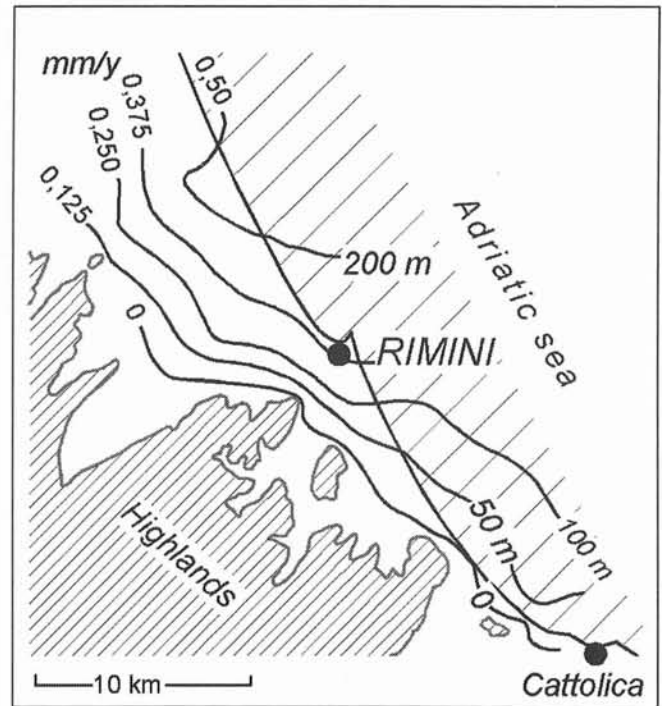


FIG. 2 - Isopach in m of the Emilia-Romagna Supersystem (age 400 ky) and relative subsidence rate in mm/y on the E margin of the Po Plain. See fig. 1 contour lines, showing comparable values (from Elmi & alii, 2003).

posits 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:

- In the Emilia-Romagna Supersystem, age 450-350 ky, the rates are completely similar to the mean Quaternary (1.7 My) values (fig. 2).
- Ravenna and the 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 sedimentation rates, obtained from the depth and the  $^{18}\text{O}$  age of four wells, are constant and similar to those of the whole Quaternary (Gambolati & Teatini 1997; Gambolati 1998, Gambolati & alii 1999).
- 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. 3). 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

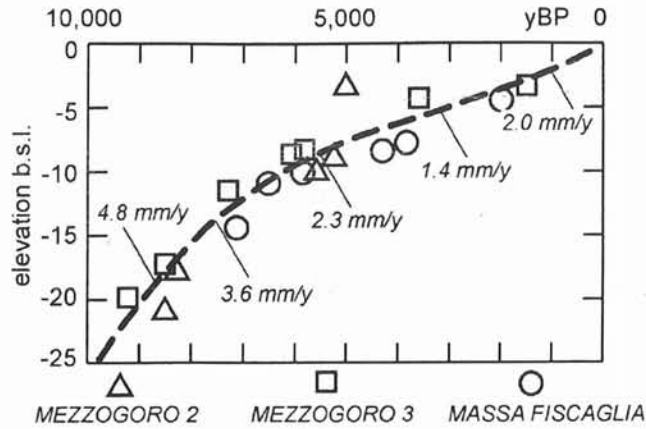


FIG. 3 - Elevation-age graph of Holocene sediments in the Po River Delta and reconstructed subsidence-sedimentation rates (redrawn from Bondesan & alii, 1999).

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.

In conclusion, in the Ravenna area and its surroundings the natural subsidence rates are the following (tab. 1).

TABLE 1 - Natural subsidence rates in Ravenna area for different time intervals

Time	Subsidence rate (mm/y)
Quaternary (1.7 My)	1.5
Upper Pleistocene (125 ky)	1.2
18-2 ky (Upper Pleistocene-Holocene)	1.2

### THE LOCAL SUBSIDENCE

Starting from about fifties, the natural trend has been suddenly modified by the intense exploitation of the underground aquifers and, to a minor extent, by gas extraction in inland and in offshore wells. The ground sinking reached its highest rates of up to ten or fifty times the natural ones. The same phenomenon affected other areas close to the Apennine border (Bologna, Modena).

A detailed description of the main sedimentary units affected by the man-induced land settlement is useful for a better understanding of the local phenomenon. 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 Neogenic age which is 4-5 km thick, and is progressively deformed by synsedimentary tectonic processes (fig. 4a).

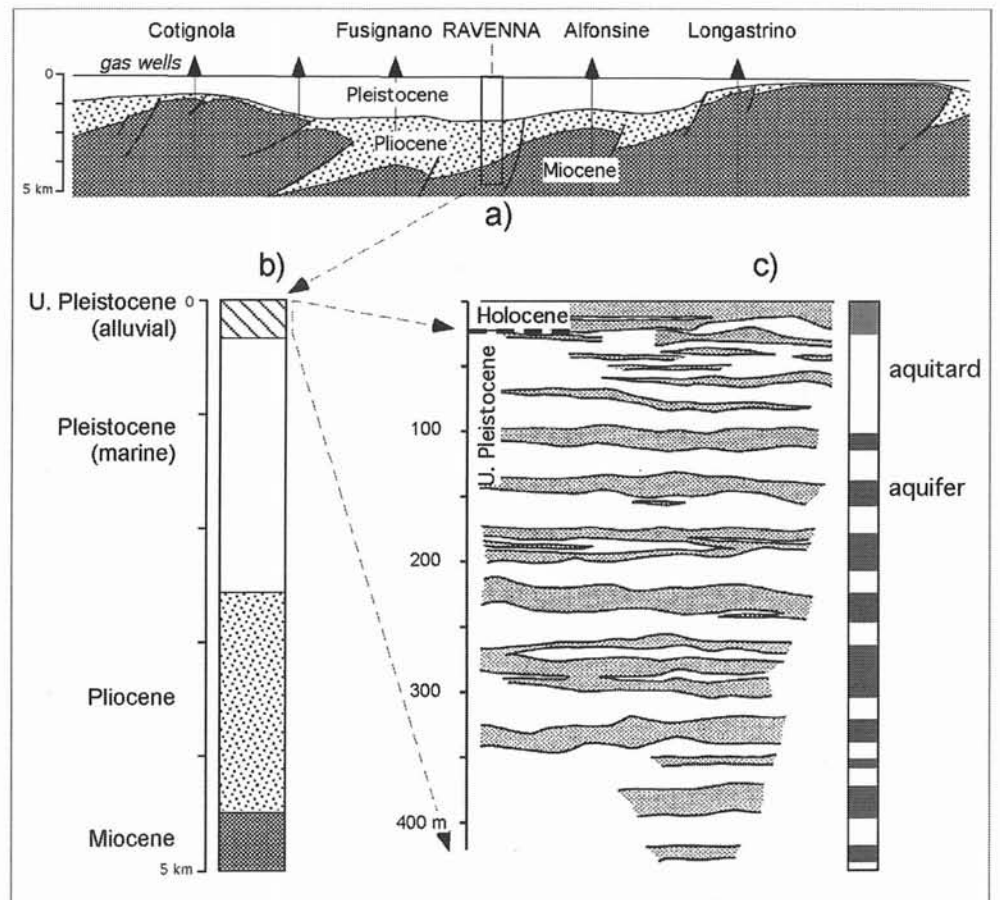


FIG. 4 - Geological setting of the Eastern Po Plain. a) N-S cross section (redrawn from Pieri & Groppi, 1981); b) stratigraphic column (Ravenna area); c) the Ravenna aquifer system (from Carbognin & alii, 1979). The man-induced subsidence is linked to water withdrawal from the alluvial Upper Pleistocene deposit c) and to gas extraction in the Plio-Pleistocene marine units b).

Ravenna lies on an ancient beach ridge of Etruscan age, (Ciabatti, 1967), followed towards the sea by other large ridges of Roman and more modern ages. These littoral sandy sediments, about 20 m thick (fig. 4c), 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 is present. It has been formed by at least 9 sandy and loamy fresh water aquifers separated by silty and clayey aquitards or aquicludes. The aquifer/aquitard thickness rate is about 1/1 (fig. 4 c).

A continuous Plio-Pleistocene marine sequence formed by alternating normally consolidated clay, silt and sand lies under the continental units. The greater depth (or thickness) of the Pleistocene sediments occurs in the Ravenna area, (fig. 4a and 4b), 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 1,000 and 4,500 m.

## THE 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 topographic measurements initiated in 1970 by the CNR of Venice and the Municipality of Ravenna provided a good understanding of the overall occurrence.

The tide-gauge records at the harbour of Porto Corsini, 10 km east of Ravenna, show a sudden change around the 1950 (fig. 5). 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 & alii, 2004), 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).

The difference between the tide-gauge (3.1) and the eustatic rise rate (1.13), i.e. land subsidence, is slightly higher than the average long period rate (tab. 1), and is probably due to either higher recent soil compaction or to the beginning of man-induced effects such as land reclamation or water agricultural use in the first decade of the century. From the 1950's onward, the relative rise in the sea level from tide gauge records increases 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.

It was quite clear that the causes of such rapid land sinking had to be ascribed to a «geotechnical» subsi-

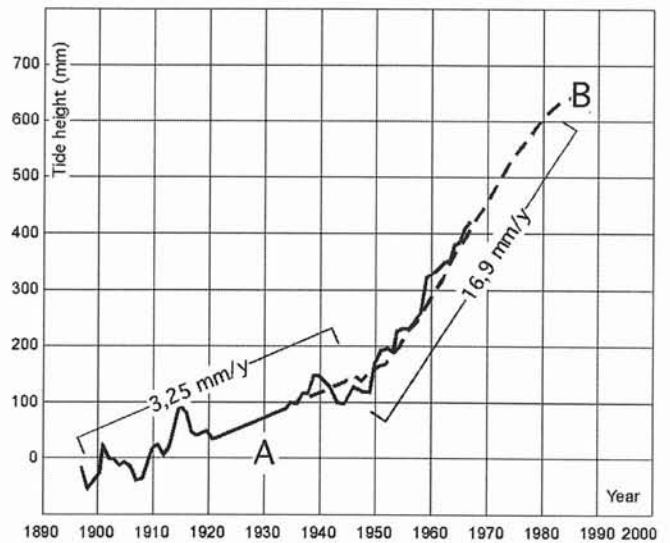


FIG. 5 - Tide gauge records (1885-1988) at Ravenna Porto Corsini (from Bondesan & alii, 1995), according to Antoniazzi, 1976 (A) and SAPIR, 1992 (B). Tide height referred to 0 IGM (Istituto Geografico Militare) of 1897.

dence. 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 centre, and that in the near Po Delta 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 & alii, 1978), which was mainly concentrated in the rapidly expanding industrial zone of Ravenna. The decline of the pore pressure along with the corresponding increase in effective stress in the aquifers sediments caused the rapid volume reduction of the normally consolidated alluvial sediments (fig. 6).

There is no doubt that the 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. 6). The contribution to the local 1949-1972 subsidence (70 cm) may be roughly estimated as 10 cm (14%).

Conclusively, 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).

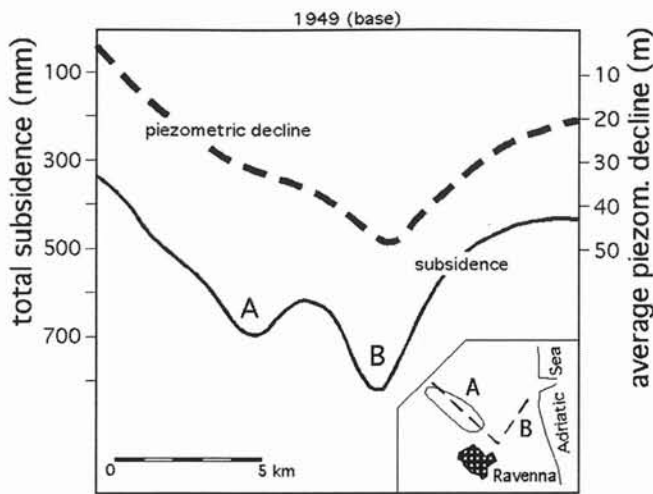


FIG. 6 - Total subsidence and average piezometric decline in the 1949-1972 period in the Ravenna area. Insert: index map and section line. (A) Ravenna Terra gas field; (B) Industrial zone (Carbognin & alii, 1979).

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 tab. 2 the land settlements in three different locations are summarized.

TABLE 2 - Subsidence rates in mm/y since 1900 in Ravenna and its surroundings. Data: <sup>1</sup>from I.G.M. geodetic surveys, reconstructed by Salvioni, 1957; <sup>2</sup>Consorzio di Bonifica di Ravenna; <sup>3</sup>Carbognin & alii, 1984; <sup>4</sup>Bertoni, 2003

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

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, is 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 fig. 7 graph shows the values registered at the benchmark of Porta Adriana, in the historic centre. The total, natural and man-induced elevation loss, recorded over a wide area of about 30 km<sup>2</sup>, are around 1.1 m during a century. A significant picture of past and present subsidence trends may be drawn.

## THE COAST SUBSIDENCE

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. 8).

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 have 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 the Ravenna harbour, between Marina di Ravenna e Marina Romea (fig. 8), with an elevation loss of 0,8-1 m. The total subsidence in the last century (XX), 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 & alii, 1984; Bondesan & alii, 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.

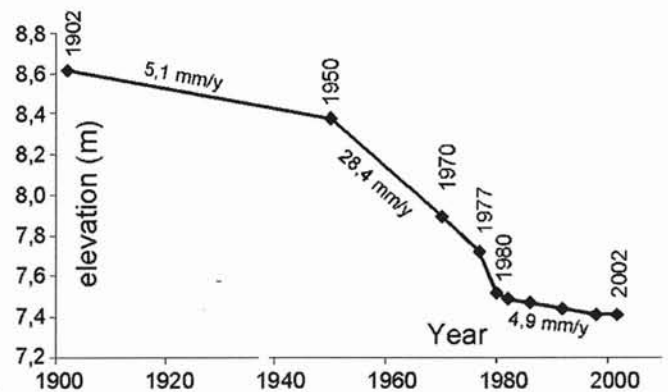


FIG. 7 - Elevation of bench mark of Porta Adriana (historic centre) from 1902 to 2002 (1902-1980 data from Carbognin & alii, 1984, updated with 1982-2002 data from Bertoni, 2003).

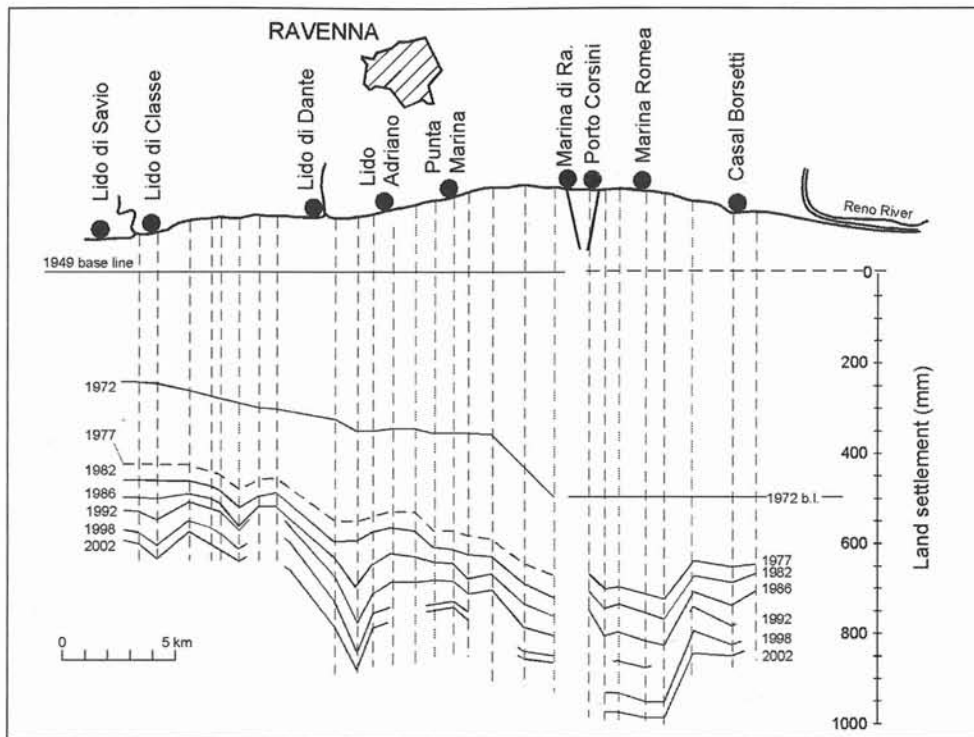


FIG. 8 - Elevation loss along the Ravenna shoreline between 1949 and 2002 (from Comune di Ravenna - C.N.R. 1993, redrawn and updated).

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 & *alii*, 1995). The first is made up of 47 pools at depths of between 3,000 and 4,000 m. Its margins intersect the coast profile (fig. 9). According to the simulations carried out by Gambolati & *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 in the overlying coastline.

The model for the prediction of the Upper Adriatic morphodynamics for the present century (Gambolati & *alii*, 1997), indicates that the Romagna coastline and the Ravenna shore area are «very sensitive to land/sea elevation changes». At the end of the 21<sup>st</sup> century, «a large part of the present lowlands will be potentially flooded by meteoric events with a 1 year return period».

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 and tree stability etc. These effects could reach critical values long before the end of the 21<sup>st</sup> century, if the observed rates 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

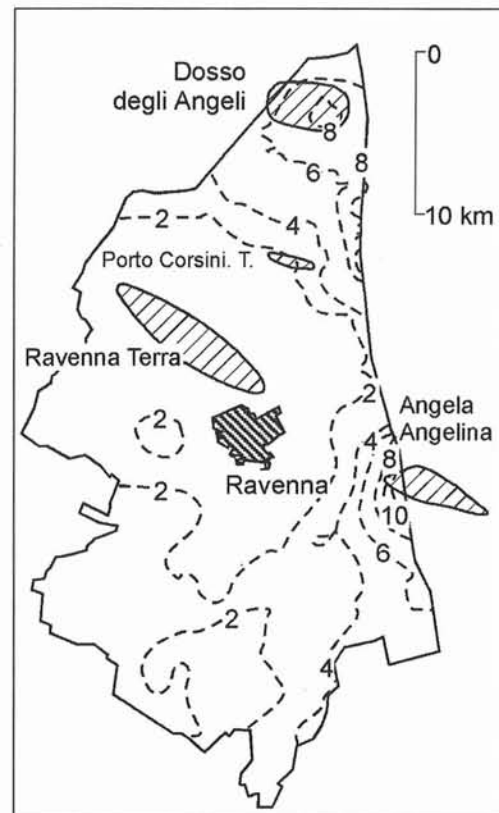


FIG. 9 - Subsidence rate contour lines (mm/y, dashed) and gas reservoirs in the Ravenna area (Redrawn from Bertoni, 2003).

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 are close to the natural value and of a medium IPCC 1992 eustatic rise (+48 cm).

In both cases, the shoreline erosion will continue to follow the same trend, resulting in a 50-70 m retreat of the beach. 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 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 & alii, 1995).

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