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THE GROWTH AND DECLINE OF PISA (TUSCANY, ITALY) UP TO THE MIDDLE AGES: CORRELATIONS WITH LANDSCAPE AND GEOLOGY

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ABSTRACT: Sarti G. *et al*., *The growth and decline of Pisa (Tuscany, Italy) up to the Middle Ages: correlations with landscape and geology*. (IT ISSN 0394-3356, 2010)
The history of Pisa up to the Middle Ages was influenced by the local landscape. Pisa is located at the confluence of two rivers, has easy access to the sea, is surrounded by wetlands, and overlies a clay-sand substrate characterized by highly plastic clay near the ground surface. All of these characteristics have played a significant role in the history of Pisa along with socio-economic and socio-political conditions. Pisa is located in western Tuscany, about 15 km from the Tyrrhenian Sea, in a very flat coastal plain (Pisa plain) crossed by the meandering Arno River. The origin of Pisa dates from the 5th century BC when Pisa was an Etruscan settlement. In the 2nd century BC the Romans built *Portus Pisanus* harbour. Pisa was known as an important commercial and political centre in the Middle Ages and obtained the status of Maritime Republic, similar to Venice, Genoa and Amalfi. In 1284, its defeat in the battle of the Meloria against Genoa caused the beginning of the city's decline. In 1509, Pisa passed definitively under the domination of Florence. The history of Pisa was influenced by many factors related to the local landscape. It started at the confluence of two large rivers, Arno and *Auser*, an old branch of the Serchio River. These rivers represented a resource for transport of goods; however, they also necessitated the continuous management of hydraulic works to protect the town from floods and to avoid the formation of the wetlands.
The Pisa plain was characterized by wide and numerous wetlands. Unlike other areas of Italy, the wetlands were more an economic resource than a cause of health problems like malaria or developmental complications for transport and agriculture. In any case, a network of artificial canals was built to partially drain these wetlands and impede their expansion. Its sea- and river-harbours made Pisa an important Marine Republic during the Late Middle Ages. Pisa had commercial influence on the coast of the Tyrrhenian Sea, Corsica, Sardinia and the Balearic Islands until progressive siltation and catastrophic events caused the abandonment of the harbours. Foundation problems vexed Pisa, as evidenced by the famous Leaning Tower. The problem originates from the nature of the subsurface, which is characterized by highly plastic clay layers at shallow depth; the thickest (7–8 m called *pancone*) occurs at about 10 m below the surface.

RIASSUNTO: G. Sarti et al., Crescita e declino di Pisa (Toscana Italia) fino al Medioevo: correlazione con il territorio e la geologia *(IT ISSN 0394-3356, 2010)*
*La storia di Pisa fino al medioevo è analizzata in funzione dell'influenza dei fattori geologici e fisiografici del territorio. La sua posizione geografica alla confluenza di due fiumi, circondata da aree palustri, con un facile accesso al mare e costruita su un substrato caratterizzato da un livello argilloso fortemente compressibile hanno giocato un ruolo importante nell'influenzare la sua storia anche se, un ruolo determinante lo hanno avuto fattori socio-economici e socio-politici. Pisa si trova nella porzione nord occidentale della Toscana a circa 15 km dal Mar Tirreno in un'area di pianura (pianura dell'Arno) caratterizzata da pendenze molto basse e delimitata dai Monti Pisani a NE dalle colline di Livorno e Pisa a S e dal Mar Tirreno ad W. E' attraversata dal fiume Arno che forma numerosi meandri prima di sfociare in mare. La storia di Pisa inizia nel V secolo AC, come insediamento Etrusco. Successivamente nel II secolo AC, quando fu costruito il Portus Pisanus, diviene una colonia Romana. Nel Medioevo è un importante centro commerciale e politico ed ottiene lo status di repubblica marinara come Venezia, Genova ed Amalfi. Nel 1284 la sconfitta della Meloria da parte di Genova segnò l'inizio del suo declino politico ed economico che culminò nel 1509 con la conquista da parte di Firenze. La città fu costruita alla confluenza di Arno e Auser, quest'ultimo un vecchio ramo del fiume Serchio ormai non più esistente. I due fiumi costituirono una risorsa per Pisa che li utilizzò per il trasporto di merci come il carbone, materiale da costruzione provenienti dai Monti Pisani, legname o come via di comunicazione. Ma fu anche costretta a continue opere di intervento e manutenzione idraulica per impedire sia le esondazioni sia la formazione e l'estensione delle aree palustri che hanno caratterizzato fino al secolo scorso buona parte della pianura di Pisa. A differenza di altre aree limitrofe le aree palustri non costituirono per Pisa un'emergenza sanitaria (malaria) o un ostacolo agli spostamenti e allo sviluppo dell'agricoltura ma piuttosto una importante risorsa socio-economica. Furono utilizzate come vie d'acqua, come riserve alimentari per la pesca e la caccia, per la raccolta di canne utilizzate nei forni per la cottura della ceramica. Le aree palustri come risorsa furono però strettamente connesse alla costruzione di una fitta rete di canali per permetterne il drenaggio e limitarne l'espansione. Tali opere furono particolarmente attive durante le fasi di crescita economica e sociale della città. Viceversa diminuirono o cessarono durante le fasi di declino di Pisa causando l'espansione incontrollata delle aree palustri che divennero a quel punto un problema. La costruzione del Portus Pisanus e del porto urbano furono le premesse che permisero a Pisa di divenire nel Medioevo una importante Repubblica marinara con influenze commerciali sulla costa tirrenica, sulla Corsica, Sardegna ed Isole Baleari. I processi di insabbiamento del Portus Pisanus ne determinarono, nel Medioevo, l'abbandono ed il successivo spostamento mentre, eventi di piena catastrofici causarono, in età romana, la distruzione del porto urbano. Problemi di stabilità delle fondazioni ben evidenziati dall'inclinazione della famosa "Torre pendente", hanno contraddistinto il centro urbano di Pisa a causa della particolare natura dei primi 10 m del sottosuolo caratterizzati dalla presenza di un livello argilloso plastico (*pancone*), spesso 7-10 m e molto compressibile.*

Keywords: Pisa, Tuscany, Roman times, Middle Ages, local landscape, geoarcheology.
Parole chiave: Pisa, Toscana, età Romana, Medioevo, territorio, fisiografia, geoarcheologia.

1. INTRODUCTION

Landscape features are the result of a complex interplay among many factors. Of these, geology represent a key-factor particularly notable because it is minimally impacted by human activities and highly influential on landscape features. The objective of this paper is to analyze how the interactions among geology, geomorphology, hydrology, and human-society behaviour influenced the development of the city of Pisa up to the Middle Ages.

Pisa lies on the banks of the Arno River, about 15 km from the Tyrrhenian Sea (Fig. 1A, B). It is situated in the centre of a very flat coastal plain (Pisa plain) boun-

ded by the Pisani Mountains to the northeast, the Leghorn and Pisa hills to the south, and the Tyrrhenian Sea to the west. It is characterized by mild Mediterranean climatic conditions.

Pisa was founded as an Etruscan settlement in the 5th century BC (BRUNI; 1998) at the confluence of two large rivers: the Arno and the *Auser* that was a former branch of the Serchio River. A riverine harbours built close to Pisa by the Etruscans and continued to be exploited by the Romans. Afterwards in the 2nd century BC, a marine harbour known as *Portus Pisanus* was constructed by Romans farther from Pisa along the Tyrrhenian sea coast near the modern Leghorn (Fig. 1a,b).

After the fall of the Roman Empire, Pisa remained an important harbour city for Goths, Longobards and Carolingians (TANGHERONI *et al*., 2004). In the Middle Ages, Pisa was an important commercial and political centre equal to the others Maritime Republic of Venice, Genoa, and Amalfi. The economic and political power of the city extended over Tuscany, Sardinia and the Corsica coast. Pisa was a carrier for the early crusades. The success of the first crusade against the Saracens led to greatly expanded maritime trade in the Mediterranean. However in 1284, Pisa was defeated by Genoa in the naval battle of Meloria, not far offshore from the present town of Leghorn (Fig. 1a). This defeat marked the beginning of the city decline that culminated in 1509 when Pisa was definitively conquered by Florence.

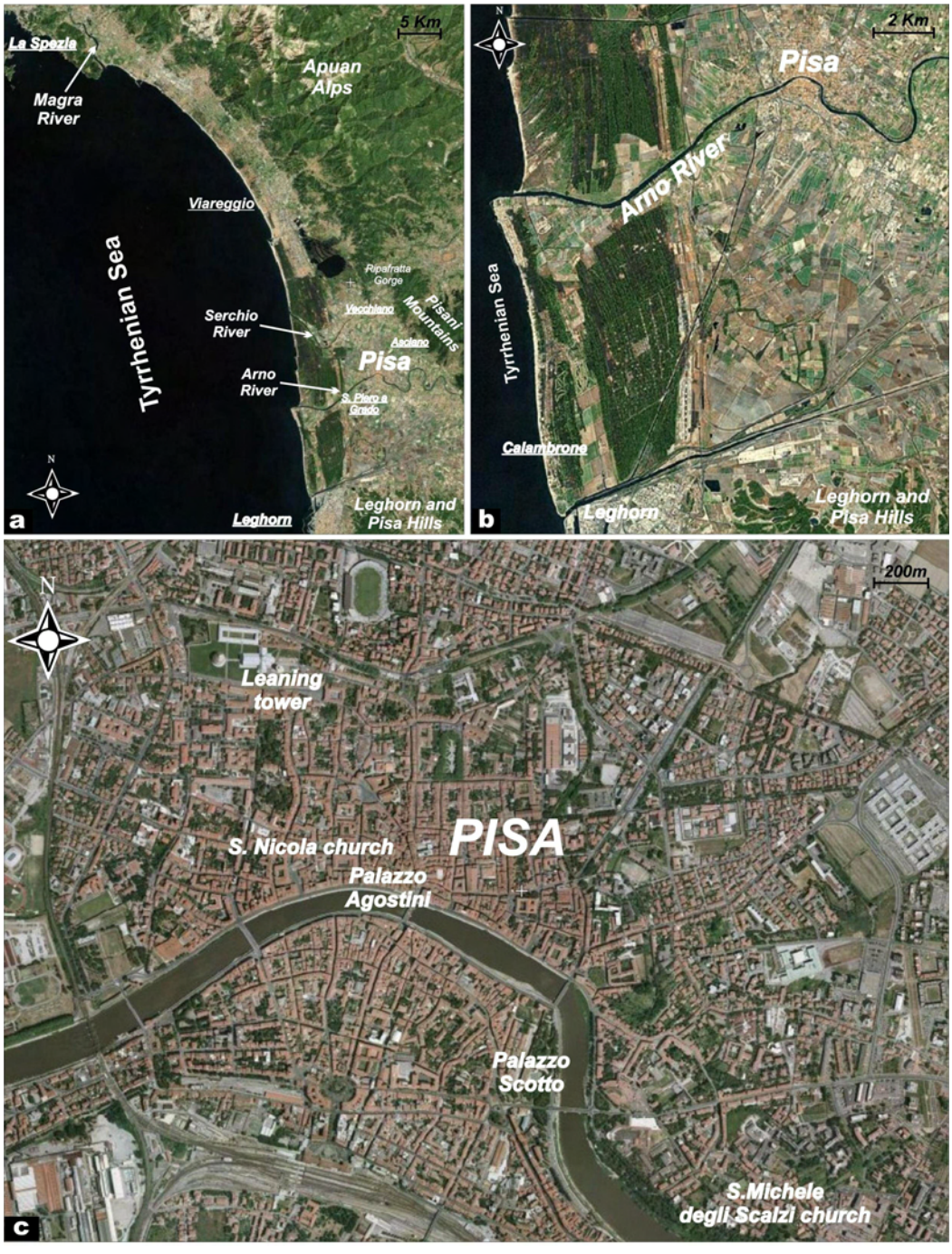

Fig. 1 - (a) Northern sector of the Tuscany coast and location of the city of Pisa; (b) Pisa coastal plain (c) aerial view of the city of Pisa.

(a) Settore settentrionale della costa toscana e posizione della città di Pisa; (b) pianura costiera di Pisa; (c) veduta aerea della città di Pisa.

2. GEOLOGICAL AND GEOMORPHOLOGIC SETTING

The Pisa coastal plain occurs in southern part of the subsiding Viareggio Basin (Western Tuscany) (Fig. 2) that developed on the southwestern side of the Northern Apennines mountain chain (Tuscany) during the Late Tortonian (MALINVERNO & RYAN, 1986; SARTORI, 1989; PATACCA *et al*., 1990; MARTINI & SAGRI, 1993; PASCUCCI *et al*., 1999, 2001; PASCUCCI, 2005). The basin formed in response to the opening of the Tyrrhenian Sea and the eastward counter-clockwise migration of the Apennine foredeep –foreland system.

The depocenter of Viareggio Basin, which is located close to the present coastline, was filled with up to 2500 m of upper Miocene–Present sediments (PASCUCCI, 2005).

AGUZZI *et al*. (2005) and AMOROSI *et al*. (2008, 2009) established the stratigraphic framework for the upper Quaternary deposits beneath the lower Arno River valley, which consists of a cyclical alternation of continental and coastal marine deposits. An incised valley, formed during the last glacial stage (OIS 2) and broadly coinciding with the present Arno River course, is found at a depth of about 60 m (Fig. 3). The thickness of the Holocene deposits reaches 50 m in the valley depocentre, but decreases drastically up to 17 m close to the valley margins (AGUZZI *et al*., 2007; AMOROSI *et al*., 2008).

The valley deposits fill includes three superposed millennial-scale sediment cycles, bounded by flooding surfaces that define small-scale parasequences. These high-frequency transgressive-regressive cycles are latest Pleistocene to Holocene in age (13 to 8 cal kyr BP) and display characteristic sequences of sharp-based estuarine clays grading upward into inner-estuary, bay-head delta, and coastal-plain deposits. Pollen data document a close relationship between parasequences development and the late-glacial to early-Holocene climate change (AMOROSI *et al*., 2009).

Following a rapid sea-level rise, the palaeovalley was completely flooded and most of the interfluves were submerged by the sea. Eastward transgression (Fig. 3) continued until around 7500 BP, when the coastline was located more than 7 km inland from its present position (MAZZANTI & PASQUINUCCI, 1983; DELLA ROCCA *et al*., 1987; SARTI *et al*., 2008a). To the east of the coast, a wide lagoon developed and plastic clay deposited (Fig. 3). These deposits, known as *pancone*, are typically 10 m thick beneath Pisa and cause the foundation problems suffered by the famous Leaning Tower.

The subsequent highstand was characterized by repetitive phases of progradation, which resulted in the development of the modern Arno delta and its adjacent coastal plain system (Fig. 3). From Pisa to the coastline, the plain is currently composed of alluvial muddy and sandy deposits that develop seaward into a wide sandy strandplain system composed of several juxtaposed coastal dune ridges (Figs. 2,3). The alignment of these ridges records the position of the coastline over the last 3000 yrs. (PRANZINI, 2001). The wetlands that historically characterized a great portion of the plain have been progressively reclaimed during recent centuries (BALDASSARI & GATTIGLIA, 2009).

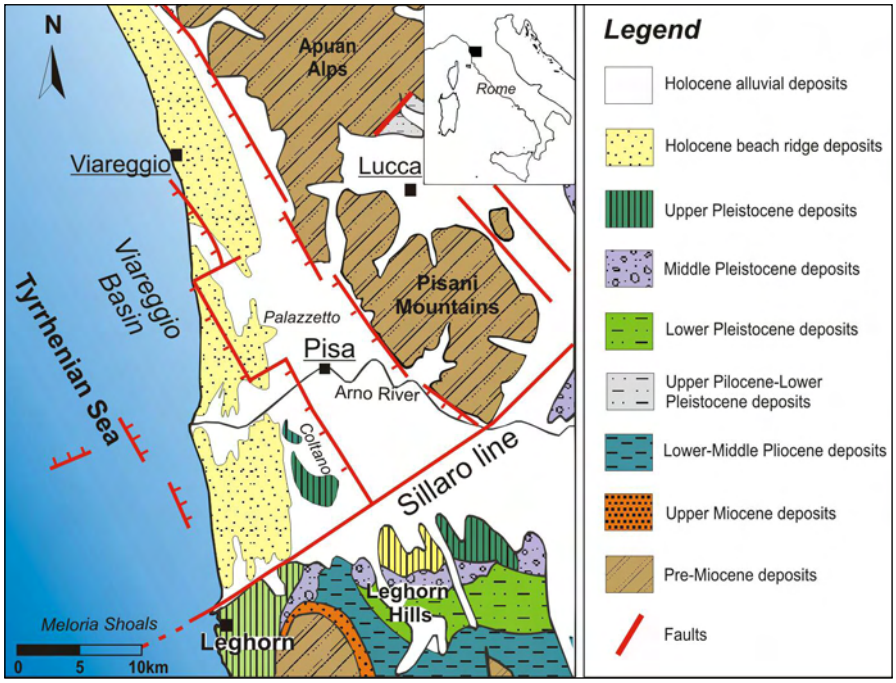

Fig. 2 - Geological map of the study area. (After SARTI *et al*., 2008c).

Carta geologica dell'area di studio. (Carta modificata da SARTI et al., *2008c).*

3. LOCAL LANDSCAPE AND DEVELOPMENT OF THE CITY

The local landscape influenced the social and economic history of Pisa through many interacting factors.

3.1. Hydrography

Pisa developed on an alluvial plain built up by Arno and palaeo-Serchio rivers that changed their hydrographic network over time due to natural and anthropogenic factors. The Arno River and the modern Serchio River have highly sinuous channels typical of low-gradient slopes (SCHUMM, 1977; MIALL, 1996). Channels of this type migrate laterally and generate a complex system of abandoned channels. They may also experience avulsions. Since the Roman period waterworks have greatly controlled this natural tendency.

The first significant writings about the hydrography of Pisa during the Roman times were by STRABONE (V, 2, 5, C 222). Recalling descriptions by other ancient authors, Strabone stated that Pisa was located at the confluence of the Arno and *Auser* rivers (Fig. 4a). At that time, the modern Serchio River was split at the gorge of Ripafratta into three branches named *Tubra, Auser* and *Auserculus*. Limited information is available from medieval sources about the course of the *Tubra* branch that probably flowed to the north of Pisa near Vecchiano. The *Auser* was the main branch of the river and flowed from north to south along the foot of the Pisani Mountains and into the Arno River at Pisa. Finally, the course of the *Auserculus* branch was similar to that of the modern Serchio, except it probably forked before reaching the sea. According to Strabone, the Arno River course split into three branches; the northernmost corresponds to the modern course, although it was more sinuous. Little is known about the two southern branches (CECCARELLI LEMUT *et al*., 1994).

Important waterworks begun during the Middle Ages including construction of levees, canals,

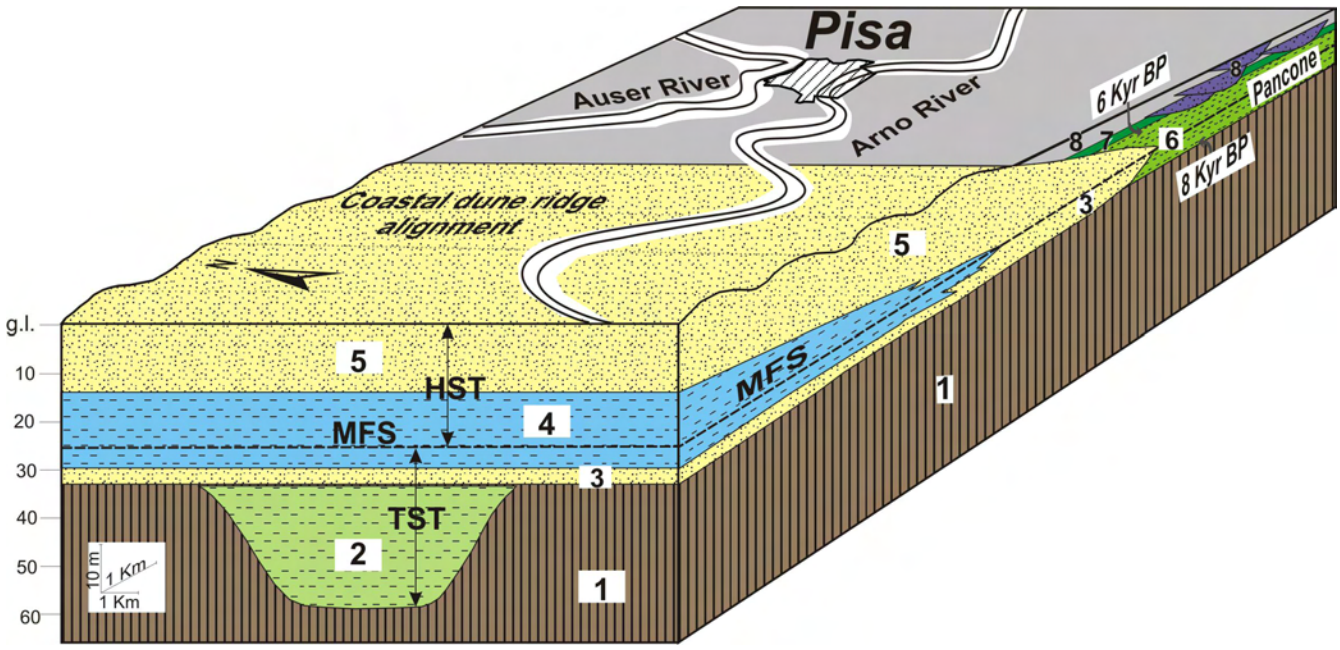

Fig. 3 - Diagram showing subsurface stratigraphic architecture of the Pisa coastal plain. 1) Upper Pleistocene deposits. 2) Incised valley fill deposits: clay estuarine deposits related to post Last Glacial Maximum (13–8 cal. kyr BP) early transgressive phase. 3) Transgressive marine sand sheet. 4) Prodelta clays. 5) Highstand marine progradational sands. 6) Lagoonal high-compressible clays (*pancone*) constituted by two lithofacies (P1 and P2). 7) Coastal plain clays. 8) Flood plain and sandy channel fluvial deposits. MFS: maximum flooding surface. HST: highstand system tract. TST: transgressive system tract. The hydrography is similar to that of about 12th centuries AD.

Architettura stratigrafico deposizionale del sottosuolo della pianura di Pisa. 1) Depositi del Pleistocene superiore. 2) Depositi di riempimento di valle incisa: argille estuarine depositatesi durante la prima fase trasgressiva posteriore all'ultimo Massimo Glaciale (13–8 cal. kyr BP). 3) Depositi marini trasgressivi. 4) Argille di prodelta. 5) Sabbie marine di stazionamento alto progradazionali. 6) Argille (pancone) fortemente compressibili costituite dalle litofacies P1 e P2. 7) Argille di pianura costiera. 8) Depositi di pianura alluvionale ed di canale fluviale. MFS: superficie di massima ingressione marina. HST: sistema deposizionale di stazionamento alto del livello del mare. TST: sistema deposizionale trasgressivo. L'idrografia approssima quella presente durante al 12th secolo DC.

ditches, and meander-loop cut-offs to improve navigability and to avoid floods and wetland formation. In this period, the *Auser* River was diverted outside the city walls. Figure 4b shows a hydrographic reconstruction of the 10th through 12th centuries based on a compilation of available sources integrated with new geological and geomorphological data (Mazzanti, 1975; Della Rocca *et al*., 1987; Redi, 1988, 1991; Tolaini, 1992; Carratori *et al*., 1994; Ceccarelli Lemut *et al*. 1994; Mazzanti & Rau, 1994; Federici & Mazzanti 1999, Marchisio *et al*., 1999; Dall'Antonia & Mazzanti, 2001; Bruni & Cosci, 2003; Fabiani, 2006; Pasquinucci, 1988, 2003a, b). Since the Middle Ages, the administration of Pisa, local lords, and the archbishopric collected duties on goods transported along the Arno and *Auser* rivers (Ceccarelli Lemut *et al*., 1994). The Arno River was navigable up to Florence, and the *Auser* and *Auserculus* rivers were navigable downstream of the gorge of Ripafratta (Fig. 4b). The Arno River was heavily used to transport wood and coal out of the Pisani Mountains (Garzella, 2000). The *Auser* River was used to provide Pisa with building materials quarried from the Pisani Mountains (Ceccarelli Lemut *et al*., 1994; Alberti *et al*., 2006). Several wharfs and small harbours were constructed to service the intense trade activities (Fig. 4b). These in turn stimulated the development of important inland communication routes such as the *Aurelia Scauri, Vallis Arnis* and *Silice Portus Pisanus* roads constructed in 109 BC and during the Middle Ages respectively (Fig. 4b) (Ceccarelli Lemut & Pasquincci, 1991). Riverine harbours were established during the Etruscan Age and further developed during the Roman Age. One of these harbours was discovered in the 1990s (San Rossore site) just one kilometre away from the Leaning Tower and is now an important archaeological site (Fig. 4b) (Bruni, 2003). This site record some strong floods that eventually destroyed 16 Roman ships buried in alluvial deposits (Fig. 5). The stratigraphy and sedimentology of these deposits suggest that the flood events were controlled by centennial climatic and eustatic cycles (Benvenuti *et al*., 2006). The correlation between the age of the ships found at Pisa and the flood frequency reported for the Tiber River between 200 BC and 500 AD indicate that these events affected river catchments in a wide portion of Central Italy.

Except for the catastrophic floods documented in the archaeological site (San Rossore Site) in the centre of Pisa, bibliographic sources do not report any other flooding events so extreme to require the abandonment of settlements during the 11th and 12th centuries. However, documented constructions of supra-elevated living floors of buildings in Pisa indicate that his was done as protection from floods (Baldassarri & Gattiglia, 2009). Evidence of this is provided by a recent excavation in the area of Palazzo Scotto (Fig. 1c) where a living floor was found about one meter above sandy and muddy flood deposits devoid of any archaeological findings (Gattiglia & Milanese, 2006). Indeed, the left side of the Arno River, where Palazzo Scotto is located, was struck by a catastrophic flood in the first half of the 14th century (Gattiglia & Milanese, 2006).

Large flooding events have been reported since

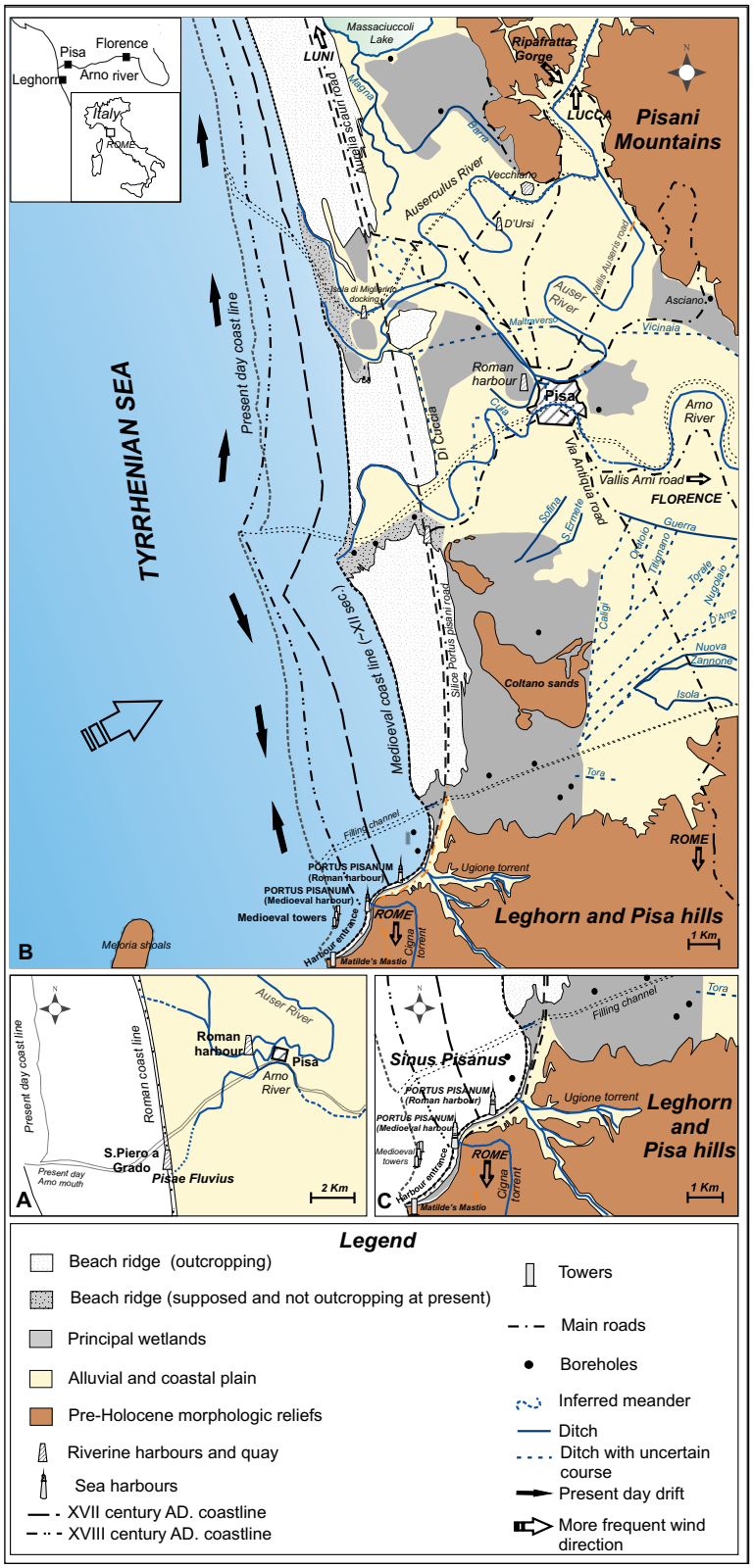

Fig 4 - (a) Pisa area during the Roman Age. (b) Pisa area during 10th–12th. (Modified after Martini *et al*., 2010). (c) Portus Pisanus area during the maximum socio-economic power of Pisa (10th–12th).

(a) La pianura costiera di Pisa durante l'Età Romana. (b) La pianura costiera di Pisa durante il 10th-12th secolo DC. (c) La zona dove fu costruito il Portus Pisanus, durante il periodo di massimo potere socio-economico di Pisa (10th–12th).

the late Middle Ages (Caporali *et al*., 2005). They are related to a combination of factors, including climatic oscillations, changes in land use (deforestation), progressive interventions to rectify and embank the riverbed of the Arno River and, since last century, modification of the longitudinal riverbed profile due to sediment quarrying (Pranzini, 2001). The infamous, catastrophic flood of 1966 destroyed inestimable art works and caused considerable damage in Florence and severe damages in Pisa as well (Fig. 6).

3.2 Wetlands

Extensive wetland development was favoured by the natural tendency of the Pisa plain to subside, occasional river flooding, seasonal precipatitations and the poor drainage capability of the flat land. Figure 4b shows a reconstruction of wetland extension during the 12th century. Extensive wetlands developed south of Massaciuccoli Lake, east and west of Pisa (Redi, 1991; Bruni & Cosci, 2003) near the mouths of the *Auser* and *Auserculus* Rivers, near Asciano in the Pisani Mountains area, and between the Arno River and the Leghorn and Pisa Hills. Efforts were made through the ages to drain them (Fig. 4b). Several drainage channels were constructed during Roman times (Bonamici, 1989; Pasquinucci, 1988; Anichini, 2004-2005, 2006; Baldassarri & Gattiglia, 2009). The channels were part of a systematic land reclamation scheme, as suggested by the centuriations (lands granted to Roman veterans) (Ceccarelli Lemut *et al*., 1994). A limited success in controlling the distribution of wetlands was achieved during Roman times. It is worth to note the positive relation between this "limited success" in reclaiming wetlands and the palynological record of the S.Rossore riverine harbour site reported by Mariotti Lippi *et al*., 2006. Between the 2nd century BC and the 2nd century AD the expansion of wetland vegetation and the decrease of arboreal cover in the plain, seem to have good correlation with a peak in the flood frequency of the Tiber River and with the catastrophic flooding of the S.Rossore harbour Benvenuti *et al*., 2006. During higher flood frequency the Pisa plain may have been flooded with longer persistence of wetlands and more difficult human management of waterlogged soils.

Renewed rapid wetland expansion during the first centuries of the Middle Ages (Dark Ages) is correlated with a period of non-expansion and even contraction of urban development. As maintenance of drainage channels decreased, new wetlands formed close to the city, mostly due to the migration of the *Auser* River (Redi, 1991). This trend reversed again during the 12th century when Pisa expanded and became an important commercial and political centre. Extensive

works on land reclamation, wetland management, building of embankments, and meander cut-offs were initiated at this time. Many new drainage channels were dug (the most significant are shown on Fig. 4b). The subsequent decline of Pisa after the defeat of the Meloria battle led to a renewed expansion of wetlands. This reversal was again caused by decreased maintenance of the drainage system but also by the increased hydrogeological instability of the area caused by massive deforestation during the Late Middle Ages (CECCARELLI LEMUT *et al*., 1994).

The wetlands of the Pisa plain were not infested by deadly malaria (SALLARES, 2002; TORELLI, 1882), and they constituted an economic resource for the city. They were exploited for fish, canes and straw as construction materials and as fuel for baking pottery, and reclaimed lands were plated with cereal. Wetlands were also efficient waterways for small flat-bottomed craft.

Fig. 5 - Archaeological site of Pisa-S. Rossore (see Figs. 4a, 4b, for location). Roman ships discovered in 1998 during works for the construction of new office near the train-station of Pisa- S. Rossore only about 500 m from the Leaning Tower (after http://www.telemaco.unibo.it/rom/italia/etruria.htm)

Sito archeologico di Pisa-S.Rossore (Figs. 4a, 4b, per l'ubicazione del sito). Navi romane scoperte nel 1998 durante i lavori per la costruzione del nuovo ufficio ferroviario vicino alla stazione di Pisa-S. Rossore a soli 500 m di distanza dalla Torre Pendente (da http://www.telemaco.unibo .it/rom/italia/etruria.htm)..

3.2. Pisa and the coast

The proximity of Pisa to the sea greatly influenced its history. Written documentations on ports and wharfs of Pisa are rare before the 12th century (CECCARELLI LEMUT, 1994, 2002, 2003; PASQUINUCCI, 2003a, b; CAMILLI & GAMBOGI, 2005). Available indirect information indicate that it was possible to reach or leave Pisa by sea but provided little to no data on the palaeogeography of those times. The available indirect archaeological sources, such as crockery and coins, document the maritime links between Pisa and various Mediterranean regions only until the 7th century and after 1000 AD (BALDASSARRI, 2003; VACCARI, 2003; BALDASSARRI & BERTI, 2006; PECCHIONI *et al*., 2007). The minimal documentation of the period between the 8th and 10th centuries leaves a gap in the historical reconstruction.

The Pisa coastal area between the mouth of the Serchio River and Leghorn experienced progradation beginning around 7500 BP (AMOROSI *et al*., 2008). The last stages of this process are recorded in the series of beach ridges, the easternmost of which is older than the 1st or 2nd century BC (Figs. 2, 4b). The rate of westward

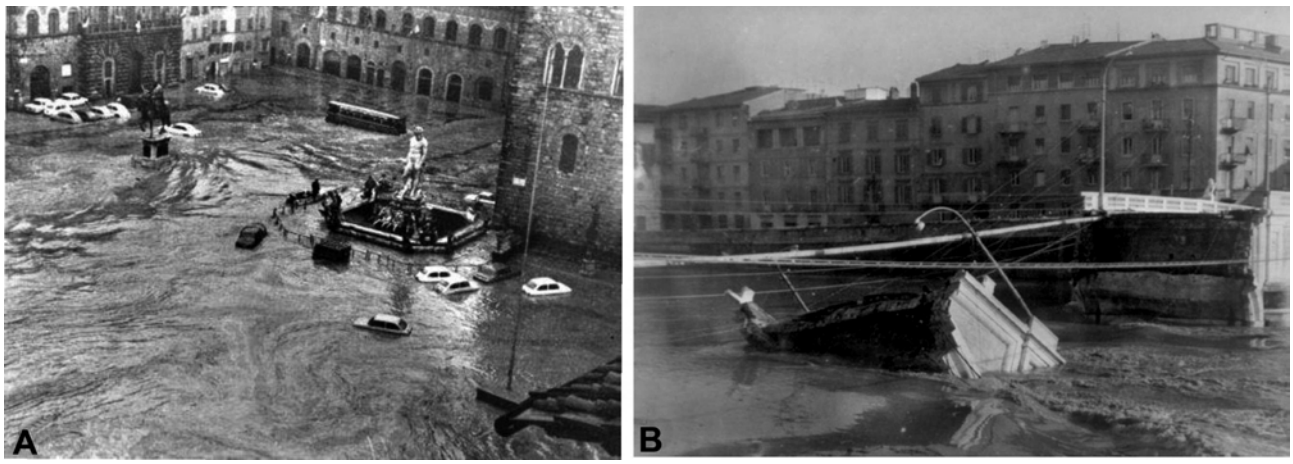

Fig. 6 - The catastrophic flood of the Arno River of 4th November 1966. (**A)** Florence, Piazza della Signoria. (**B)** Pisa, the Solferino bridge destroyed after the flood. It was reconstructed and inaugurated in 1974. (After http://ilventilatore.splinder.com/archive/ and http://www.comune.pisa.it/biblioteca/img/alluvinione.jpg).

*L'alluvione catastrofica del Fiume Arno il 4 Novembre 1966. (**A**) Firenze, piazza della Signoria. (**B**) Pisa, ponte Solferino crollato dopo l'alluvione. Il ponte fu ricostruito ed inaugurato nel 1974 (da http://ilventilatore.splinder.com/archive/ and http://www.comune.pisa.it/biblioteca/img/alluvinione.jpg).*

progradation of the coastline varied owing to high-frequency climatic variations and changes in land use (alternating periods of reforestation and deforestation) (PRANZINI, 2001; CAPORALI *et al*., 2005, BINI *et al*., 2010b). Progradation was continued up to 1830 (Fig. 4b). After that date, riverbed dredging and damming cut supply of sediments to the delta and triggered erosive coastal processes. The construction of local protective structures sometimes enhanced erosion elsewhere.

The Pisa coast belongs to the physiographic unit that extends from the mouth of the Magra River to the north and the Leghorn and Pisa hills to the south. It is characterized by strandplains mostly supplied by sediments of the Arno and Serchio rivers. The littoral drift from the mouth of the Arno River is divergent; it flows southward on the left side of the delta and to the north on the right side (Fig. 4b). A convergence area has also been detected just north of the ancient *Portus Pisanus* site near Leghorn, in the Calambrone area (Fig. 1b, 4b). The drift convergence could be associated to the dominant south-southwestern wave front approach to the Meloria shoals and the mainland coast, driven by strong southwesterly storm winds (Figs. 4b, 7) (RAPETTI & VITTORINI, 1978). The resultant incident wave diffraction and refraction processes generate two currents (BINI *et al*., 2008, SARTI *et al*., 2010a). The northern current is partially responsible for generating the south-trending drift that transports Arno River sediments towards Tirrenia and Leghorn (CIPRIANI *et al*., 2001). The southern current generates the north-trending drift, which could be responsible for transporting and distributing the sand in the Calambrone area (GANDOLFI & PAGANELLI, 1975).

The morphodynamic configuration during the Roman and Middle Ages may not have differed much from the present configuration in terms of littoral-drift direction and sediment-supply sources. In fact, no textural and compositional differences are noted between the oldest beach ridge (pre-2nd or 1st century) and more recent ones (SARTI *et al*., 2008b). Coastal morphology

Fig. 7 - Meloria shoals (Figs. 2, 4b for location). The tower, about 20 m high, is a rebuilding (1709) of 13th century structure. The original was destroyed in 1284 by the Genoese fleet after the Battle of Meloria that signed the beginning of the Pisa decline.

Secche della Meloria (Figs, 2 e 4b per l'ubicazione). La torre, alta circa 20 m, fu ricostruita nel 1709 sulle rovine della struttura originaria del 13th secolo distrutta nel 1284 dalla flotta Genovese a seguito della battaglia della Meloria che segnò l'inizio del declino di Pisa.

was also similar to the present except that a bay existed in the southern portion (Fig. 4b, c). This bay, known as *Sinus Pisanus*, gradually developed into a wetland, now entirely silted over. The *Portus Pisanus* was constructed in the southern edge of this bay (Fig. 4c) near Leghorn and Pisa hills (PASQUINUCCI, 1988; BALDASSARRI & GATTIGLIA, 2009).

In the Pisa–Arno delta area, the coastline during Roman Age was located about 6 km east of its present position (Fig. 4b). STRABONE (V, 2, 5, C 222) during the 1st century positioned Pisa about 20 *stadi* from the coastline (about 3.8 km). As reported in the poem by RUTILIO NAMAZIANO (Itinerarium Maritimum 501, Rutilio Namaziano, De reditu suo 1 527-540; 2, 11-12), Pisa possessed two harbours, nine miles apart: the *Pisae fluvius* was near S. Piero a Grado at the Arno River mouth, and the *Portus Pisanus* was located near the Leghorn and Pisa hills, within the *Sinus Pisanus* (Fig. 4b).

There are no direct reports about the S. Piero a Grado harbour that was less important than the *Portus Pisanus* (BALDASSARRI & GATTIGLIA, 2009). The San Piero a Grado riverine harbour became progressively more distant from the river mouth due the coastal progradation; it was 2.5 km from the coastline during mid-12th century (Fig. 4b). This distance from the coastline, along with the siltation near the river mouth, greatly reduced the harbour importance. The siltation process was enhanced by the orientation of the Arno River mouth, which faced the prevailing southwesterly winds up to the early 17th century. During the most intense storms, this configuration prevented the Arno River from discharging naturally into the sea, sediments were deposited near the river mouth rather than distributed along the coast, and serious floods developed close to the city of Pisa. Therefore, in 1606 the river mouth was eventually artificially diverted several kilometres to the north flowing in a west-northwest direction (Fig. 4a, b). Before the river diversion, historical sources reported several navigability issues due to repeated episodes of siltation at the river mouth. For instance, in 1113, Pisani ships were stranded and had to be lifted out of the water before reaching the Arno River mouth and then placed in the sea water in order to sail towards the Baleari Islands to free them from the moors (BENVENUTI 1989). Therefore, only small vessel could navigate through the Arno River to the sea.

To the south, *Sinus Pisanus* bay was a more suitable area to locate a sea harbour (Fig. 4c). Rutilio Namaziano described the *Portus Pisanus* as located in a wide gulf characterized by calm, shallow waters and sheltered by widespread development of *Posidonia oceanica* (PASQUINUCCI, 2003a). The analysis of continuous cores drilled in the area of *Sinus Pisanus* (DALL'ANTONIA *et al*., 2004) confirms this description, reporting alternating silty sands and *Posidonia* levels (unit 7b of DALL'ANTONIA *et al*., 2004). The basal portion of this unit is identified between -11 and +1 m from sea level and overlies a deposit dated at 4530 ± 60 ^{14}C yr BP (not calibrated age). This suggests a stable depositional environment and subsidence in part associated to sedimentary compaction. The harbour was an active military base since Roman times (3r^{d} century BC) and reached its maximum development during the Middle Ages when Pisa became a major trading centre, having contact with several Mediterranean regions, and having

acted as a transit place for pilgrims and travellers to Rome, Jerusalem, and southern France (Baldassarri & Gattiglia, 2009). Shallowing water due to siltation hindered the navigation of large ships to the harbour, and the ancient Roman harbour was eventually moved one kilometre to the west during the Middle Ages (Fig. 4c). After Pisa was defeated at Meloria (1284) the victorious Genoeses disrupted the port. The *Portus Pisanus* was not reconstructed and a new harbour (*Porto Mediceo*) was instead built later during the Renaissance just to the south at Leghorn by the Florentine Medici Family (Baldassarri & Gattiglia, 2009).

3.4. Nature of subsurface

A characteristic of Pisa is the leaning of few bell towers and other buildings. The most famous is the Leaning Tower (Fig. 8), but other leaning constructions include the bell towers of the San Michele degli Scalzi church (10th–11th centuries) and San Nicola church (12th century), about 800 m south of the Leaning Tower, parts of the city walls, and Palazzo Agostini (14th–15th century) (Fig. 9).

The Leaning Tower has a "banana shape", is 55.86 m high on its lowest side and 56.70 m tall on the highest side. It is constructed entirely of stone and marble and its more than 14,000-ton weight is focused on a limited area of 300 m^2 (Burland *et al*., 1998). Its shape is in part due to the fact that it was built crooked to compensate for the leaning experienced during early construction, but mostly because of the differential sinking associated with variable substrate lithology. In the substrate there is a highly plastic, 7 to 10 m thick clay layer, known as *pancone* (unit 6 in Fig.3), at about 5 to 15 m below the surface. The clay was deposited in a low-energy, lagoon environment between about 8000 BP and 6000 BP (Benvenuti *et al*., 2006, Amorosi *et al*., 2008, 2009). This period represents a late transgressive stage and early high stand (HST) in the late Holocene because the maximum flooding surface (MFS) is found within those deposits (Fig. 3) (Amorosi *et al*., 2009). This clay is easily recognizable by its higher compressibility than adjacent deposits. Within the *pancone*, two lithofacies (P1 and P2) in latero vertical relationship constitute a shallowing-upward sequence and record the gradual filling of the mid-Holocene lagoon (Sarti *et al*., 2010b). Lithofacies P1 consists of a fossilferous monotonous succession of brackish-water blue clay and silt, which is sometimes interrupted by centimetre-thick layers of fine sand. Lithofacies P2 is characterized by dark, soft clay with much fresh-water swamp organic matter. The *pancone* layer is overlain by sandy distributary and fluvial channel deposits, which are organized in small fining-upward sequences and grade laterally into silty clay overbank deposits (Sarti *et al*., 2010c). They correspond to unit 8 in Fig. 3. It is worth noting that the oldest distributary channels cut into the underlying lagoon deposits up to 4 m suggesting a small amplitude sea-level fall occuring during a pre Roman period (ca. 6000-

Fig. 8 - A recent (April 2010) picture of the Leaning Tower.
Una fotografia recente (Aprile 2010) della Torre Pendente.

Fig. 9 - Pisa, examples of leaning building (Fig. 1c for their location). (**A)** San Michele degli Scalzi church. (**B)** San Nicola church. (**C)** Section of the city walls. (**D)** Palazzo Agostini.

Pisa, esempi di edifici pendenti (Fig. 1c per la loro ubicazione). (***A)*** *Chiesa di San Michele degli Scalzi.* (***B)*** *Chiesa di San Nicola.* (***C***) *Porzioni della cinta muraria di Pisa.* (***D)*** *Palazzo Agostini.*

2000 cal YrBP). These alluvial deposits have consolidated or pre-consolidated geotechnical properties (*sensu* LANCELLOTTA, 2004). Moreover a shallower highly discontinuous compressible thin layers (common less than 3 m) constitued by alluvial to swampy wet silty sand and silt is recorded in the upper 5 metres of the subsurface (SARTI *et al*., 2010c).

Foundation stability problems are related, therefore, not only to the presence of the *pancone* but also to the facies relationships between *pancone* and the overlying layers. Differential sinking of the Leaning Tower most likely is related to the juxtaposition of high-compressibility clay and pre-consolidated or consolidated lenticular channel sands (BURLAND *et al*. 1998). The subsurface conditions were also exacerbated by the fluctuation of the shallow water table (usually at 1–2 metre below the surface) due to pumping. Water extraction is currently prohibited within about 1500 m from the Leaning Tower.

4. CONCLUSIVE CONSIDERATIONS

The history of Pisa has been influenced by the landscape of the territory but this did not play a major role in the development of the city. Pisa site has been successfully occupied since Etruscan times. It is located on a vast fluvial to coastal plain on the banks of sizeable streams, near the sea, under a relatively mild climate, and not affected by extreme natural disasters. The city location at the confluence of two important rivers constituted a great advantage for the city and its commercial activities. Suitable places were selected for construction of harbours and wharfs. Occasional floods have vexed some of the riverine harbours, like the recently discovered Etruscan-Roman harbour located near the Leaning Tower. Flood-related risks increased after the 14th century because the area was increasing impacted by anthropogenic activities.

Vast wetlands developed in the Pisa plain, but

they could be used at advantage for fisheries, and source of fodder, building material and fuel. They never presented the threat of malaria experienced by the wetlands farther south (about 120 km) in the Grosseto area. The Pisani did however encounter some difficulty in reclaiming of wetlands for agricultural purposes. They were partly successful during periods of socio-economic growth when drainage channels were dug and well maintained. Conversely, during periods of city decline during the Dark Ages, maintenance of the drainage systems was reduced, uncontrolled flooding occurred, and the wetlands expanded.

Easy access to the sea and harbour facilities greatly favoured the economic recovery of Pisa during the Middle Ages. However, gradual siltation of the main harbour of *Portus Pisanus* and its disruption by the Genoeses after the Meloria defeat in late 13th century contributed to the decline of the city that eventually surrender definitely to Florence in early 16th century. A new more modern harbour (*Porto Mediceo*) was built farther south of the *Portus Pisanus* in the Leghorn area by the Florentines.

The very soft clay in the subsurface did not appear to represent a major problem for urban buildings except for the Leaning Tower and a few others, according to historical sources. The differential subsidence of buildings with narrow footprint and high operating loads (kg/cm^2) is attributed to the lithological heterogeneity in the subsurface, which is characterized by frequent and abrupt stratigraphic latero-vertical lithological variations. Tower-houses were common urban element of medieval Pisa but were always relatively limited in height and often leaned on other buildings (Baldassari & Gattiglia, 2009). Until the 11th century, wood was frequently used instead of stones, limiting building weight. Stones were increasingly used in heavier buildings after that time, but wood continued to be utilized for girders, stairs, balconies, and floors. The inclination of the Leaning Tower can be attributed to a combination of its foundation, which overlies heterogeneous lithology (soft-clay and sand) above the *pancone*, a shallow groundwater table, and a huge operating load.

Pisa had the potential to become a strong power because apparently it had it all: sea and land viability, possibility of hydraulic power, nearby fertile hills, vast terrains in the plains. Indeed it was a great power of the region when it could use the asset of its harbours to the maximum during the early part of High Middle Ages with extensive trading throughout the Mediterranean Sea, and when servicing the crusades. Afterward the decline started. The city never grew much in population and although it fought valiantly it could not oppose the overwhelming power of Florence, that relished (needed) the Pisa harbours. Pisa was definitively conquered by Florence in 1509.

Comparing the history of the two city-states, Florence developed under apparently less favourable landscape conditions. Florence was landlocked and built along the Arno River that was hardly navigable and subjected to repeated and sometimes catastrophic floods. In addition, it was not crossed by primary terrestrial communication routes for a long time. However, in a few decades during the later part of the Middle Age-early Renaissance the fortunes of Florence changed and it became the dominant power of the region thanks to successful political alliances and industrial innovations that led to industrial production of wool and silk cloth making use of the hydraulic power of the Arno River. So, landscape factors contributed to early success, but socio-economic factors were determinant to the later decline and final demise of Pisa and others as independent city-states.

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