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A study on the effects of seismicity on subsidence in foreland basins: An application to the Venice area

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Abstract

Foreland basins are flat elongated areas occurring along subduction and collision zones worldwide. We show that, in such basins, subsidence can be induced by earthquakes generated along bordering thrust faults due to coseismic displacement, postseismic displacement and liquefaction-induced compaction.

As an example, the potential effects of earthquakes on the subsidence of Venice, which is located in the Po Plain foreland basin, are discussed. It is generally assumed that natural subsidence of Venice is continuous and that subsidence rates are rather constant through time. However, catastrophic pulses of subsidence cannot be ruled out as taught by the sudden disappearance of the island of Malamocco at the beginning of the XII century.

The results of numerical models specifically run suggest that the risk of subsidence accelerations in Venice due to coseismic displacements is negligible. Modelling results from literature suggest that postseismic subsidence could be of the order of 1 cm. Although the effects of a single event should be improbably detectable, such a subsidence is not a priori negligible considering the number of seismogenic sources located within 100 km from the town.

Historical sources are utilized to discuss the feasibility of liquefaction-induced subsidence in Venice. It is shown that the destruction and sinking of ancient Malamocco is roughly coincident with a strong earthquake cycle that was associated to phenomena that can be explained with liquefaction of sandy layers. Although the historical documents do not permit to establish a clear causal link between the earthquake and land subsidence, it is concluded that liquefaction-induced subsidence cannot be ruled out as a potential source for local subsidence acceleration.

Keywords: subsidence; Venice; Italy; earthquake; liquefaction

1. Introduction

Dramatic subsidence has been related to earthquakes occurring along subduction zones. For example, subsidence up to 1–2 m along a 1000 km long coastal area of Chile was induced by the magnitude 9.5, 1960 Chile earthquake, which generated along the subduction of the

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Nazca plate underneath the South American plate (Cisternas et al., 2005). During the magnitude 9, 2004 Sumatra earthquake, 1–4 m of subsidence were preliminarily reported in the Nicobar islands (Bilham et al., 2005). Not necessarily coastal areas are affected by subsidence during subduction related earthquakes. For example, Darwin during his Beagle voyage witnessed an earthquake that occurred along the Chile coast in March 1835 and reported that “the most remarkable effect (….) of this earthquake was the permanent elevation of the land” (Darwin, 1839). During the 2004 Sumatra earthquake, the western shorelines of the Andaman islands was affected by 1–2 m of uplift (Bilham et al., 2005). The kind of vertical motion depends on the position of an area with respect to the seismogenic fault.

Foreland basins are elongated subsiding areas located at the front of mountain belts (De Celles and Giles, 1996) and are associated to subduction or collision zones. Such basins are widespread worldwide and the fact that they are generally flat areas characterized by subsidence renders them vulnerable to sea level changes when they are located in coastal areas. They are generally bordered by active reverse (or thrust) faults that contribute to the build-up of adjacent mountain belts, although in some cases thrust faults can be buried also beneath the basin sediments (Doglioni, 1993). Earthquakes induced by the movement along such faults can generate subsidence pulses, which can accelerate the general subsidence trend. Examples of earthquake-related subsidence are reported for foreland basins worldwide. For example, during the magnitude 7.6, 1999 Chi-Chi earthquake, Taiwan, up to 36 cm of subsidence occurred in the foreland basin of the Taiwan mountain belt (Pathier et al., 2003).

In this contribution we analyse, for foreland basins, the potential sources of earthquake-related subsidence, namely coseismic deformation, postseismic deformation and local sediment compaction due to liquefaction of sand layers. As an application we analyse the potential impact of earthquakes on the subsidence of Venice, which is located in the Po Plain. The Po Plain is the foreland basin of two mountain belts (the Alps and the Apennines; Doglioni, 1993; Fig. 1) and several active (mainly thrust) faults occur along the northern and southern borders of the plain and buried under the clastic sedimentary cover (Valensise and Pantosti, 2001; Fig. 2). This makes Venice potentially sensitive to earthquake-related subsidence.

The assessment of all the potential sources of subsidence in coastal lowlands in general, and of Venice in particular, is crucial for the preservation and for the physical survival of such coastal areas, a problem which gained increasing international interest due to the potential effects of the near-future sea-level rise predicted by climatic models (IPCC, 2001).

The subsidence history of Venice has been extensively studied using geological (e.g., Pirazzoli, 1987; Carminati and Di Donato, 1999), geophysical (e.g., Carminati et al., 2003a) geodetic (e.g., Tosi et al., 2002; Carbognin et al., 2004; Teatini et al., 2005) and historical/archeological (Ammerman et al., 1999; Ammerman and McClennen, 2000; Camuffo and Sturaro, 2003) data. These studies highlighted that different processes contribute to subsidence. Subsidence in the Venice area is the sum of natural and anthropic processes. With this contribution we focus on natural contributors to subsidence.

A background subsidence around 1 mm/yr is induced by geodynamic processes acting on time scales of the order of 10^6 years. In particular, it has been shown that the subduction of the Adriatic plate, on which Venice rests, under the Apennines determines a downflexure of the Po Plain increasing from north to south (Doglioni, 1993; Carminati et al., 2003a, 2005). A much smaller contribution (around 0.3 mm/yr; Fontes and Bortolami, 1973; Bortolami et al., 1977; Carminati et al., 2003b) comes from the effects of the melting of ice caps, which started some 18,000 years ago and drove to a sea level

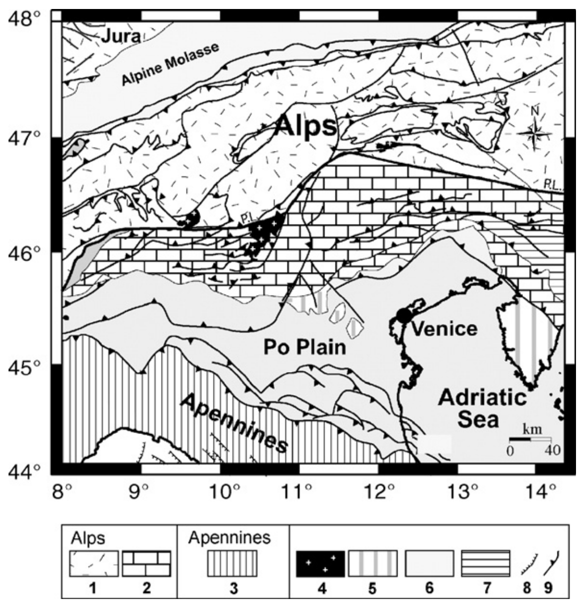

Fig. 1. Simplified geological map of the Po Plain and surrounding mountain belts. Alps: 1) Australpine, Penninic and Helvetic units; 2) Southern Alps units. Apennines: 3) Apenninic units; 4) Tertiary and Quaternary volcanic and plutonic bodies; 5) foreland units; 6) foreland basin units; 7) Dinaric units; 8) normal faults; 9) thrust faults. Redrawn and simplified from Bigi et al. (1990). P.L. Periadriatic line.

rise in the northern Adriatic sea (Amorosi et al., 1999). Since these two subsidence components sum up, the total rates of subsidence in the Venice area due to natural (geological processes) determined from geological data are around 1.3 mm/yr.

The problem of Venice is the combined effect of the land subsidence and the absolute sea level rise (eusthatism), as both contribute to increase the apparent sea level (ASL). The ASL is the sea level experienced by people as measured with tide gauges fixed to buildings, which take reference to the local subsiding land. A natural proxy index of the average high tide level is the brown-green belt left by algae on the canal buildings.

Tide gauge records of the ASL started in 1872 and the average ASL rise vas 2.4 mm/yr; this however includes an additional worsening due to the extraction of underground water in the period 1925–1965. Prior to instrumental records, the ASL rise in Venice was estimated after the level of archaeological remains and the displacement of the algae belt. The observations of archaeological evidence cover almost two millennia, the early remains being dated AD 200. In this long period, the average ASL rise has been estimated to be 1.3 mm/yr (Ammerman et al., 1999; Ammerman and McClennen, 2000) showing that the eusthatism had a negligible contribution, or that it has been partially masked by the uncertainty of the methodology. An evaluation of the ASL rise over the last three centuries, i.e., since the last phase of the Little Ice Age, has been made from the displacement of the algae belt, which were accurately documented in the Canaletto's (1697–1768) and Bellotto's (1722–1780) paintings. The average trend is 1.9 mm/yr (Camuffo and Sturaro, 2003; Camuffo et al., 2005) showing a relevant contribution of the eusthatism during the global warming period.

Until now the discussion on the ASL rise has assumed that the background natural subsidence is a continuous process at constant rate and that only the eusthatism is variable. We want to test if averaging the subsidence rates hides the occurrence of subsidence-rate accelerations due to catastrophic processes, such as seismic events.

2. Seismicity-related sources for subsidence

The seismic cycle is composed of three main stages (Scholz, 1990): i) loading or pre-seismic stage,

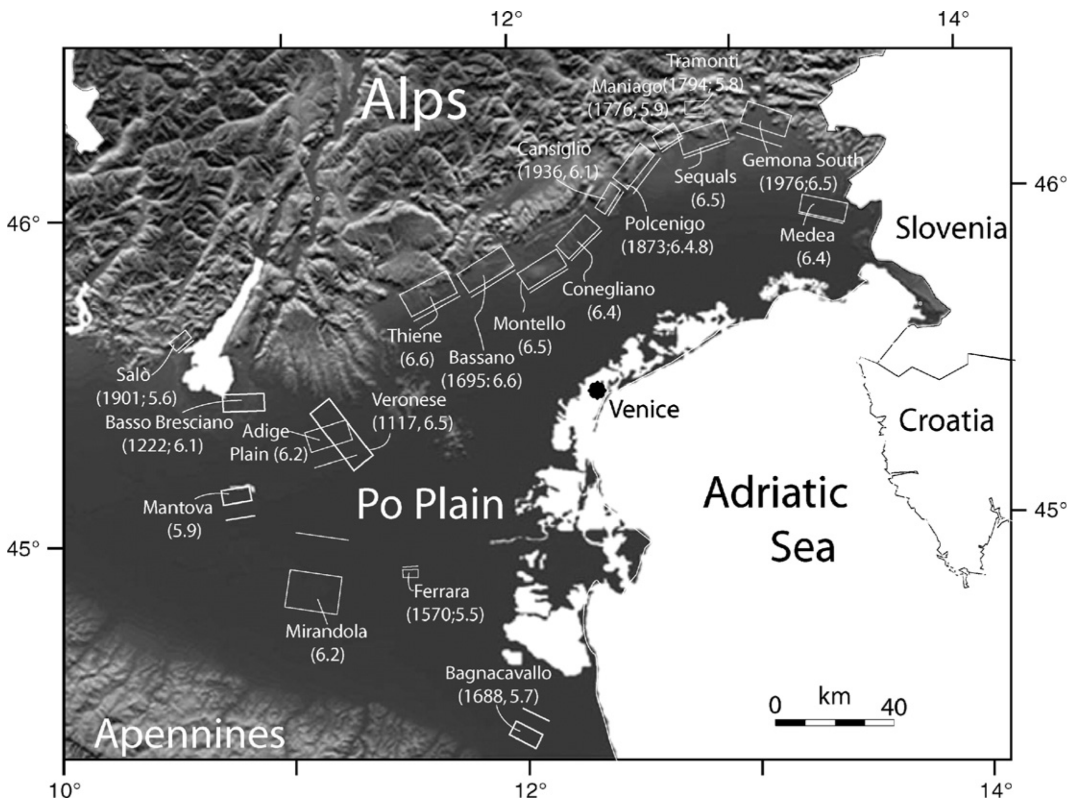

Fig. 2. Tectonic map showing the location and extension of potentially active faults in the Po Plain area. In parenthesis, the year of the last known large earthquake associated to the fault (if known), and the maximum expected magnitude.

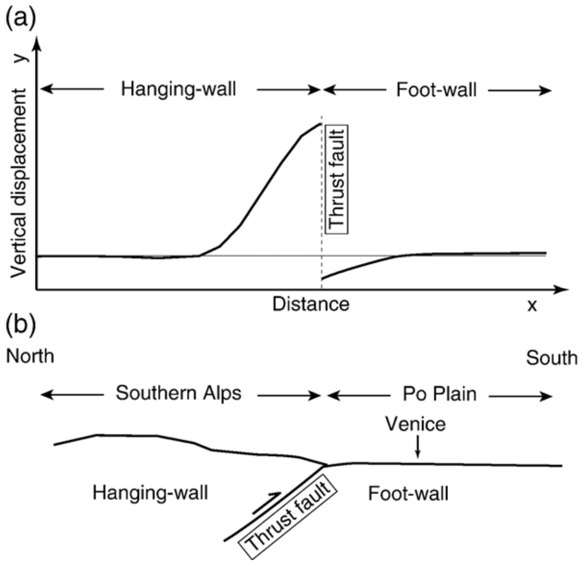

Fig. 3. Sketch of vertical motions expected during coseismic phase along a profile perpendicular to a thrust fault.

characterised by strain accumulation and stress build up; ii) coseismic stage, corresponding to the irreversible slip along the fault occurring when yield stress along the fault is exceeded; iii) post-seismic stage, characterised by the viscous adjustment of crust and mantle to the fast displacements occurred during the coseismic stage.

It is widely accepted that significant vertical displacements can occur during coseismic and post-seismic stages. For this reason the following discussion will focus mainly on these stages. However, it has been recognised that minor vertical motions can occur also during pre-seismic stages.

In the following sections we consider all the possible earthquake-related factors that can lead to subsidence in the footwall of thrust faults, with the exception of pre-seismic deformation.

Slip along thrust faults, being the sense of motion perpendicular to the fault direction, is expected to generate far larger vertical displacements with respect to that occurring along strike-slip faults both during coseismic and post-seismic phases. For this reason, and for the reason that thrust faults predominate in foreland basins in general and in the Po plain in particular, the following discussion will focus on thrust faults.

2.1. Coseismic displacement

As shown in Fig. 3, the upward motion of the hangingwall block along thrust faults causes a complex pattern of vertical displacement (e.g., Zhao et al., 2004). The part of the hangingwall which is far from the fault suffers a very moderate subsidence, whereas the portion of the hangingwall close to the fault is characterised by a significant uplift, which is systematically increasing towards the fault tip. The footwall is characterised by subsidence which is mainly flexure related. It is here emphasised that Venice is located on the footwall of all the thrust faults surrounding the Po Plain. For this reason Venice could potentially be the site of earthquake related subsidence. It may be noticed, however, that subsidence decreases almost exponentially with increasing distance from the fault. Moreover, the footwall subsidence is far smaller than the hangingwall uplift. This means that, in order to have a moderate but sensible footwall subsidence, the slip along the fault has to be relevant.

Coseismic subsidence of the footwall was detected both with InSAR and GPS techniques for the $M_W = 7.6$ 1999 Chi-Chi (Taiwan) earthquake (Pathier et al., 2003), developed along a nearly 100-km-long surface rupture zone. In profiles perpendicular to the fault strike, the subsidence decreases form a maximum of 36 cm in the vicinity of the fault to a minimum of 5 cm, some 30–40 km far from the fault, in correspondence with the coast. No data for offshore subsidence are available.

The pattern shown in Fig. 3 is typical of earthquakes along faults whose displacement reaches the surface. Also in the 1999 Chi-Chi earthquake rupture reached the surface (Lin et al., 2001). The rupture depth interval of the faults surrounding Venice does not reach the surface (Valensise and Pantosti, 2001). For this reason a slightly different displacement profile is expected, although the main features (i.e., uplift of the hangingwall and subsidence of the footwall) are expected to persist.

Moreover, the magnitude of the Chi-Chi earthquake is much larger (by more than an order of magnitude) than the magnitudes of earthquakes expected around Venice. It is finally emphasized that Venice is some 50 km far from the closest potentially active fault.

It is therefore difficult to infer from literature data whether Venice could be potentially in danger from coseismic subsidence. Given these uncertainties, modelling simulating vertical motions induced by slip along potentially active faults around Venice has been performed and the results will be presented in a later section.

2.2. Postseismic displacement

An earthquake accommodates the sudden elastic release of the stress accumulated during the preseismic phase and consists therefore in a stress step. The Earth reacts to such an imposed stress step with time-dependent deformations. The relaxation of Earth after an earthquake is termed post-seismic deformation and its activity spans over periods ranging from days to years (e.g., Nur and Mavko, 1974).

Postseismic deformation, that has been observed in many cases using geodetic techniques, is accommodated by several relaxation mechanisms, which are active on different timescales (Lyzenga et al., 2000). Long term measurements of the earthquake cycle show that lower crustal and mantle viscoelastic response to the stress step occurs with decadal timescales. In other words, the rock volume surrounding a fault along which an earthquake

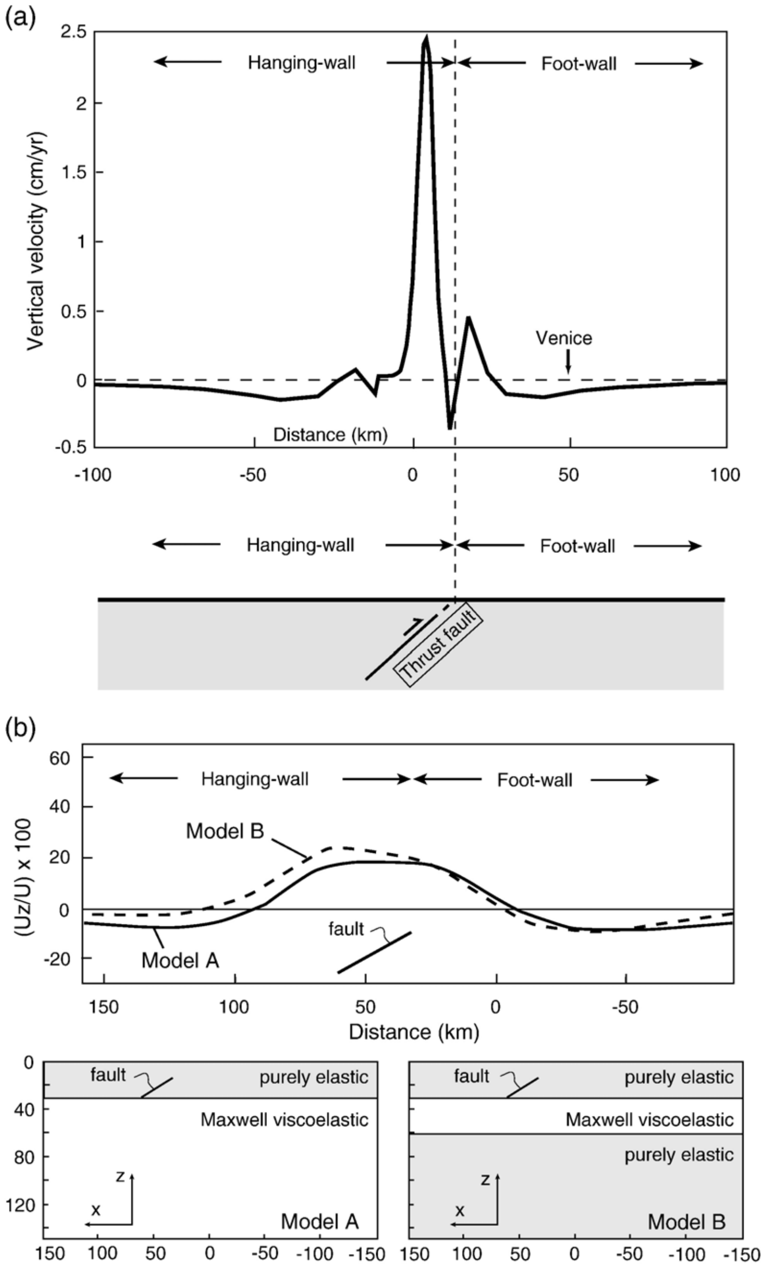

Fig. 4. (a)Vertical velocities (mm/yr; positive values mean uplift and negative values subsidence) predicted from finite elements modelling at a time $t=1$ year following the 1994 earthquake along the Northridge thrust fault dipping 40°. Redrawn and modified after Lyzenga et al. (2000). (b) Postseismic vertical displacement accumulated along thrust faults at a time $t=105$ years after the earthquake. U_z is the vertical displacement at the surface and U is the displacement along the fault. The solid and dashed curves are the results of two numerical models (A and B) characterised by radically different Earth's rheological stratifications (see lower panels). Notice that such radical changes are not accompanied by commensurate changes in the predicted vertical motions. Modified after Pollitz (1997).

occurred is characterized by time-dependent readjustment as the underlying viscoelastic material relaxes in response to the imposed static stresses (Pollitz, 2003). Postseismic transient motions occurring with timescales of several months have been also recognised. These deformations have been related to fault plane afterslip and bulk relaxation in the uppermost shallow crust due, for example, to poroelastic relaxation (Scholz, 1990).

Postseismic deformation vanishes exponentially with time, as shown by continuous GPS monitoring of deformations after the 1994 M_W=6.7 Northridge (California) earthquake, which showed that postseismic deformation was practically over only two years after the seism (Donnellan and Lyzenga, 1998). A similar behaviour has been recognised after the 1989 Loma Prieta (California) earthquake (Bürgmann et al., 1997). Five years after the earthquakes, vertical motions were not significantly different from those measured in the 20 years prior to the earthquake.

Fig. 4a shows the results of a forward finite element model (see Lyzenga et al., 2000 for a complete description of the model and of the assumed parameters) simulating rates of post-seismic vertical motion following the 1994 Northridge earthquake. The earthquake resulted from motion along a 40° dipping blind thrust fault (Hauksson et al., 1995). Modelling results are consistent with GPS measurement data (Donnellan and Lyzenga, 1998). The modelling considers only the relaxation in viscoelastic near surface layers. In other words, only one of the potential mechanisms determining postseismic deformation is included. The pattern of vertical velocities predicted is quite complex, with an uplift peak (with rates up to 2.5 mm/yr) on the vertical of the fault. Moving away from the fault in both footwall and hangingwall, a first local subsidence area (with rates of 4 and 1 mm/yr in the footwall and in the hangingwall respectively) is followed by a secondary peak of uplift (with rates of 5 and 0.5 mm/yr in the footwall and in the hangingwall respectively). Two broad areas of subsidence follow in both footwall and hangingwall with maximum subsidence rates of about 2 mm/yr. In the footwall such subsidence area extends to some 90 km from the fault. The subsidence predicted for the footwall is consistent with geodetic observations. For example, Bürgmann et al. (1997) showed that cumulative postseismic vertical displacement in the footwall of the Loma Prieta thrust fault was as high as 4 cm.

Fig. 4b shows the results of another model of postseismic deformation (see Rundle, 1982; Pollitz, 1997 for a complete description of the model and of the assumed parameters). In this figure the total postseismic vertical displacement at the surface some 105 years after the earthquake is expressed as a percent of the slip on the fault. If, for instance, the predicted relative vertical motion (U_z/U) is −0.08, as resulting for the footwall areas, a subsidence of 8 cm is to be expected in the realistic case of 1 m fault slip. The solid and dashed curves are the results for two radically different Earth's rheological stratifications (models A and B). It appears that only minor differences occur in the subsidence predicted for the footwall areas. Comparing Fig. 4a and b, it is evident that the curves predicted by the Lyzenga et al. (2000) and the Pollitz (1997) models are qualitatively similar: both predict uplift above the fault and subsidence in the hangingwall and in the footwall.

It can be concluded that both results of numerical modelling and geodetic measurements suggest that postseismic deformation could have an impact on subsidence in Venice, as more widely discussed in a later section.

2.3. Liquefaction and soil compaction

A third relevant cause of subsidence related to earthquakes is to be found in the behaviour of soil once it is affected by the shaking induced by the transit of seismic waves.

A process potentially affecting subsidence is liquefaction, i.e., the transformation of a granular deposit from a solid state into a liquefied state as a consequence of the increased pore-water pressure determined by cyclic shaking (Youd, 1977).

This occurs when the surface is underlain by a saturated, sand rich layer of soil. Prolonged shaking can cause the expulsion of fluid from the sand layer resulting in large mud and sand volcanoes that erupt through the overlying strata. Fluid and soil expulsion consequently induce local subsidence effects.

Sediment compaction and subsidence have been induced by the 2001 M_W=6.8 Nisqually (Washington) earthquake, a deep intraslab event within the subducting Juan de Fuca plate with a hypocentre 52 km below the ground surface. Montgomery et al. (2003) suggest that settling and compaction of surface deposits of the Seattle Basin and liquefaction of partially saturated valley-bottom deposits were responsible for post-seismic increases in streamflow.

The compaction response to earthquakes is quantitatively controlled by local geological conditions such as the presence of unconsolidated or liquefiable deposits. For this reason it is not possible to predict quantitatively subsidence related to earthquake-induced compaction.

A prerequisite for this process to occur is the occurrence of unconsolidated shallow aquifers. It is here emphasized that Venice is built on lagoon sediments rich

Table 1
Main characteristics of the seismic sources located in a radius of 100 km around Venice. The same sources are displayed in Fig. 2

Fault name	Distance from Venice (km)	Max. magnitude	Average slip (m)	Fault dimensions: length and width (km)	Min. and Max recurrence time (yr)
Medea	100	6.4	1.0	16 × 9	3536–10,000
Sequals	94	6.5	1.3	16.5 × 9	4915–13,000
Maniago	90	5.9	0.66	8 × 5.5	1941–6600
Gemona South	110	6.5	1.32	16 × 9	1143–13,200
Polcenigo	78	6.4	1.0	15 × 8.5	1286–3214
Cansiglio	66	6.1	0.75	10 × 6.4	1149–1436
Conegliano	53	6.4	1.0	15 × 8.5	964–3214
Montello	45	6.5	1.5	16 × 8.9	964–3214
Bassano	56	6.6	1.5	18 × 9.5	1721–2151
Thiene	66	6.6	1.5	18 × 9.5	1500–15,000
Adige plain	93	6.2	0.64	15 × 8.5	700–6400
Ferrara	90	5.5	0.35	5.1 × 4	700–3500

in water. The soil of Venice has been for centuries under the weight of the town buildings; however, the city has always grown with new buildings or creating new buildable areas covering with earth canals and marshes, producing a new overload and increasing deep pressure. Therefore, it cannot be excluded that processes such as vibration induced compaction or liquefaction of water rich lenses of sediments can lead to local subsidence effects. Evidence that this process can have occurred in the past in Venice (as suggested by Galli, 2000) will be discussed later.

3. Assessment of seismicity-related subsidence risk for Venice

In the following sections we will focus, as an example of subsidence in foreland basins, on the risk of subsidence induced by earthquakes in the Venice area. The discussion will be based on modelling results both from literature and obtained specifically for this study as the coseismic and post-seismic deformations are concerned. The danger related to liquefaction and soil compaction will be analysed considering historical data.

3.1. Coseismic displacement

Venice is located closer to the Southern Alps, where earthquakes are generated by top to the south thrust faults, than to the active faults associated to the Apennines belt. A comprehensive list of such seismogenic faults is provided by the database of potential sources for earthquakes larger than $M = 5.5$ in Italy named "Database of Individual Seismic Sources", version 3.0.1 (DISS; Valensise and Pantosti, 2001; http://www.ingv.it/%7ewwwpaleo/DISS3/). Such faults are represented in Fig. 2 and their main characteristics (taken from the DISS 3.0.1 database) are listed in Table 1. To discuss the risk of coseismic subsidence in the Venice area induced by earthquakes, we present the results of calculations which simulate the deformations induced by a seismic event that could be potentially generated by the motion along the Montello thrust fault (see Fig. 2 for the location). However, calculations were performed for all the sources located within 100 km from Venice and listed in Table 1. We display the results obtained only for the Montello fault because the other sources generate negligible motions in Venice. This is due to the following reasons.

Table 2
Location, geometric characters (location, dip, strike, rupture depth range, fault length) and potential seismic behaviour (characteristic slip, rake) of the Montello fault. These parameters were used in the modelling of the coseismic vertical motions

Fault name	Longitude; latitude (deg)	Length (km)	Strike (deg)	Dip (deg)	Rake (deg)	Depth (deg)	Average slip (m)
Montello	12.2315; 45.8265 12.0528; 45.7545 12.0089; 45.8076 12.1875; 45.8796	16.0	240	40	80	1.0–6.7	1.5

First, the Montello fault is the recognised seismogenic source that is closest to Venice (at a distance of about 45 km). As it can be observed in Table 1, it is the only seismic source located within 50 km from the town. When assessing coseismic vertical motions, the distance from the source is one of the most important factors, since vertical motion decreases with the square of the distance from the source (e.g., Turcotte and Schubert, 1982). Cavallin and Marchetti (1995) drew in a structural map of northern Italy a fault crossing the Venice lagoon (i.e., much closer to Venice than the Montello fault). According to these authors the fault was recognised by inspection of aerial photographs. However, no evidence of recent activity along the fault exists and such a fault is not included in the DISS 3.0.1 database (Valensise and Pantosti, 2001). Moreover this fault has not been imaged in seismic lines running just off the lagoon (Carminati et al., 2003a). For this reason such a fault has not been considered for coseismic displacement modelling.

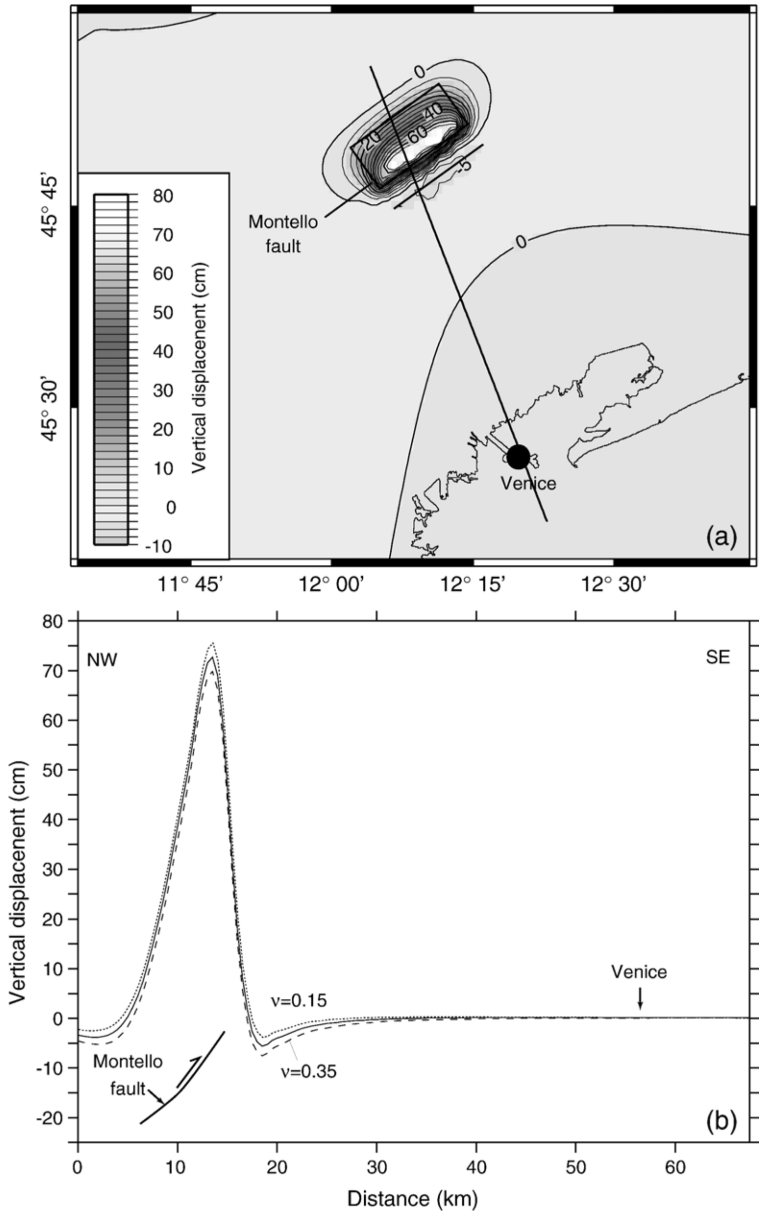

Fig. 5. Vertical displacement (in cm) in map view (a) and along a profile (b) predicted for the Montello Fault. The map (a) and the solid line in (b) were calculated assuming Young's modulus $E=8\times10^4$ MPa and Poisson's Ratio $\nu=0.25$. The dotted and dashed lines in the graph of panel (b) show coseismic vertical motions obtained varying the Poisson's ratio between 0.15 and 0.35, keeping fixed the remaining parameters.

Second, the Montello fault is characterised by the largest average slip along the fault (1.5 m) and by one of the largest expected maximum magnitudes (6.5 against the 6.6 magnitude predicted for the Bassano and Thiene faults).

Third, the Montello fault is favourably oriented with respect to Venice, since the town is located exactly in front of the fault. Other faults, such as Bassano and Thiene, although characterised by slip and magnitude comparable to that of the Montello fault are slightly more distant from Venice and less favourably oriented. Seismic sources located outside Italy (e.g., in Slovenia or in Croatia) are located at distances greater than 150 km and are therefore negligible for the purpose of calculating coseismic subsidence of Venice.

The simulations were performed using the Coulomb 2.5 software (Toda and Stein, 2002), which lets one calculate static displacements caused by fault slip implementing the elastic dislocation formulae of Okada (1992). In the calculations, a laterally homogeneous medium assumption is adopted. The following elastic parameters are assumed for the crust in the discussed calculations: shear modulus, $G=3.2\times10^4$ MPa; Young's modulus $E=8\times10^4$ MPa; Poisson's Ratio $\nu=0.25$. The coefficient of friction is 0.4. These are the default values of the Coulomb 2.5 software and are widely accepted in literature. As later discussed, a sensitivity analysis on these parameters indicated that significant changes of the elastic properties do not change the significance of calculation results for the Venice area.

The geometric characters (location, dip, strike, rupture depth range, fault length) and the potential seismic behaviour (characteristic slip, rake) of the Montello fault were taken from the DISS 3.0.1 database (Valensise and Pantosti, 2001) and are shown in Table 2.

Fig. 5 shows the results of our modelling both in map-view and in a profile. The slip along the Montello thrust fault produces a very pronounced uplift of about 80 cm of the hangingwall on top of the fault. A subsidence of about 4 cm is predicted for the hangingwall just NE of the fault. The footwall is characterised by uplift in the first 10 km SE of the fault. At greater distance, a small (ca. 5 km long) area of subsidence with displacements of 6 cm is predicted. At the Venice location, no vertical displacement associated to the coseismic deformation is predicted, as it can be observed in the graph of Fig. 5b (solid line). These results are in good agreement with the results obtained for 1976 $M_S=6.5$ Friuli earthquake (Northern Italy) obtained with numerical modelling by Armigliato and Tinti (2003). This earthquake occurred along a top to the south thrust fault and induced a slip comparable to that predicted by Valensise and Pantosti (2001) for the Montello fault.

As already mentioned, we made several simulations changing elastic parameters without remarkable changes in the predicted motions. As an example, in Fig. 5b we show the results (dashed and dotted lines) obtained varying the Poisson's ratio (ν) between 0.15 and 0.35. It can be observed that slight changes occur in the motions predicted in the vicinity of the fault. However, the three curves display a null coseismic vertical motion of Venice.

It can be concluded that the results of our modelling excludes that coseismic displacement can be envisaged as a possible cause of subsidence in the Venice area. This conclusion should be, however, revisited, if other potential seismic sources closer to Venice will be discovered in the future.

3.2. Postseismic displacement

The modelling results shown in Fig. 4a seem to suggest a potential danger for Venice from postseismic subsidence. Both the modelled fault (Northridge) and the Montello thrust faults are blind thrusts. Venice is located some 50 km from the fault and the model predicts for this location a subsidence of about 2 mm/yr at a time $t=1$ year after the occurrence of the earthquake. Although post-seismic deformations are expected to vanish rapidly with time, such relatively fast subsidence rates could be sufficient to create danger to the town of Venice. If, supposedly, such subsidence rates were active for only five years, the resulting subsidence of 1 cm would be equivalent to the natural subsidence predicted to occur in about ten years.

A few notes of caution are, however, necessary. First, a change of the adopted rheological stratification of the Earth within a naturally reasonable interval would certainly change the results, but such changes should be limited to a few factors, as shown by the results of Pollitz (1997) models (Fig. 4b). In other words, total postseismic subsidence greater than 2–3 cm is unlikely considering the discussed Lyzenga et al. (2000) modelling results. If the results shown in Fig. 4a and b are qualitatively comparable, the Pollitz (1997) model (Fig. 4b) predicts much larger subsidence for the footwall of thrust faults (i.e., some 8–12 cm for a fault with a slip of 1.5 m, as the Montello fault). However, the results of Fig. 4b were obtained for a fault (dimension: 200 × 15 km) much bigger than the Montello fault (dimension: 16 × 8.9 km) and the other seismic sources located in the Venice area. As a consequence the results shown in Fig. 4b cannot be used to infer the magnitude of subsidence in the Venice area. Fig. 4b is rather shown to evaluate the result changes due to changes in the assumed rheological stratification.

Second, only one postseismic relaxation mechanism, the viscoelastic relaxation, is considered in the discussed model. However, it has been demonstrated that the viscoelastic relaxation is the only process susceptible to produce postseismic deformation over long time periods (5 years and longer) and large spatial scales (over 100 km). The inclusion of the remaining two mechanisms (fault plane afterslip and pore pressure reequilibration) should lead to minor changes.

Third, the Montello fault is shallower (the shallower tip is at a depth of 1 km) than the fault modelled (shallower tip at 5 km depth) by Lyzenga et al. (2000).

Fourth, in the postseismic modelling, a laterally homogeneous medium assumption is adopted. This is clearly a simplification of real environments.

A postseismic subsidence of Venice of the order of 1 cm, as predicted by the Lyzenga et al. (2000) model, would produce very limited impact on the town. This result would not change if postseismic subsidence would raise to 2–3 cm. However, the notes of caution listed above suggest that the numerical results displayed in Fig. 4a should not be acritically applied to the Venice case. Even if the value of 1 cm should be considered reasonable, a further note of caution is necessary. Such a subsidence estimate is referred to a single seismic event. The Venice area is, however, surrounded by several potential seismic sources located within 100 km from the town. Both Fig. 4a and b show that subsidence in the footwall can extend to distances of 100 km (or more) from the fault. As a consequence, each source of Fig. 2 could potentially drive to postseismic subsidence of the order of 1 cm. The activation in a relatively short time period of more than one source could lead to a summation of the subsidence effects and be less negligible.

3.3. Liquefaction

The possibility of soil compaction and subsidence related to liquefaction induced by earthquakes is investigated using historical documentary sources.

A useful source of information is provided by the analysis of written documents, e.g., chronicles, annals, diaries covering two millennia and describe natural hazards, climatic situations, extreme meteorological events and sometimes also the daily weather by direct or quoted witness. Sometimes, the sources report both events and their impact on the environment and society, in which case it is also possible to establish a semi-quantitative value, or to classify the events according to a scale of severity, as deduced from the effects. This uninterrupted set of data provides a unique opportunity to discover the response of the sea to past climate changes over a particularly long period including the Medieval Climatic Optimum, the Little Ice Age, and the period of Present-Day Warming, as well as their transition.

Starting from 1980, the climatic unit of CNR in Padova, now CNR-ISAC, started to gather the documentary proxies seeking in public and private archives and libraries in Italy. When a useful information was collected, it was associated with the original date supplied by the source, the critically revised date, key words, bibliographical reference, exact text quotation in the original language and, finally, some historical notes concerning reliability of the author, the context, or cross checking with other controllable items. In this way a huge Data Bank was formed, that includes more than 1000 extended documents of different periods and various lengths. The crude text of documents extends for 6.3 MB on the hard disk. The methodology, content and validation were described in a number of papers (Camuffo and Enzi, 1994; Enzi and Camuffo, 1995; Pfister et al., 1999). The choice of the sources is based on their historical reliability (for a discussion on this subject see Alexandre, 1987; Enzi, 1993; Enzi and Camuffo, 1995; Pfister et al., 1999). For the period AD 1200–1800, a test on the accuracy of dating and completeness of the information was made by comparing the occurrence of solar and lunar eclipses and the passage of comets included in the Data Bank with the actual number of these events known after astronomical calculations (Camuffo and Sturaro, 2004). The proxy data from this Bank have been used for several studies (e.g., the ongoing EU project MILLENNIUM) and publications, but are not yet for public release.

In this CNR-ISAC Data Bank, that includes meteorological events and natural hazards for the period from the foundation of Venice (mid-4th Century AD) to 1800 (end of the period considered in the Data Bank), we find copy of documentary sources mentioning earthquakes at Venice per each of the following 52 years:

445; 745; 815; 840; 1020; 1099; 1102; 1105*; 1108*; 1110*; 1114*; 1117*; 1119*; 1183; 1213; 1222; 1223; 1225; 1229; 1233; 1268; 1275; 1278; 1280; 1283; 1286; 1288; 1299; 1302; 1308; 1348; 1372; 1413; 1426; 1451; 1457; 1504; 1511; 1513; 1522; 1523; 1563; 1575; 1576; 1591; 1667; 1680; 1688; 1780; 1781; 1786.

For this work, several sources have been analysed, but only the main and more reliable ones were considered, i.e.,:

(1) Anonymous, “Cronaca Veneziana o meglio Zibaldone con molti ricordi meteorologici”, Library of Museo Correr, Venice, Ms prov. divv. C 815 3, c. 18.
(2) P. Justiniano, Venetiarium historia vulge Petro Justiniano Justiniani filio adiudicata, pp. 89–90, in “Deputazione di Storia Patria per le Venezie”, edited by R. Cessi and F. Bennato, Venice, 1964.

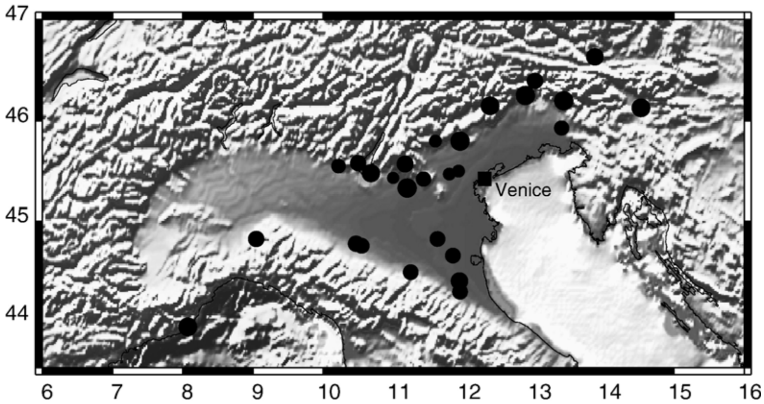

Fig. 6. Location of the epicentres (located within the map) of historical earthquakes which, according historical fonts according to the (Boschi et al., 1995) catalogue, affected Venice in the past 2000 years. The circle diameters are scaled to the earthquake magnitude reported in the catalogue.

(3) Anonymous, Annales Venetici breves, pg 71, in "Monumenta Germanicae Historiae, Scriptorum", XIV, edited by H. Simonsfeld, Hannover, 1883.
(4) Annales Mediolanenes Breves, p. 390, in "Monumenta Germanicae Historiae", Scriptorum, XVIII, Hannover 1863.
(5) Romualdi Salernitani Chronicon, p. 208, in "Rerum Italicarum Scriptores", T. VII, V. I, Zanichelli, Bologna, 1935.

A difficult problem concerns the exact dating to avoid duplication or even multiplication of the same event, which may have an incorrect or obscure dating. This is especially true for the medieval or early sources, where a number of events occurred in different years are quoted in the same date of the most relevant one. Furthermore, often only the period of the occurrence is given, e.g., the rule of a Doge or a Pope. This use makes difficult to establish the exact temporal order and cause–effect relationships of these events, as the listing was often made on subjective criteria. Unfortunately, the Ducal Palace, where the original documents of the Republic were conserved, suffered several fires, the most famous in 976, 1105, 1574, 1577, and many original documents were lost. The present collection (Corpus) of Venetian manuscripts begins in the 14th century, with some previous documents; starting from this period, a number of chroniclers collected and reported the main events, so that the early period is documented with many second hand sources that make difficult, or even impossible, an exact dating. Boschi et al. (1995) published a comprehensive database of historical earthquakes that affected Venice in the last ca 1600 years. A search of strong earthquakes felt in northeastern Italy but not reported in documents referred to Venice was also performed. From the analysis of historical sources Boschi et al. (1995) suggest that Venice was affected by at least 39 earthquakes in the last 2000 years. Fig. 6 shows the location of the epicentres of these earthquakes.

However, our attention is not focused on normal earthquakes, but on the most catastrophic ones that may have changed the subsidence rate in Venice. Only one earthquake may be considered to this aim, i.e., the terrible one that in the early 1100s determined the total decline of the ancient Metamauco (in the island of Malamocco). It was the most important island of Venice, but during the span of years 1102–1117 (following the more reliable sources) its settlements were destroyed by a sequence of catastrophic events: fires and sea surges followed by an earthquake. This last one is defined by several chronicles from the whole Northern Italy as tremendous and "universal". The sources describing the event in the Venetian area write about buildings crumbled; some documents mention also mountains collapsing and fissures on the land. "Sulphur water" sprang and caused the fire in a church of Venice, as described <year 1117> in the following document:

> In the 15th year of the Doge <Ordelaf Falier, 1102–1118>, on January 13th, an earthquake occurred, at places weaker and at places stronger. The earthquake destroyed buildings, upset mountains and slopes and the earth cracked and sulphur rich water came out. Due to this, the church of Saint Ermagora <now S. Marcuola> got burnt together with adjoining buildings... This happened in the day of St. Paul's Conversion, and since then this day was called "St. Paul of earthquakes" *(Translated from the Latin).*

The mention of sulphur was probably due to the fact that this mineral was used to light fire and for the smell. Probably the land emitted some methane, that is abundant in the marshy areas, and that still today continues to bubble in the sea. Fires in homes may have ignited the methane with dramatic effects, maybe worsened by the wind. The third key fact was the sea, which completely submersed the town of Malamocco.

The most intriguing explanation for the dramatic sea-level rise in the Malamocco area is liquefaction and related soil compaction. The liquefaction process may have been enhanced by the presence of local geomorphologic unconformities, such as paleo-river beds.

Some lines of evidence support this hypothesis. Firstly, the sediments of the Venice lagoon are mostly unconsolidated and consist in an alternation of sand silt and clay (Frassetto, 2005 and references therein). They are therefore rich in water and therefore some sandy layers may be prone to liquefaction if shaken by seismic waves.

Secondly, the expulsion of water through fissures in the soil, mentioned in historical sources, is perfectly compatible with the expulsion of fluid from the sand layer resulting in large mud and sand volcanoes, typical of the liquefaction process. The loss of water in sandy layer is necessarily accompanied by sediment compaction and, therefore, subsidence. The expulsion of water proves satisfactorily that liquefaction occurred. It remains to be proven that the causal link exists between liquefaction and compaction related subsidence and sea-level rise. The local nature of such phenomena in the case of the disappearance of the town of Malamocco is, however, consistent with the local nature of liquefaction, which occurs only in areas where saturated sandy layers exist.

However, other scenarios cannot be completely excluded. A first scenario considers a surge generated by the Sirocco wind, similar to that occurred in 1966, which raised by 2 m the sea level in Venice. The fresh Sirocco wind may have favoured the spread of fire, especially in the case of wooden buildings. Alternatively it can be argued that the earthquake and the fire destroyed the island and, only later, a series of 'normal' surges cancelled the island abandoned by its inhabitants.

A third scenario considers a tsunami generated by the earthquake. Historical sources suggest that several tsunami waves hit the northeastern Italian coast (Caputo and Faita, 1984). In the northern Adriatic area, main earthquake sources (mainly thrust faults) are located in inland areas of northeastern Italy, Slovenia and Croatia and in the northern Adriatic offshore of Croatia and Italy (e.g., Peresan et al., 2002, 2003). Due to the inland location of the sources and to the shallow water depth of the northern Adriatic Sea, the generation of tsunami could seem improbable. However, numerical models have shown that earthquakes along faults located under the coast or in the immediate inland can generate tsunami waves (Yanovskaya et al., 2003). The decay of tsunami intensity when moving the source toward the inland depends on dip, length, and depth of the fault. As a reference, the intensity of a tsunami generated by a 10 km inland fault is about 25% of that from an offshore earthquake. Moreover Yanovskaya et al. (2003) have shown that a tsunami wave can be generated irrespective of the water depth of a basin. A well-preserved tidal notch at a depth of 0.5–0.6 m below the present mean sea level occurs along the eastern Adriatic coast from Zadar (Croatia) to the Italian border (Pirazzoli, 2005). The submergence of such a morphological feature has been interpreted as generated by coseismic subsidence, thus supporting the feasibility of strong earthquakes along the Adriatic coasts. It can be concluded the earthquake sources surrounding the northern Adriatic could potentially be tsunamigenic.

According to Caputo and Faita (1984) the main events that affected the northern Adriatic occurred in the years 792, 963, 1106 and 1511. The 1106 event was directly related, in ancient sources, to the destruction of Malamocco. However in a more recent tsunami catalogue for Italy (Tinti et al., 2004; http://www.ingv.it/italiantsunamis/tsun.html) only the 1511 event is still included. This 1511 event was induced by an earthquake located in inland (40 km from the coast) northeastern Italy (Friuli region) and produced severe damage in Venice, where it was characterized by anomalous oscillations in the canals (some of them dried). In the same catalogue, the 1106 event has been considered as a false event. If the false nature of the event is correct, the tsunami origin for the destruction of Malamocco should be excluded. In any case, a tsunami can be responsible for damage and for morphological changes (particularly changes of the coastline) but it is by no means responsible for permanent land subsidence and sea level changes.

All of the above discussed scenarios are possible: the key point is that we lack a precise timing of all of these events that may have occurred all together, in the same night, or in the course of years.

The dating is uncertain, and those mentioned in the manuscripts are indicated with an asterisk in the above list, i.e.,: 1105; 1108; 1110; 1114; 1117; 1119. The year 1117 is the most attested, being quoted by 11 documents. The day is also uncertain, with more reliable attribution to 3 March or 25 January, the day of the St Paul conversion. The latter is more probable for the local tradition which attributes to this Saint a special protection against earthquakes. The same date is also supported by the earliest available document (see quoted text above), i.e., a Venice History (Historiae Venetae) from the origins to 1382 by Anonymous, preserved in the

Marciana Library (Codex cl. VII, cod. 127, n. 8034, c. 769). From the main historical evidences, the sequence of the dramatic events in Venice area seems to be the following: 1105: fires, earthquake; 1108–1110: sea surges, fires destroying Malamocco; 1117: earthquake, “sulphur water”, fires. Anyway, a different succession or a simultaneous nature of the events cannot be excluded.

4. Conclusions

Several lines of evidence show that subsidence can be induced by earthquakes along subduction and collision zones, and in particular in foreland basins. In such areas, the main potential sources of subsidence induced by earthquakes generated along thrust faults bordering the basins are: coseismic displacement, postseismic displacement and liquefaction-induced compaction. As an example, in this work we analysed the potential effects of earthquakes on the subsidence of Venice, which is located in the foreland basin of two mountain chains (the Alps and the Apennines). The results of numerical models specifically run suggest that the risk of subsidence accelerations in Venice due to coseismic displacements associated to earthquakes developed along active faults around and within the Po Plain is negligible. Modelling results from literature suggest that postseismic subsidence associated to seismogenic movements of thrust faults located around the Po plain, at the foothills of the eastern Alps, could be of the order of 1 cm. Although the effects of a single event should be improbably detectable, such a subsidence is not a priori negligible considering the number of seismogenic sources located within 100 km from the town. Analysing historical sources we suggest that liquefaction affected Venice during the 1117 earthquake, in agreement with previous studies (Galli, 2000). We show that the destruction and sinking of Malamocco is roughly coincident with this strong earthquake cycle. Although the historical documents do not permit the establishment of a clear causal link between the earthquake and land subsidence, it is concluded that liquefaction-induced subsidence cannot be ruled out as a potential source for local subsidence acceleration. An alternative tsunami origin for the destruction of Malamocco, although physically feasible as shown by numerical modelling results, has been excluded in the most recent catalogue of Italian tsunami.

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