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The Lagoon of Venice: geological setting, evolution and land subsidence

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The paper deals with the geological setting, history and subsidence of the Venetian Plain. Major attention is paid to the Pleistocene-Holocene stratigraphic sequence in the Lagoon of Venice, in relation to its origin that dates back to 6–7 kyr BP. Geological land subsidence, which played an important role in the origin and the evolution of the lagoon, and anthropogenic subsidence, that has recently assumed a major importance for the Venetian environment, are discussed. Considering also the sea level rise, 23 cm loss in land elevation has occurred in the last century, leading to increased flooding events and environmental problems that require protective works.

Introduction

The lagoon of Venice is the largest lagoon in Italy, and the most important survivor of the system of lagoons which in Roman times characterized the upper Adriatic coast from Ravenna to Trieste. Bounded by the Sile River to the North and the Brenta River to the South, the Venice Lagoon is oblong and arched in shape. It covers an area of about 550 km^2, being 50 km long and 8–14 km wide. Its morphology consists of shallows, tidal flats, salt marshes, islands and a net of channels. The lagoon boundaries also include fish ponds, reclaimed areas and the coast that is presently interrupted by three inlets, namely Lido, Malamocco and Chioggia, which permit water exchange with the Adriatic Sea (Figure 1). The present setting of the Venice Lagoon is mainly the result of a number of human interventions.

Origin and evolution of the Lagoon

It has been demonstrated (Gatto and Carbognin, 1981) that the lagoon of Venice originated nearly 6–7 kyr BP during the Flandrian transgression, when the rising sea flooded the Upper Adriatic Würmian paleoplain and outlined the coast in approximately the present position. The early lagoon was smaller than the present one and the exchange of its waters with the sea occurred through eight inlets, against the three it has now. Originally, two main factors affecting the lagoon basin: i) the continuous sediment supply from Adige, Bacchiglione, Brenta, Sile and Piave rivers flowing into the lagoon, so that the filling was greater than the natural subsidence and the eustatic sea level rising; ii) the noticeable coastal nourishment, also coming from the Po river to the South, that led to a gradual silting-up of the tidal inlets.

These two processes steered unavoidably to the disappearing of the lagoon basin. Venetians, considering the lagoon a source of security against enemies and power with its channels and port, began to carry out several hydraulic works to preserve it. Mostly, the diversion of the major tributaries into the sea was started in 1400 AD and concluded in 1600 AD. They avoided making the lagoon a marshland, but also induced an abrupt reversal in its natural evolution. With the passing of time, sea properties began to prevail, enhanced further by human interventions. In fact, since 1800 man has newly altered the lagoon setting very intensely. He dug new deep canals and modified the sea openings, both in the number and the setting, to serve the industrial harbour; occupied intertidal flats to provide the necessary areas for new industrial and urban centers, and permanently closed areas for fish farms. These changes were decisive in spurring the lagoon hydrodynamics, accelerating erosion and modifying the flora and fauna habitat. Furthermore, in the last decades the industrial water supply was provided by rash exploitation of artesian aquifers causing a serious land subsidence. An induced consequence is a weakening of the littoral system (Brambati, 1987) with a deepening of the sea bottom that also contributes to the instability of the lagoon itself (Carbognin et. al., 1995).

Geological and sedimentological setting of the Gulf of Venice

Referring to the whole Venetian Plain, the geological setting down to about 5,000 m consists of Prepliocene, Pliocene and Quaternary deposits (Figure 2). The pre-Quaternary substratum southwards is characterized by fold and faulted overfolds, which are parallel to the main tectonic trend of the Apennines and include several gas-bearing traps at depths on the order of 2,000 m. Quaternary sediments range between 3,000 m (southern zone) and hundreds of meters (northern zone). They mostly consist of sandy and silty-clayey layers of alluvial and marine origin. The bottom follows the structure of the substratum showing a little tectonic disturbance only in the northern sector where the lagoon of Venice is found. The thickness of the Neozoic formations and, consequently, the subsidence rate exhibits a non-uniform space distribution.

The area of Venice is located in a complex foreland setting near the pinchout of both the Southalpine and the Apenninic wedges, that developed during Serravallian-Messinian and early Pliocene-Pleistocene times, respectively. The post-Messinian depositional sequence is represented by deep-sea hemipelagic deposits that drape the eroded Messinian surface: the *Santerno Clays* (Figure 3). This formation comprises Pliocene to middle Pleistocene sequences that crop out along the northern edge of the Apennines and is represented by isolated outcrops on the Alpine edge of the Po Valley. Its depositional environment is quite deep, from outer neritic to bathyal. The Santerno Formation is confined between the Messinian unconformity and the overlying Pleistocene *Asti Sands*. The Asti Formation displays an overall shallowing trend from turbiditic to deltaic/shallow-marine and finally continental settings. The present-day Venetian area was reached by the north-Adriatic turbidite system during the early to middle Pleistocene, due to the north-eastward shifting of the Apenninic foredeep. The *Asti Sands* turbiditic sequences show

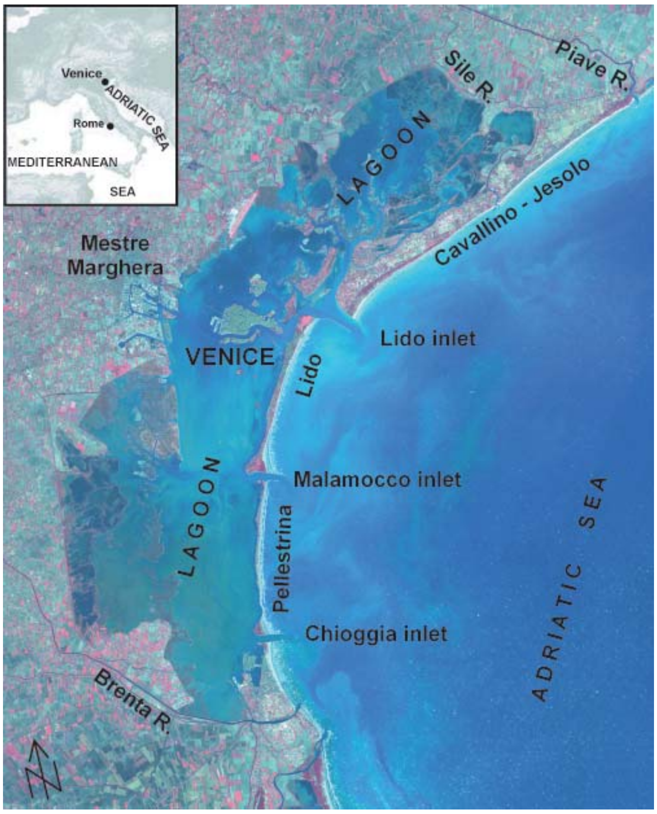

Figure 1 ASTER image of the Venice Lagoon and its surrounding mainland. Main localities are indicated.

flat parallel surfaces that onlap against the clayey substratum of the *Santerno Clays*. Peat-rich deposits close to the top of the *Asti Sands* indicate a floodplain environment. The thickness of the Asti formation is fairly uniform and averages 1,000 m. Close to the Po River delta, its thickness increases to up to 2,000 m.

Geological and palaeogeographical feature of the Venice area

Knowledge on geological and lithostratigraphical settings of the Venice area results from thousands of different analyses based on hundreds of cores drilled on purpose.

Main information sources about the Plio-Pleistocene subsoil are two boreholes: the VE-1 CNR, that extends down to 947 m with continuous coring, and the VE-2 CNR, down to 400 m, drilled with discontinuous coring. Recently, using an integrated magneto-bio-cyclo-stratigraphy of lithofacies and palynofloral analyses in the VE-1 core, Kent at al. (2002) could infer the following history: in the late Pliocene the depositional area was a strongly subsiding shelf which shoaled to near sea level; following a hiatus of at least 0.2 Myr the shelf rapidly drowned to bathyal depths over the early Pleistocene, and hemipelagic muds with sapropel layers were deposited; these are followed by a thick package of basinal turbidites, fed from the eastern Southern Alps; then, in the middle part of Brunhes, Po-related deltaic sedimentation led to the progressive infill of the basin; this episode ended with the first appearance of continental deposits; the upper part of the succession shows a cyclothemic organization with submergence of Venice area during glacio-eustatic highstands and emergence during glacial lowstands.

From the bottom of the borehole up to about 513 m in depth, the sands are characterized by a high amount of carbonate rock fragments (eastern South Alpine provenance). Going up to about 438 m in depth the composition abruptly changes into quartzolithic with large amounts of quartz and metamorphic rock fragments (from Alps/Northern Apennine). This change is indicative of a significant middle-Pleistocene tectonic movement of the region related to the dynamic of the Apennine foredeep. From about –438 to –19 m in depth, the sand composition is a mixture of the two types of sediments, reflecting the simultaneous activity of the two sources (Stefani, 2002). The uppermost part of the succession contains numerous peat layers indicative of floodplain to marsh environmental settings; in this part of the core a chronology was established on the basis of radiocarbon data.

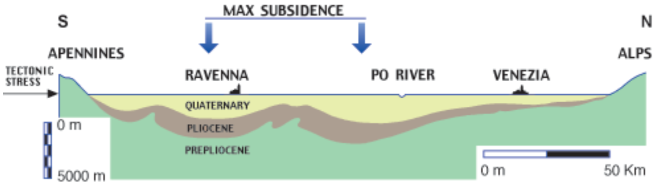

Figure 2 Schematic geological section across the eastern Po Plain (modified after AGIP Mineraria, 1969).

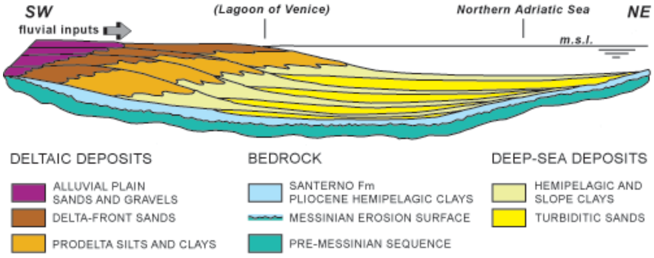

Figure 3 Sedimentological model of the post-Messinian basin across the Lagoon of Venice area and the northwestern Adriatic Sea (modified after AGIP Mineraria, 1999, unpublished report).

Kent et al. (2002) distinguished six prominent sea-level transgressions *tr1* throughout *tr6*, that occur at depths 10.5, 79, 136, 152, 202 and 262 m respectively, where continental sediments are overlain by shoreface and shelf marine deposits.

A good correlation with these transgressions results from recent analyses performed on thousands of cores. As examples, *tr6* and *tr3* may correspond to the top of regional aquifers 5 and 2 (Figure 4) and *tr1* reflects the base of the Flandrian transgression (Figure 5). The limit Holocene-Pleistocene is marked by a clay layer called *caranto* (Figure 6) which overcompacted because of the dry climate during the last phase of the low stand sea level. In spite of its discontinuity, it is an optimum marker horizon that ends the alluvial Pleistocene sequence (Gatto and Carbognin, 1981; Bortolami et. al, 1985). The *caranto* tends to emerge on the mainland, and varying between –5 and –23 m, gradually deepens towards the littoral (see Figure 5). A hiatus covering a period between 7 and 10 kyr from the last Pleistocene to the first Holocene deposition has been found (Bortolami et al., 1985; Tosi, 1994). The following marine Flandrian transgression progressively submerged the Würmian paleoplain and the *caranto*. The first presence of marine-lagoonal Holocene deposits founded in layers underlying the present southern littoral (Figure 7) have been dated 10–11 kyr BP (Bortolami et al., 1985). The early Holocene sediments are represented by a discontinuous level of silt and sand often in chaotic structure mixed with shelly marine-lagoon sands. The maximum flooding position was reached at 6–7 kyr BP when the primeval lagoon established. The middle-upper part of the series is a typical alternation of marine-lagoon and flood-plain sediments. During the following high-stand sea level, alluvial sedimentation re-established at the southern and northern outermost belts corresponding to the fluvial mouths. Moreover, some areas have been affected by episodes of emersion and submersion related to changes in climate, sediment source, subsidence rate and, finally, human intervention (Tosi, 1994; Bonardi et al., 1998; Carbognin and Tosi, 2002).

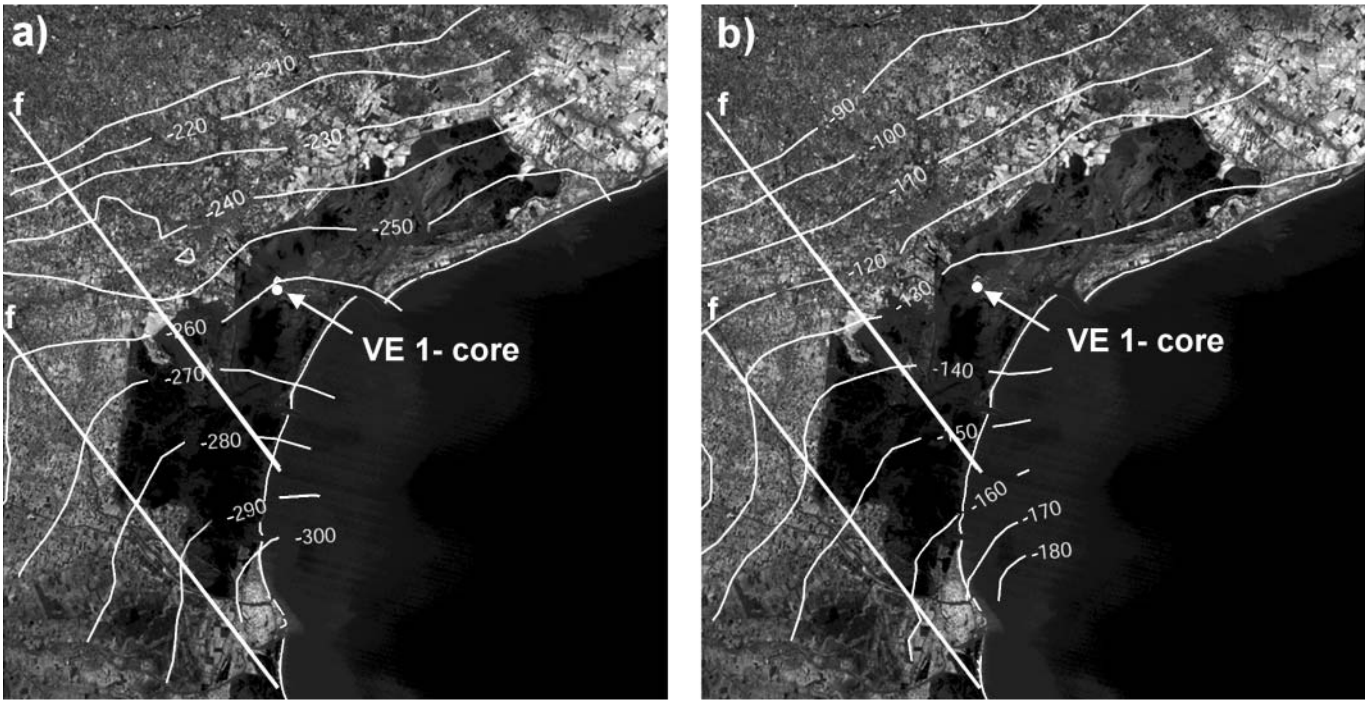

***Figure 4** Maps of the top (m a.s.l.) of: a) aquifer 5 and b) aquifer 2, which may correspond to tr6 and tr3, respectively, described by Kent et al. (2002). Straight lines (f) are drawn in correspondence to regional faults.*

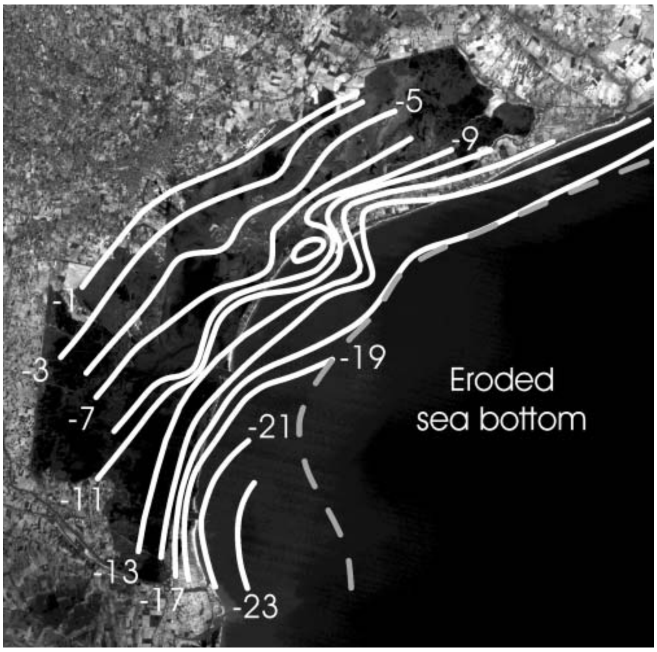

***Figure 5** Depth of Pleistocene-Holocene boundary (m a.s.l.) drawn on the basis of cores analyses and high-resolution seismic survey (courtesy of Aliotta, Carbognin, Stefanon). This surface agrees with the tr1 by Kent et al. (2002). Dashed line delimits the marine area where Holocene deposition has been eroding.*

Geological Subsidence

Estimates of natural subsidence rates result from both analysis on the VE 1-core, and from radiocarbon dating of latest Pleistocene and Holocene sediments collected in the lagoon and littorals (Bortolami et al., 1985).

According to Kent et al. (2002) the average long-term subsidence rate (less than 0.5 mm/yr) reflects mainly tectonic processes; it is rather lower than that occurring in the late Pleistocene-Holocene period (average rate of 1.3 mm/yr) which likely reflects the consolidation of sediments, and it is decidedly lower than the recent man-induced one (≥ 2.5 mm/yr). The average rate of 1.3 mm/yr dropped over recent centuries, reaching the current figure of 0–0.5 mm/yr (Gatto and Carbognin, 1981; Carbognin et al., 1995, 2003). Evidence of past tectonic influence could be the anomalous shape of the *tr3* and *tr6* contour dips close to the faults (see Figure 4).

Land subsidence due to natural consolidation played a major role during initial evolutionary phases of the modern lagoon. Later, the increased salt concentration in the clayey sediments of the substratum, inducing an electrochemical compaction process, caused a further lowering of the lagoon floor (Gatto and Carbognin, 1981).

Anthropogenic subsidence

Subsidence induced by groundwater withdrawals became a problem with the industrial boom after the 2nd World War. This process has been deeply studied, the cause-and-effect relationship quantified, and a 2-D and a 3-D simulation models were developed.

The exploited aquifer-aquitard system is located in the upper 350 m of the 1000 m thick unconsolidated Quaternary formation. Groundwater withdrawal, which progressively led to a noticeable drawdown of aquifer pressure, began in the 1930s reaching a peak between 1950–1970 together with the subsidence it caused (the maximum rate of 17 mm/yr was recorded between 1968–69 over the industrial zone). After this critical 20-year phase, a general improvement occurred quickly because of the closure of artesian wells and the diversification of water supply. The 1973 levelling clearly showed a reversed trend of subsidence and a slight but significant rebound was measured in 1975, with a maximum of 2 cm in the historical city, as predicted by simulation models (i.e. Gambolati et al., 1974). The 1993 and 2000 regional surveys confirmed the arrest of anthropogenic subsidence as a widespread phenomenon. Subsidence maps for the lagoon territory and the hinterland (Figure 8) show an ideal *line of demarcation* between the ground stability zones in the mainland, Venice and its surroundings, and the subsiding zones at the northern and southern extremities of the lagoon edge and along the littoral. This fact may be related to the greater thickness of the

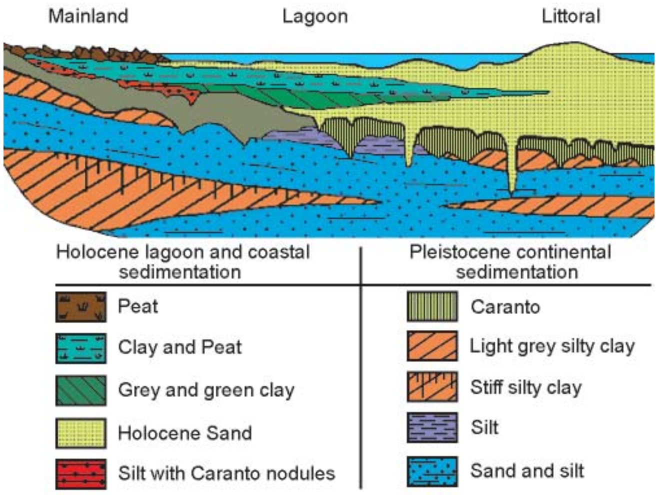

***Figure 6** Holocene-Pleistocene stratigraphical sequence across the central Lagoon of Venice (after Gatto and Previatello, 1974).*

sandy layers present along the Mestre-Lido axis with respect to those found in north and south lagoon areas where compressible clayey layers predominate. On the other hand, this *line of demarcation* could be correlated with maximum Flandrian transgression of about 6 kyr BP (see Figure 7). Concerning the subsidence recorded along the coastline (1–3 mm/yr), and at the furthermost northern and southern boundaries (2–4 mm/yr), it can be attributed to the greater natural consolidation of more recent formation in these areas, and to different local situations. Finally, both the uplift and the highest subsidence rate found in the central-southern lagoon edges may partly reflect tectonic activity. Integrated researches, still in progress, based on hydrogeological, geomorphological, geophysical and geoelectrical investigations, indicate the presence of the two faults (Figures 4 and 8). Satellite Radar Interferometry (InSAR) maps confirm this regional subsidence behaviour (Figure 8) and supply useful details of urban areas (Tosi et al., 2002).

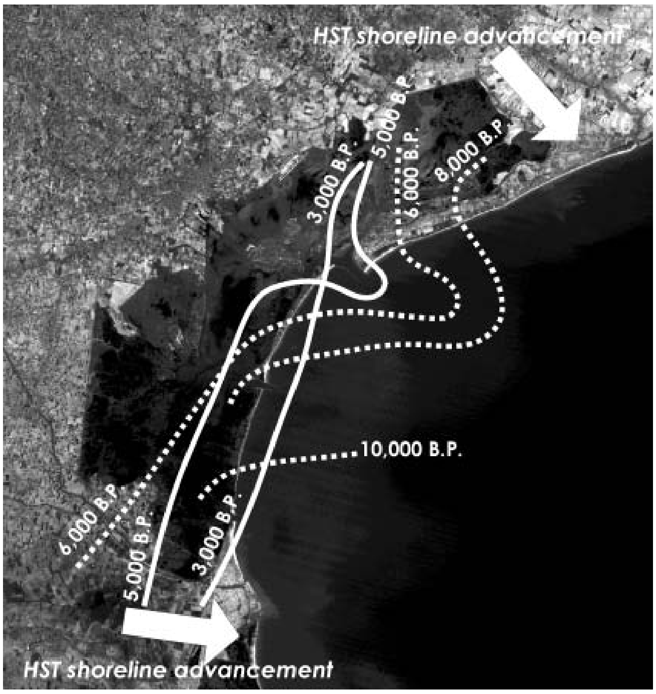

***Figure 7** Schematic model of the Venetian littoral evolution during the Flandrian transgression. Arrows indicate the shoreline advancement during the high-stand sea level because of the progradation of the river mouths (modified after Tosi, 1994).*

The overall relative land subsidence

The relative land subsidence of the city is associated with sea level rise. During the last century the elevation loss of 23 cm, consisting of about 12 cm of land subsidence, both natural (3 cm) and anthropogenic (9 cm), and 11 cm of sea level rise, has occurred. Referring to the latter issue, the most reliable estimate of the sea level rise in the Upper Adriatic over the last 100 years is given by Carbognin and Taroni (1996): excluding subsidence, a rising rate of 1.13 mm/yr was computed. The extent of the period is sufficient to average alternating

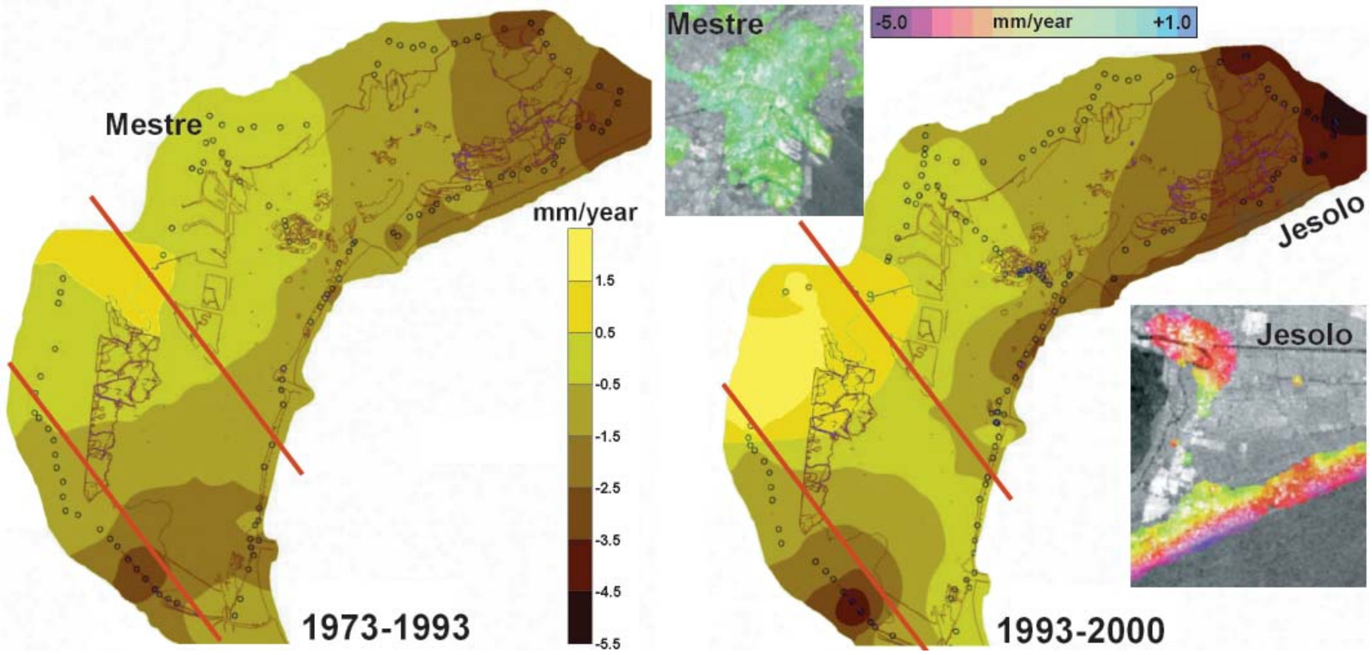

***Figure 8** Maps of annual vertical displacement (mm/yr) occurred in the periods 1973–1993 and 1993–2000 (after Carbognin et al., 2003). For the latter period, inserted smaller InSar deformation maps (after Strozzi et al., 2003) show in detail the two different situations of land stability at Mestre and subsidence at the northern littoral (Jesolo). Red lines correspond to regional faults.*

trends, corresponding to alternating climate changes. This rate is consistent with the data provided by others tide gauges in the Mediterranean Sea. Worth mentioning is that in the last decades the rise of sea level is slowing down slightly both in the Mediterranean Sea and in the Indian Ocean (Tsimplis and Baker, 2000; Mörner et al., 2003).

The relative 23 cm rise in the sea level in the Lagoon has created a great concern since it has contributed to the increasing of: i) the flooding phenomenon, both in frequency and degree, with immediate and indirect damages to population and monumental patrimony; ii) the hydrodynamics inside the lagoon, leading to erosion of its floor, channel silting up, and changes in the internal eco-morphology; and iii) the fragility of littorals, enhancing the risk of destructive sea storms and flooding from overtopping.

Conclusions

The Lagoon of Venice is the largest one of the Mediterranean Sea and is located on a foreland between the Alps and the Apennines. The lagoon originated 6–7 kyr BP, establishing its domain over the Würmian paleoplain, which has influenced its original morphology. Subsequent evolution of the basin has occurred through different phases. Initially, during the high-stand sea level, a significant role was played by the alluvial yield, which was not counterbalanced by both sea level rise and subsidence causing the filling in of the basin and progradation of the river mouths. In historical times, human intervention, going from the diversion of tributaries to more recent rash groundwater exploitation, has reversed the natural evolutionary trend, favouring the deepening of the lagoon and seriously modified the morphological setting of the environment.

Summarizing the results, it can be said that natural subsidence ranged between 0.5 and 1.3 mm/yr during the Quaternary, and that man-induced processes more than doubled the rate in the period 1950–1970. The land survey of 2000 shows that subsidence is no longer occurring in the central part of Venetian area, which includes the city, the Mestre-industrial zone and surrounding territories, but it is still going on at the northern and southern lagoon areas and bordering lands. Anyway, since subsidence is mostly irreversible and a contribution to the land lowering with respect to mean sea level is given by eustasy, 23 cm of relative elevation loss has occurred during the last century, inducing consequences that require restoration and safeguarding measures.

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