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THE INTERACTION OF GEOLOGICAL AND ANTHROPIC PROCESSES SHAPING THE URBAN GROWTH OF FERRARA AND THE EVOLUTION OF THE SURROUNDING PLAIN

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ABSTRACT: Stefani M. & Zuppiroli M., *The interaction of geological and anthropic processes shaping the urban growth of Ferrara and the evolution of the surrounding plain.* (IT ISSN 0394-3356, 2010)
The town of Ferrara is placed at the junction of the alluvial plain of the Po River, the innermost portion of the Po River delta plain, and the alluvial plain fed by the Reno River and other Apennines-derived streams. The depositional evolution of the fluvial system largely affected the urban shape, but human intervention in turn modified the river dynamics, to eventually subjugate it into the present-day artificial state. Ferrara is the only city of the Emilia region not sharing Roman or a pre-Roman origin; the future urban region was nevertheless well populated during ancient times. During Roman times major artificial intervention was performed on the natural river framework, through long canal digging and river embankment. After the fall of the Roman Empire, a major restructuring of the river drainage system took place, leading to the development of two new distributary channels. Ferrara nucleated during the early Middle Ages (7th century), near the divergence point of these channels, as a Byzantine fortified structure, built on a crevasse splay, part of the northern levee body of the main Po channel of the time. The southern side of the fortified village, was about 240 m long, its area 35,000 squared metres. The proto-urban structure then grew in a linear way, on the levee crest, because the elevated site offered protection against flooding waters and provided comparatively firm and well drained ground. During the first half of the 11th century, the urbanised area on the northern levee broadly stretched over a distance of about 2300 m, with a width of often less than 100 m. Also the southern levee of the Po di Ferrara was progressively built over, during the Middle Ages. At the beginning of the 12th century, the present-day Po channel, flowing at the north of the town, was generated through a river reorganisation phase traditionally known as *Rotta di Ficarolo*. During the same century, the Romanesque cathedral was founded, at the distal edge of the sedimentary levee complex. During the following centuries, the early growth way of the urban tissue through individual building cell implantation gave way to discrete episodes of town growth and district planning. Land reclamation works made the expansion of the urban area toward interfluvial argillaceous depressions possible. At the ending of the 15th century, this northward expansion culminated into a large Renaissance expansion (*Addizione Erculea*). During the following century, the water flow in the southern Po delta channels was suddenly terminated by an ill-fated attempt to artificially force the Reno River to reach the sea through the former Po di Primaro channel. The very low topographic gradients and the elevated sediment load transported by this Apennines-derived river rapidly silted up the ancient Po di Ferrara channel, just at the west of the town. Large marsh therefore developed in the areas surrounding the town. After a long period of stagnation, the urban growth restarted only during the 20th century, in ways utterly unaware of the geological and environmental constrains and thus exposed to significant level of environment hazards, such river floods and earthquakes.

RIASSUNTO: Stefani M. & Zuppiroli M., L'interazione dinamica tra processi geologici e antropogenici nel controllo della crescita urbana di Ferrara. *(IT ISSN 0394-3356, 2010)*
Il lavoro interdisciplinare esamina le strette relazioni dinamiche che hanno legato lo sviluppo della città di Ferrara all'evoluzione idrografica e deposizionale della pianura circostante. Lo studio ha riguardato l'architettura stratigrafica del sottosuolo, la cartografia geologica di superficie, ed il dettagliato rilievo topografico ed architettonico del centro storico. La distribuzione dei corpi sedimentari e delle strutture geomorfologiche fluviali hanno controllato le forme della crescita urbana, ma l'azione antropica ha a sua volta fortemente influenzato l'evoluzione del reticolo idrografico, fino a renderlo totalmente artificiale. Ferrara sorge alla giunzione fra la pianura a meandri del Po, la parte più interna della piana deltizia padana e la pianura formata dagli apporti del Reno e di altri fiumi di provenienza appenninica. Tutti i sedimenti affioranti nella Provincia di Ferrara sono di età olocenica. Le geometrie dei corpi sedimentari tardo-quaternari sono state influenzate dall'attività tettonica compressiva in atto in questa porzione dell'Avanfossa Appenninica. Ferrara è l'unico capoluogo dell'Emilia-Romagna a non avere avuto un'origine antica. In età romana l'area era però sede di un diffuso insediamento agricolo. In questa età furono realizzati importanti interventi di ingegneria idraulica sul ramo deltizio principale del Po e su suoi affluenti appenninici. La fine dell'Impero fu seguita da una drammatica fase di riorganizzazione idrografica, indotta sia da un cambiamento climatico verso condizione più fredde e umide, sia dal venire meno dell'irregimentazione idraulica artificiale. Questa fase di riorganizzazione idrografica generò i due nuovi canali distributori deltizi del Po di Volano e del Po di Primaro. Questi canali divergevano proprio in corrispondenza del futuro nucleo dell'area urbana di Ferrara. Il convergere di percorsi fluviali e terrestri, al confine fra le aree di influenza longobarda e greca, fece scegliere come sede di un nucleo fortificato bizantino un ventaglio di rotta topograficamente elevato, parte dell'argine naturale sinistro del Po. Questo insediamento, costituito da circa due dozzine di case in legno, fornì il primo nucleo di aggregazione del centro urbano, che inizialmente si sviluppò in modo fortemente lineare, sulla cresta del corpo sabbioso-limoso di argine naturale. Questa struttura sabbiosa forniva infatti terreni drenati relativamente al riparo dal ristagno delle acque di piena. Durante il XI secolo, l'abitato aveva raggiunto una lunghezza di oltre due chilometri, ma presentava una larghezza media di soli cento metri. Nel secolo successivo, l'abitato si espanse verso il margine esterno del corpo di argine naturale, al cui piede fu fondata, in età comunale, la cattedrale romanica. Nello stesso secolo XII, a monte di Ferrara, una serie di rotte fluviali, conosciute come "Rotta di Ficarolo" generò l'attuale alveo del Po, passante a nord della città. In età basso-medievale, il tessuto urbano si espanse lentamente verso la depressione interalvea, conservando comunque una forma fortemente allungata. Sotto la signoria estense, le modalità di espansione passarono da una graduale espansione "spontanea" del tessuto, per crescita di singole cellule abitative radicate nel substrato stratigrafico, alla pianificazione di significative addizioni urbane, precedute da importanti lavori di bonifica e protezione idraulica. Nel corso del XIV secolo, la città fu circondata da una cortina continua di fortificazioni, ancora allungate lungo il corpo arginale. Il tratto meridionale delle mura mostrava un andamento concavo assai peculiare, che seguiva da vicino la sponda fluviale del XIII secolo. Nel corso del XIV e del XV secolo, la progressiva riduzione del flusso nei rami meridionali del Po, permise una certa espansione urbana nell'area sabbiosa di alveo. Questa espansione incorporò nell'abitato la precedente isola fluviale di San Antonio.

Nel corso del XV secolo, le modalità di gestione del territorio di pianura mutarono più fortemente, con l'imposizione di grandi progetti territoriali geometrici, ormai distanti dalla strutturazione naturale della pianura. Grandi opere di bonifica idraulica per gravità permisero alla città di colonizzare ampie depressioni interalvee, più che raddoppiando la superficie circondata dalle mura. Questa espansione (Addizione Erculea) avvenne in gran parte su sedimenti argillosi e argilloso-torbosi, ormai lontani dai corpi di canale fluviale. Negli anni immediatamente successivi al 1522, i rami meridionali del Po furono definitivamente abbandonati, a causa di un infelice tentativo di immissione in essi del fiume Reno. L'elevato apporto di sedimenti appenninici ed i bassi gradienti topografici condussero infatti rapidamente all'interrimento deposizionale degli alvei. La città fu quindi nuovamente circondata da ampie aree paludose. Nel 1570, la città fu colpita da un forte terremoto, i cui effetti locali furono modulati dalle caratteristiche sedimentologico-stratigrafiche del substrato. Dopo un lungo intervallo di stagnazione socio-economica, di contrazione demografica e di diradamento edilizio, nella seconda metà del XX secolo, l'organismo urbano riprese ad espandersi, ignorando però le preesistenze storiche e naturali, con modalità che lo espongono ad elevati rischi da terremoto, alluvione fluviale ed inquinamento delle acque di falda.

Keywords: Stratigraphy, Geomorphology, Geography, Holocene, River Processes, Urban History, Po Plain.

Parole chiave: Stratigrafia, Geomorfologia, Geografia, Olocene, Processi Fluviali, Storia Urbana, Pianura Padana.

1. INTRODUCTION

The geological framework always exerts a strong influence on the shape of towns. If this control shows up in hill-sited cities, as it for example in Siena, its influence is less easy to perceive, but not lesser in importance, in alluvial plain towns. This paper illustrates an example of such an influence through the analysis of the alluvial plain urban nucleus of Ferrara. The contribution tries to unravel the complex interplay of the urban growth process with the late Quaternary river evolution of this south-eastern portion of the Po plain (Castiglioni, 1999; Castiglionil & Pellegrini, 2001), belonging to the Apennines Foreland Basin (Pieri & Groppi, 1981; Castellarin *et al*., 1996; Toscani *et al*., 2008). To achieve an interdisciplinary understanding of this interplay, subsurface and outcropping stratigraphy data were integrated with geomorphological and micro-relief study, archaeological data, architectural surveying, and ancient mapping and written historic information analysis.

1.1. The importance of geology in controlling the urban morphology

The stratigraphic architecture and geomorphic framework of an alluvial plain affects the urban growth in many ways. The presence of a permeable sand substratum or of an impermeable muddy unit strongly influences the agriculture practise, the region viability, and the building techniques; less than one metre in elevation difference may largely change the river flooding frequency and severity. In areas involved into active hydrographic and sedimentary evolution, the depositional history and the urban growth often interact very closely, as recorded by the Ravenna and Venice histories. This relationship was particularly strong during the urban growth of Ferrara, which did not simply "ice" a pre-existing topography, but dynamically interacted with the evolution of the Po River channels (Bondesan *et al*., 1995). Natural factors largely shaped the town structures, but human action in turn impacted on the fluvial dynamics, at a growing pace, to eventually subjugate it into the present-day artificial state.

1.2. The regional geology framework of the Ferrara area

Regional physical correlation, ^{14}C dating, archaeological information, and historiography data suggest that the outcropping sediments in the Ferrara province (Figs. 1, 4) are entirely of Holocene age, often dating back to only a few centuries ago. In the urban area, some sediments are even younger than the city buildings.

The town is placed at the triple junction (Figs. 2c, 3a) between the Po River alluvial plain, the innermost portion of the Po delta, and the lower alluvial plain of the Reno River and of other Apennines-derived streams.

This innermost portion of the Po River delta adjacent to Ferrara is marked by a splay of divergent distributary channel bodies, but its evolution was totally dominated by riverine processes. Marine and brackish facies are lacking in the whole of the upper Pleistocene and Holocene formation of the Ferrara area. The urban area therefore shares more sedimentary and geomorphic feature with the fluvial plains than with the lower delta lobes, prograding into sea.

The geometry of the outcropping sedimentary units is well known, whereas the reconstruction of the three dimension depositional architecture is only locally fathomed in some detail, because of the lack of subsurface information. It is clear, though, that the late Quaternary depositional units show strong lateral variations in stratigraphic thickness and facies architecture (Regione Emilia Romagna & ENI, 1998; Molinari *et al*., 2007), recording different subsidence rates (Fig. 4a, b). Subsidence variation is documented also by the deformation of the present-day topographic surface (Bondesan *et al*., 1997). The subsidence gradients are induced by both the different compaction potential of the stratigraphic successions and the tectonic deformation of the Apennines foreland-basin (Pieri & Groppi, 1981; Bigi *et al*., 1990; Amorosi *et al*., 2004; Galadini, 2004; Amorosi, 2008). Beneath the study area, the overthrust front of the Apennines chain is associated with the growth of a large ramp fold (Casaglia Anticline; Pieri & Groppi, 1981; Montone & Mariucci, 1999). The active structural regime induced several historic earthquakes, such as the 1570 one (Guidoboni, 1984; Postpischl, 1985; Boschi *et al*., 1997). Thermal fluid leaking from the fractured anticline reservoir affects the composition of near surface waters (see Paragraph 3.5.2). The anticline area acted as the northern boundary for the Apennines-derived sediments and as a repulsion area for the Po River flow (Fig. 2c). The spontaneous divagation of the fluvial channels was therefore not only induced by the natural aggradation of the fluvial bodies, but it was also influenced by the lateral gradient of subsidence and by palaeoclimatic modification.

2. METHODOLOGY

2.1. Subsurface geology

In these difficult socio-economic times, the lack of financial support prevents new subsurface data from being acquired. To support the three dimension reconstruction of the stratigraphic bodies, hundreds of technical drillings, penetration tests, and water wells data were therefore collected. Many subsurface data were provided by the Ufficio Geologico, Sismico e dei Suoli della Regione Emilia Romagna and by the Ferrara municipality administration. The data were never previously analysed for scientific purposes. The majority of these tests reached a depth of less than 40 m. The spatial density of information is largely variable, because of the data clustering in industrial or recently developed areas, leaving the historic centre and the agricultural zones poorly tested. For the interpretation of near-surface sediments and of buried anthropic structures, an observation of trenches excavated during infrastructure and maintenance works was carried on through the last 25 years. Shallow drills, less than 8 m in depth, were performed in gardens and yards, particularly in the historic centre area of the town of Ferrara.

2.2. Surface geological mapping

The making of a large scale geological cartography provided a major source of information on the study area (Fig. 2c). The map drawing integrates surface surveying, sediment sampling, and shallow core drilling. Pedological information was also considered. After the examination of the previous geomorphological map of the Ferrara region (Bondesan, 1975), the new mapping effort was carried out through the integration of several remote sensing information sources, from the Spot satellite image to the Landsat infrared data. Aerial photographs deriving from recent and historic flights, like *ITALY 2000, Volo Italia CGR*, the II World War U.S.A.A.F. and R.A.F. air-reconnaissance photos, and a 1911 airship survey.

2.3. Topographic survey

Micro-relief information is especially valuable for the understanding of the city centre, since the ancient morphology is there preserved by the growth of the historic town (Fig. 5). The previously available topographic representation (Carta Tecnica Regionale 1/10,000; Mappe Catastali) were largely inaccurate, particularly so for the elevation data. A new survey was therefore performed through the entire historic town and adjacent areas. Previously acquired (surveying by Paolo Russo and Alberto Pellegrinelli), but unpublished, point elevation data were integrated with new topographic measurements and manually interpolated to produce a digital elevation model, with a centimetre order of accuracy. The model was bench marked to the national geodetic framework. In the areas urbanised during the 20th century, the anthropogenic alteration was more severe; even rural zones recently experienced major morphological modification. For analysing the areas surrounding the historic town, a lower resolution elevation model was therefore deemed sufficient. This digital model was developed through the critical interpolation of the elevation data available from the Carta Tecnica Regionale at the 1/10,000 scale, integrated with field controls.

2.4. Ancient cartography and historic documentation

The geomorphologic interpretation was largely helped by the examination of ancient written information and cartographic representations, predating the modern pervasive morphological alteration. A major contribution was provided by the geocoding of historic cartography, such as the early Italian 1/25,000 scale mapping, the 1814 watercolour map (Pezzoli & Venturi, 1987), and 18th century large scale land-register maps (Consorzio di Bonifica I Circondario Polesine di Ferrara & Consorzio di bonifica II Circondario Polesine di San Giorgio, 2005). Valuable information on the ancient geomorphology framework and the town evolution derived from graphic and written information on the historic sewer system, as in the 1728 map (Fig. 3c). Older cartographic representational of the 17th, 16th, and 15th centuries and ancient written information can also be located on a present-day cartography, as it is the case for the 1494 land-register manuscript (Bocchi, 1976).

2.5. Architecture survey and urban tissue analysis

An extensive survey of the entire building tissue of the historic town is being carried on. By now, the ground floor plan of the majority of the Medieval town has been drawn (Example in Fig. 6). Maps from the land-register archives were also digitised and incorporated into the GIS project. Façades were continuously measured along entire roads (Fig. 6) and the isometric representation of many building was achieved. This architectural data bank is relevant to this contribution, because of the close genetic linkage of the growth phases of the town, the urban tissue structure, the moistening and degradation state of walls, the underlying geomorphic and stratigraphic structures, and the depositional evolution of the area (Fig. 6).

3. FLUVIAL EVOLUTION, SEDIMENTARY HISTORY, AND URBAN GROWTH PHASES

3.1. From the Late Pleistocene braided rivers to proto-historical meandering channels

During phases of the last glaciation (Alpine Würmian), associated with an eustatic lowstand, the study region was the site of widespread braided-river sedimentation, at more than 250 km from the seashore of the time (more than 18,000 yr BP). The late Pleistocene sands (lower portion of Fig. 3a) are well developed in the urban area subsurface (Bondesan *et al.*, 1974), where they form the first semi-confined aquifer (Regione Emilia Romagna & ENI, 1998; Molinari *et al.*, 2007). The depth to the sand top varies from 35-40 m, in the depocentres (Stefani *et al.*, 2003; Stefani & Vincenzi, 2005; Stefani & Cibin, 2010), to 10 m, on anticline culminations (Casaglia, at the north-western border of town). Beneath the urban area, the surface rapidly rises northward, from 32 to 13 m. The spatial gradient of the sand body depth controlled its interaction potential with later sedimentary processes. During early deglaciation,

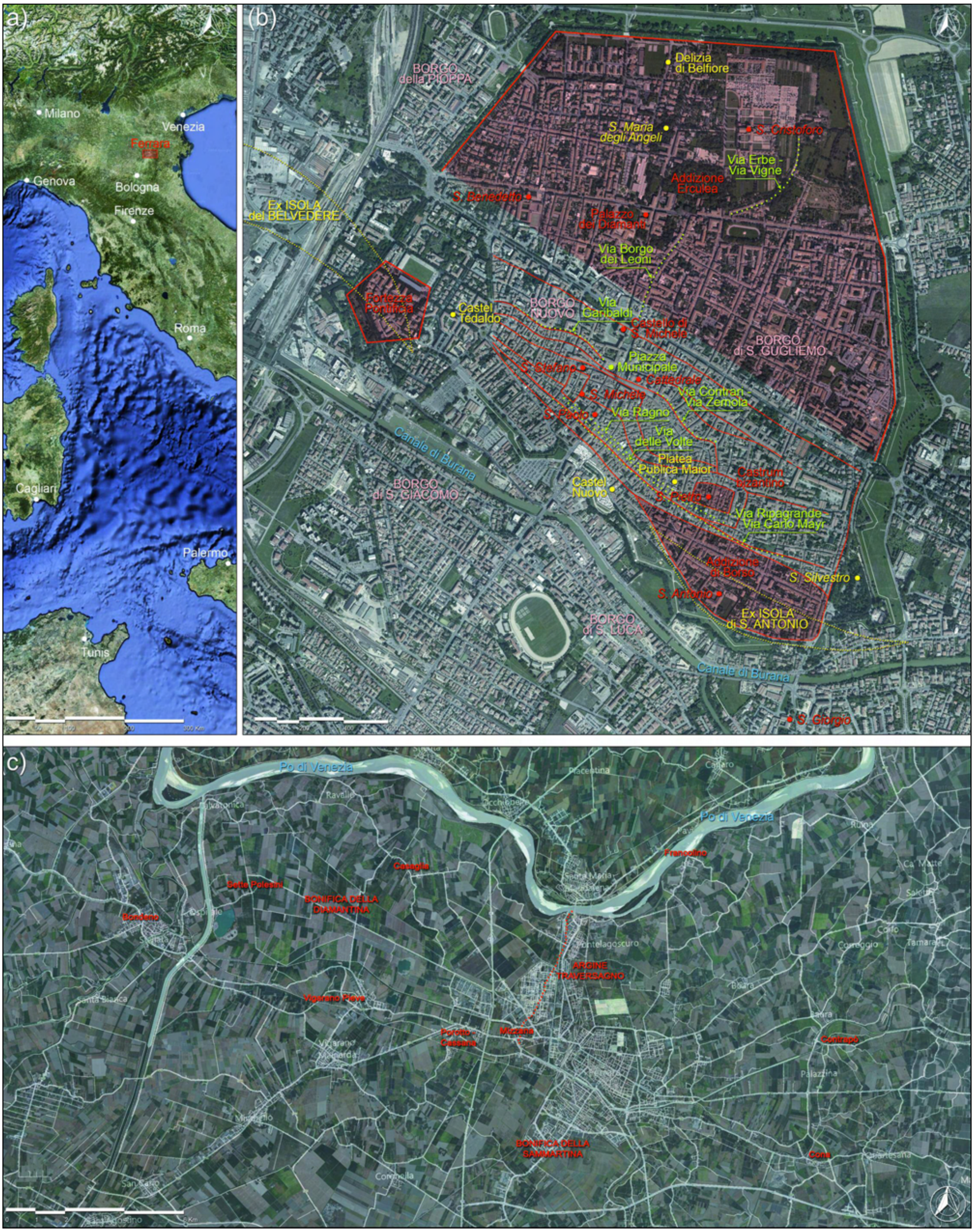

Fig. 1 - Geographic framework of the research area and place name localisation. The study Ferrara town developed in the lower alluvial plain of the Po River, which now flows a few kilometres to the north of the urban centre. The historic town is still surrounded by fortified Renaissance walls, limiting the area described by the digital elevation model, visible in Fig. 2c and 3b.

Localizzazione geografica dell'area di studio e dei toponimi citati nel testo. Ferrara è posta nella bassa Pianura Padana, pochi chilometri a sud dell'attuale corso del Po. Il centro storico è ancora quasi interamente circondato da mura, che limitano l'area descitta dal modello digitale del terreno visibile in Fig. 2c e 3b.

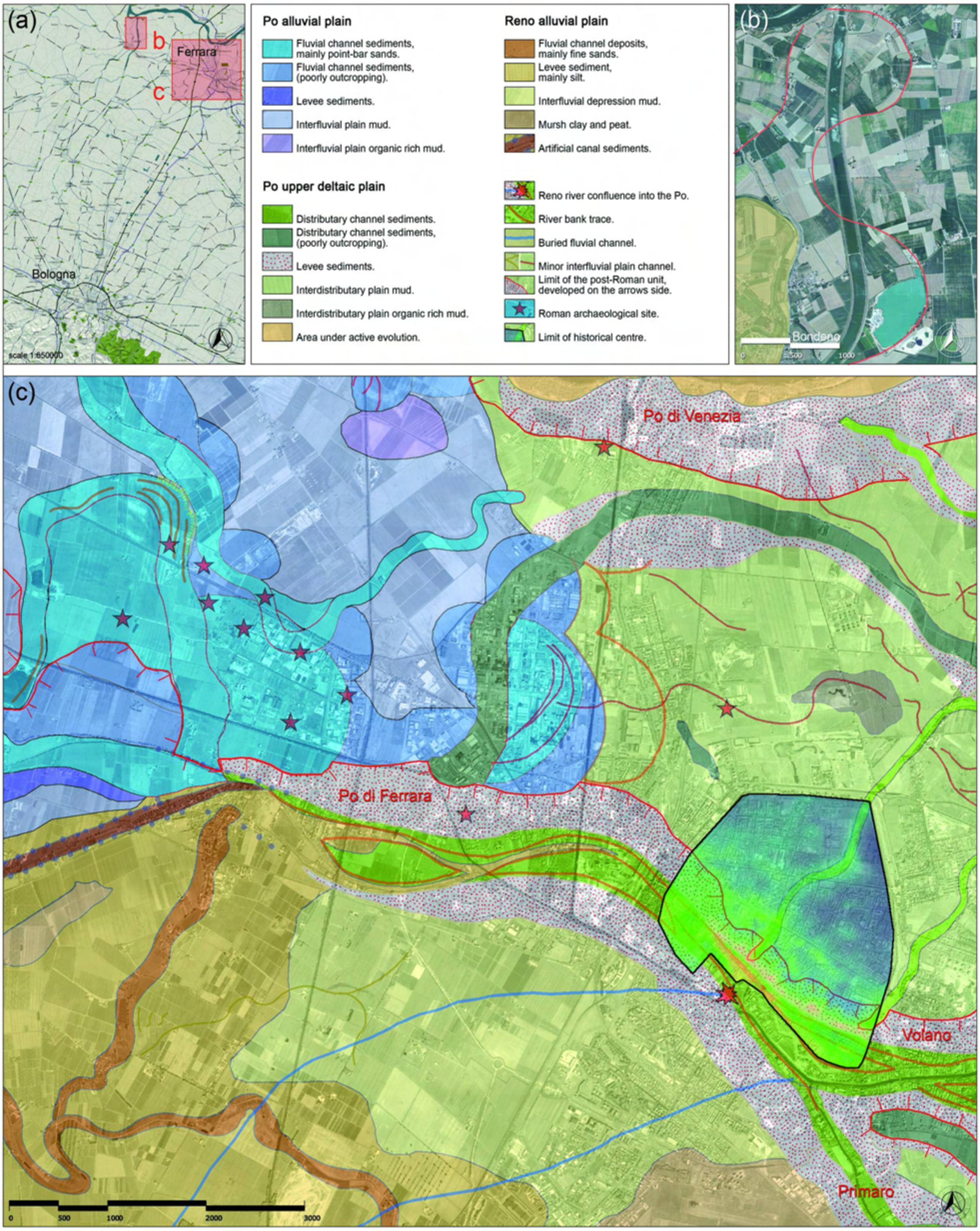

Fig. 2 - Location of the areas illustrated in this figure (a). Roman times meander structures of the Po River fed by the reworking of Pleistocene sands (b). Geological map of the Ferrara area (c). The town developed at the triple junction between the meander fluvial plain of the Po River, the lower alluvial plain of the Reno and other Apennines sourced rivers, and the innermost portion of the Po Delta region, dominated by riverine deposits. Red stars locate the main finding of Roman time sites; the digital elevation model is visible in the historic centre area.

Localizzazione delle aree illustrate in figure (a). Corpi sabbiosi depostesi in meandri di età romana e derivanti in buona parte dal rimaneggiamento di sabbie pleistoceniche singlaciali (b). Carta geologica di dettaglio dell'area di Ferrara. La città si enucleò durante l'Alto Medioevo sul corpo arginale sinistro del Po, nella regione di contatto fra la pianura a meandri di questo fiume, la bassa pianura alluvionale formata dal Reno e da altri fiumi appenninici, e la parte più interna della pianura deltizia del Po, dominata da processi fluviali. Le stelle rosse indicano i principali rinvenimenti di siti archeologici di età romana. All'area del centro storico si sovrappone il modello altimetrico semplificato.

the change in the fluvial regime, the genesis of pre- and intra-Alpine lakes, and the return to a biostasis regime induced a sharp reduction in the fluvial sedimentary load. This reduction produced alluvial fan incision and interruption of the sedimentary accumulation, through large portions of the Po River and Venetian plains (Fontana *et al*., 2004; Stefani & Vincenzi, 2005). In the investigated region, the top of the Pleistocene is therefore marked by an erosive, discordance surface.

The post-glacial sea-level rise triggered renewed alluvial plain sedimentation. The first, discontinuous sediments consist of silt deposits, infilling shallow incisions. Complex alluvial plain deposition followed, through Holocene times. The depositional style of the Po River was strongly influenced by the nature of the local substratum. At the starting of the renewed accumulation, the Pleistocene sands were largely outcropping and thus easily reworked by the meandering river flow. Point-bar systems therefore largely derived from the cannibalistic reworking of the local Pleistocene sand substratum. The extension of the meandering belt then shrunk, because in the lagoon flooding the northern side of the Roman time main delta lobe (*Eridanum*), the port town of Comacchio was growing of the spreading out of lower alluvial plain, fine-grained deposits, protecting the upper Pleistocene sands from erosion. During late transgressive and highstand times, this sedimentary trend confined the meander development to the less subsiding areas, where the Pleistocene sand remained exposed to reworking. The maximum flooding phase, dating at about 5500 yr B.P. (Correggiari *et al*., 2005; Stefani & Vincenzi, 2005), is difficult to precisely detect at this inland position. In the subsurface, this phase can be correlated with widespread marsh sediments, organic rich clays, and peat horizons, grading eastward into brackish deposits.

3.2. Meander to upper delta plain channels and Bronze Age proto-urban sites

The environmental evolution of the last 3000 yr is known in growing detail, since the corresponding sediments are often outcropping, at least at the north and north-east of Medieval channel bodies of the Po di Ferrara and Po di Primaro (Fig. 2c). To the south of this channel system, only sediments younger than 1500 AD are visible, and what is known about the ancient evolution derives from discontinuous subsurface data. The Bronze Age saw an important Po River channel flowing through northern areas (Po di Adria; Bondesan, 1990). Meanders were still migrating at the north-west of Ferrara (Fig. 2c) and a Po channel already flowed at the southern side of the future urban centre. Bronze Age sites are well documented at the west of Ferrara (Bondeno, Fig. 1c, Cremaschi *et al*., 1980). Photo interpretation evidence suggesting the existence of similar sites in the Ferrara region has yet to be confirmed by stratigraphic and archaeological excavation. Evidence is however clear of a diffuse human colonisation of the lower alluvial plain area, in Bronze Age time. The Bronze age settlement (Terramare Civilisation) was terminated by large environmental modification and human abandonment through large alluvial plain areas of the Po River basin (Cremaschi *et al*., 2006).

3.3. Etruscan to Roman Age fluvial channel stability and agricultural colonisation of the plain

During Etruscan times, the Po River flowed through the site of Ferrara and formed a large delta lobe prograding into the Adriatic sea, about 60 km downstream from the present-day town (Fig. 4). On the front of this delta lobe, the Etruscan town of *Spina* flourished for a few centuries, soon to decay, also because of the silting up of its port, induced by the depositional progradation of the coastline. The Bronze Age and the Etruscan sites suffered repeated episodes of abandonment and never developed into later times towns.

The widening of the sediment outcrop area, the availability of archaeological data, and the starting of the literary transmission of geographic information allow a more precise reconstruction of the Roman age palaeogeography (Fig. 4a). During Roman Empire times, marsh areas were reduced in extension and human colonisation widespread, in the lower alluvial plain and delta top areas. The main Po River channel still formed a meandering belt at the west of Ferrara (Figs. 2c, 4a), and flowed at the south of the future town area, following a path that was to persist into the Medieval time Po di Ferrara (Figs. 2c, 4a, 4b). A few kilometres to the east of the modern town (near Cona, at the *Trigaboli* site reported by Strabo's *Geographya*, Fig. 1), the ancient Po River diverged into two distributary channels, the *Carbonarae*, at the north, and the *Eridanum*, at the south, according to Plinius' *Naturalis Historia*. The northern distributary channel fed a small delta lobe, where the (*Volana*) mouth was active. The larger southern flow (*Eridanum*) further split into several terminal distributary channels, feeding the progradation of a large delta lobe into the open sea, at the south of the present-day site of Comacchio (Fig. 4b). The previous town of *Spina* was almost abandoned, within delta top marshes. During late Republican and Imperial times, human intervention on the fluvial drainage system was massif, as suggested by evidence of river artificial embankment, the rectilinearisation of the *Eridanum* channel, in the Verginese zone, and the canalisation of the Santerno River (*Vatrenus*), in the Filo d'Argenta area, at the landward edge of the *Eridanum* delta lobe (Fig. 4a). Human intervention stabilised the drainage framework for a comparatively long period of time. Ongoing subsurface research is suggesting that, during Roman or pre-Roman times, the Reno River flowed into the Po at the modern site of Ferrara (Borgo San Luca, Fig. 5). The ancient Reno River channel was associated with a road from Bologna (*Bononia*), well documented as far as Maccaretolo (Fig. 4a), but probably reaching the Ferrara area. The Po River levees provided a pathway for a regional road crossing the future site of the study town, the *"ad Hostiliam per Padum"* (i.e. to the town of Ostilia along the Po River) depicted by the Peutingerian Map (*Pars V*, Ciurletti, 1991). Along this fluvial path the village of *Vicus Varianus* was located, likely to be identified with the present-day Vigarano Pieve (Fig. 4a). Other important sites (*Vicus Habentia* = Voghenza, *Vercellae* = Verginese; Stefani, 2006) were thread along the main Po delta distributary channel, the *Eridanum* (Uggeri, 1989), which was also associated with river bank roads. Through the coastal region, the *Via Popilia* connected Rimini (*Ariminum*) to *Ravenna*, Adria (*Atria*), and Altino (*Altinum*), running on fossil aeolian dunes, largely dating back to late Bronze Age times.

Although Ferrara is the only city of the Emilia-Romagna Region lacking a Roman time urban template, its region was nevertheless rich in agricultural sites and land reclamation works. A dense colonisation is documented by the common occurrence of Roman finding and by the photo-interpretation evidence, at the west, north and east of Ferrara. Land reclamation canals and agricultural subdivision are visible, showing an irregular geometry influenced by the local geomorphic and stratigraphic framework. A cluster of Roman sites occurs on meander river sand bodies, at the north-west of Ferrara (star symbols on Fig. 2c). Systematic archaeological investigation have been performed only at a few localities, such as in the Roman *villa* built on point-bar sands near Cassana (Fig. 1c), at the west of Ferrara (UGGERI, 1989). In the southern portion of the Ferrara province, the depositional evolution on the contrary prevents the Roman remains from being easily discovered, since they are buried at depth of even 6-7 m. In the Ferrara province (Fig. 4), just a few of the Roman sites were to survive into Medieval structures, the majority of them fading away at around the demise time of the Roman Empire, during a dramatic reorganisation phase of the fluvial system. The present-day inheritance of the Roman structures is therefore comparatively reduced in the Ferrara area, in sharp contrast with the continuity recorded through the *Via Aemilia* belt, both at the east and west of Bologna. The Roman Po River levee was however to play a major role in the following urban genesis, by providing the matrix pathway to the middle age linear town implantation.

3.4. Early Medieval reorganisation of the fluvial system and the town implantation

3.4.1. The palaeogeographic framework of the urban nucleation

Following the fall of the Roman Empire, a major restructuring of the river drainage framework took place (Fig. 4b), induced by a climate shift toward cooler and moister conditions (Bib.; VEGGIANI, 1994) and by the abandoning of the extensive hydraulic works that forced the drainage system into an artificial unstable state. A new fluvial framework eventually emerged from a phase of chaotic disorganisation and flooding, associated with a speeding up of the riverine sedimentation (CREMASCHI & GASPERI, 1989). This phase corresponds to the widespread flooding of the Po and Venetian plain referred by a relevant historic source of the time (*Fuit aquae diluvium in finibus Venetiarum et Liguriae seu ceteris regionibus Italiae*, in Paoulus Diaconus' *Historia Langobardorum*; CRIVELLUCCI, 1914). The phase is geologically recorded by widespread peat horizons and by inland delta bodies, developed from crevasse channels. North-west of Bologna, fluvial avulsion generated a new channel of the Reno River, flowing to the west of the Roman time river. The abandoned Reno levees stood for a while elevated, preventing the drainage of overland water and thus inducing widespread marsh formation. A new Po River system also developed, through the upstream interconnection of various channels. These structures were often inherited from previous phases and sometimes even derived from the capturing of artificial canals, as it is the case of the new southern distributary channel of the Po, the Primaro. This channel reused a Roman canalisation of the Santerno water, near Filo di Argenta, (see previous paragraph and Fig. 4a, b). The fluvial reorganisation process joined upstream this channel to the main Po River flux, using a crevasse passage, within the future urban area of Ferrara. This crevasse pierced the Po River levee immediately downstream of the joining point of the Roman time Reno River with the Po di Ferrara channel (marks in Figs. 2c, 4a, 5). During these early Medieval times, the northern channel of the Po di Volano was also generated. The new main distributary channel diverged from the former *Carbonarae* Po at Contrapò and flowed eastward, toward its prograding delta lobe, at the east of Codigoro (Fig. 4b). The new channel funnelled the majority of the Po River flux and thus drained out the main Roman time distributary channel, the *Eridanum*.

During this drainage reorganisation phase, the majority of the Roman settlements was abandoned and often buried by fluvial and marsh sediments, while a new generation of nuclei developed, on the levees of the recently generated Po channels. Argenta was founded on the northern levee of the new Po di Primaro channel, along the pathway toward Ravenna. In the lagoon flooding the northern side of the Roman time abandoned delta lobe (*Eridanum*), the port town of Comacchio was growing. At the apex of the fast prograding Po di Volano delta lobe, the Benedictine Abbey of Pomposa was founded, probably in the 7^{th} century. Along the coastline, a new route (*Via Romea*) developed, passing by the Pomposa Abbey, while the older Roman road (*Popilia*) remained active at the west on aeolian dunes, site of Medieval nuclei (San Basilio). The coastal roads were easily connected to the Ferrara region through the new levee pathways, along the Po di Primaro and Po di Volano channels.

3.4.2. The sitting of the early settlement of Ferrara

During the early Middle Ages (7^{th} century), the new geographic scenario (previous paragraph) guided the sitting of a fortification that was to provide the aggregation nucleus to Ferrara. This fortification is in literature known as *Castrum* (PATITUCCI UGGERI, 1989), after a 15^{th} century source (Flavio Biondo), describing a *castrum* foundation on the Po River bank by Greeks against Longobards. Even if not supported by sound written documentation, the story fits well with the physical evidence preserved by the present-day town. The convergence of terrestrial and fluvial pathways into this boundary area guided the location of the new military nucleus and supported its following expansion. The Ferrara site was at the junction of the fluvial and levee routes from Ravenna, Argenta, Comacchio and Pomposa that followed the distributary channels of the Po River (Fig. 4b). The Po River pathway led upstream to inner Po Plain regions, as far as the Longobard capital town of Pavia. A road from Bologna probably still existed on the Roman time Reno River sedimentary body, reaching the Po levee in front of the new military site (Figs. 2, 4a, 5). Other paths converged into the *Castrum* site, following pre-Roman fluvial bodies (Figs. 2c, 5), at the north-west of the town (from Mizzana to

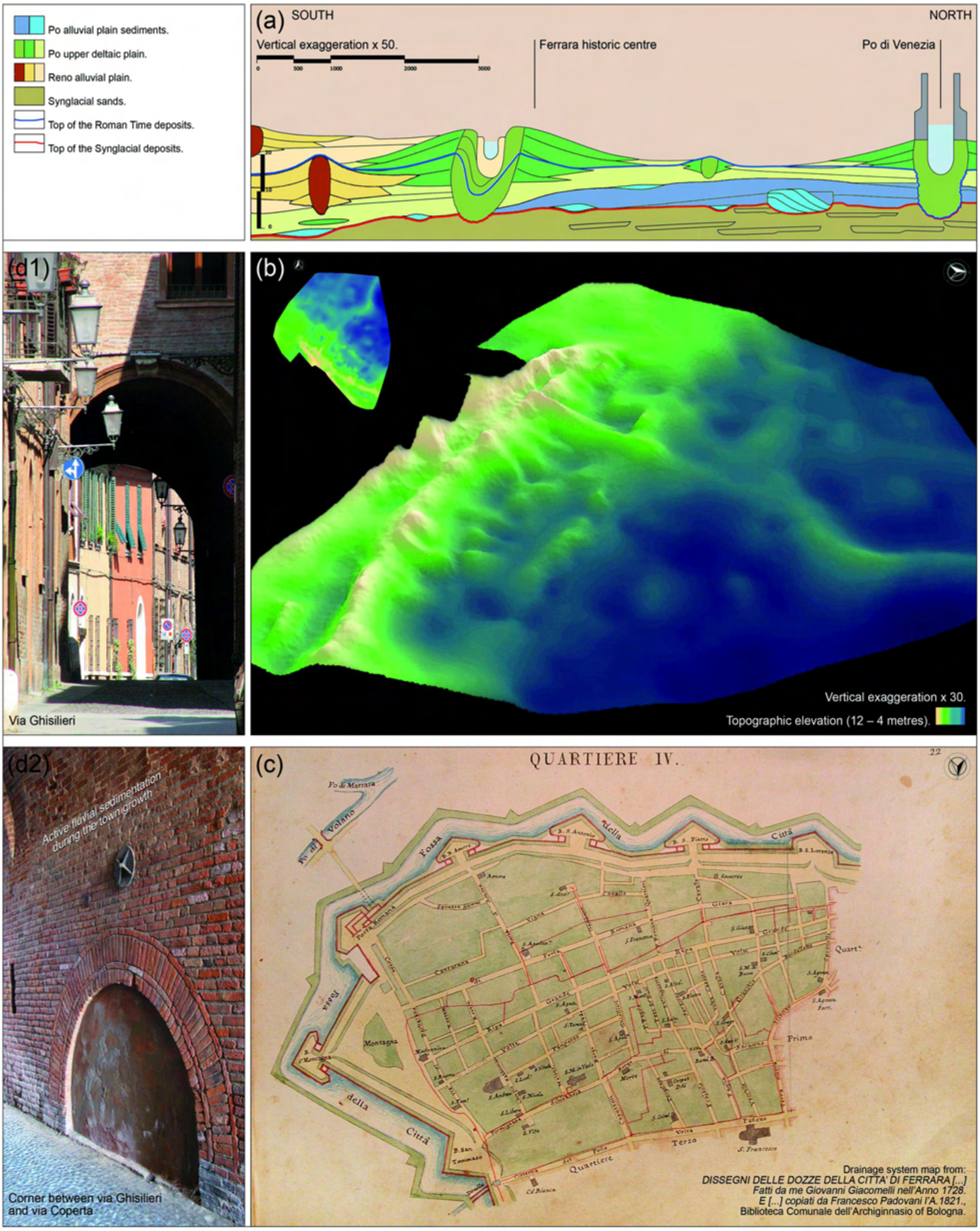

Fig. 3 - Geometric scheme of the stratigraphic relationships (**a**) between upper Pleistocene synglacial sands and Holocene Po and Reno fluvial deposits in the Ferrara urban area, along a north-south profile. Digital elevation model (**b**) of the historic centre of Ferrara (location in Fig. 2c), recording the morphological expression of the northern levee sediments of the Po di Ferrara River; the area ranges in elevation from + 3.7 m to + 12.2 m above sea level. An example of historic map representation of the ancient drainage system (**c**), recording valuable information on the environmental and urban history of the area. Two photographs (**d1, d2**) illustrating the morphological affect of the levee-top sedimentation and during the Medieval urban growth; the arch structure is deeply buried by sediment and anthropic deposits. In Medieval times, the urban growth was mainly confined to the more elevated levee body, depicted by yellow and green colours in the elevation model; during the late 15th century, the town expansion colonised the morphological depression described by the blue colours, in the northern portion of the model.

*Schema geometrico delle relazioni stratigrafiche fra i corpi sedimentari del Pleistocene superiore e dell'Olocene lungo un transetto nord-sud, nell'area urbana di Ferrara (**a**). Modello numerico della topografia del centro storico (**b**), Localizzazione in Fig. 2c), che registra una variazione altimetrica da 3,7 a 12,2 m sul livello del mare; il microrilievo registra chiaramente l'argine settentrionale del Po di Ferrara ed il suo rapporto con l'adiacente depressione interalvea. Un esempio di cartografia storica (**c**), che descrivendo l'andamento del reticolo fognario storico fornisce importanti informazioni sull'evoluzione dell'area urbana. Due fotografie (**d1, d2**) che illustrano l'aggradazione del corpo arginale avvenuta durante la crescita medievale della città; notare i piedritti dell'arco profondamente sepolti da sedimenti e depositi antropici. Durante il Medioevo, la crescita urbana fu sostanzialmente confinata al corpo arginale, rappresentato nel modello topografico dai colori gialli e verde-chiaro; solo fra XV e XVI secolo la grande espansione rinascimentale riuscì a colonizzare la depressione interalvea, rappresentata dai colori bluastri.*

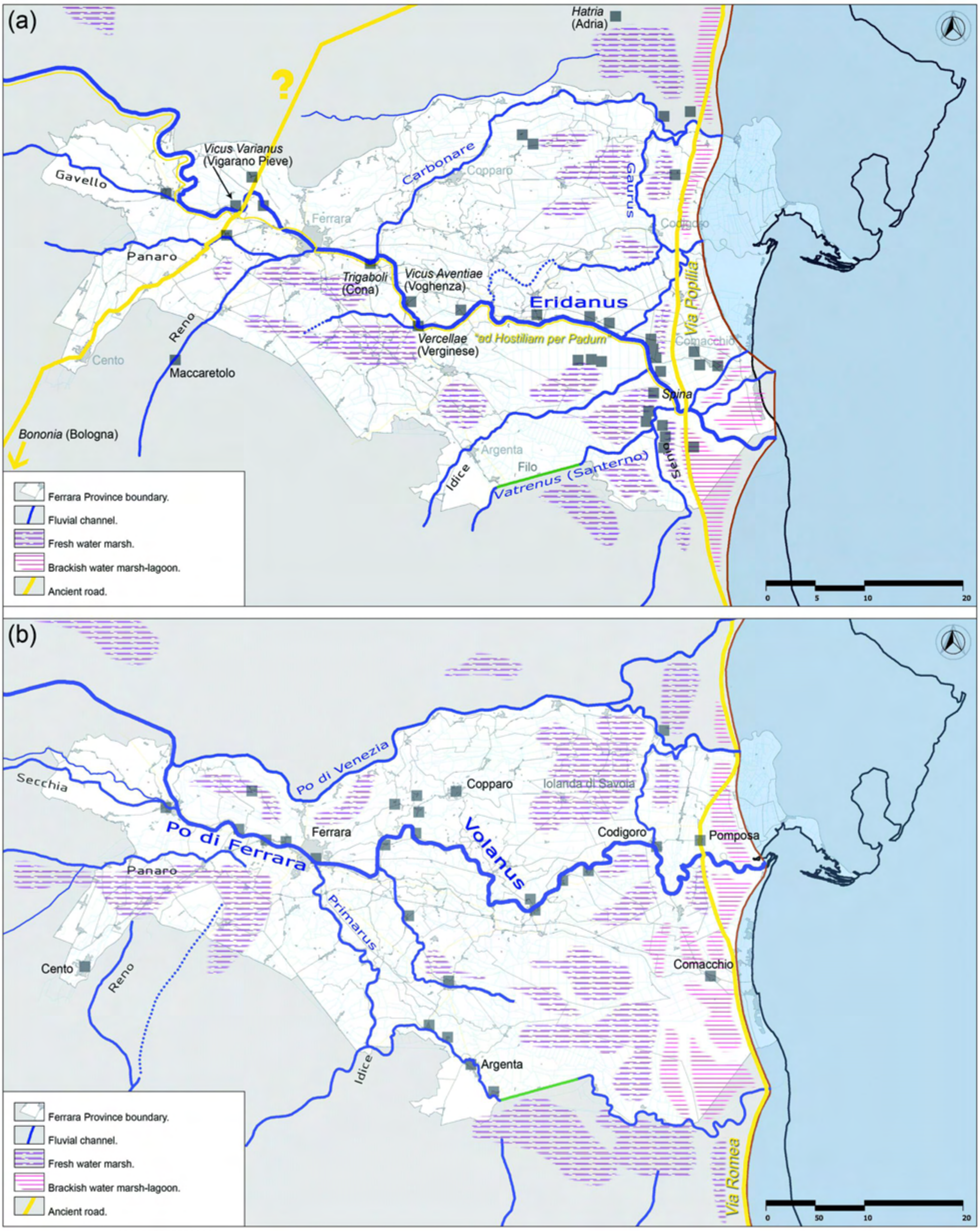

Fig. 4 - Schematic reconstruction of the palaeogeographic framework of the Ferrara province during Roman Empire times (**a**) and in the late 12th century (**b**). During early Medieval times, the area experienced a widespread fluvial system reorganization that controlled the foundation site of Ferrara; the northern Po channel developed in the 12th century and it is only one surviving into the present-day.

*Ricostruzione paleogeografica della provincia di Ferrara in epoca imperiale (**a)** e alla fine del XII secolo (**b**). Durante il primo Medioevo, l'area fu soggetta ad una drammatica fase di riorganizzazione del reticolo fluviale, che controllò la localizzazione del nucleo originario di Ferrara. L'attuale alveo passante a nord della città si venne individuando solo durante il XII secolo.*

western areas), in the core of the future city centre (Borgo Leoni toward the Venetian region, Figs. 2c, 3b), and within the triangular area between the Po di Volano and Po di Primaro (from San Giorgio to Voghenza). A location adjacent to the river provided a plentiful source of surface and underground fresh water, even during the dry summer seasons, a factor that was to affect the urban development for many centuries to follow (STEFANI & ZUPPIROLI, 2010).

The southern border of the fortified structure of the *Castrum* was tangential to the levee crest, over which the regional pathway from the sea to the inner Po Plain was passing (Phase 1 in Fig. 5). The early settlers chose a sandy crevasse splay structure elevated on the northern levee of the Po River as their dwelling place. This site provided drier and firmer ground than the surrounding argillaceous interfluvial depressions (Figs. 2, 4, 5). The choice of a risen area was particularly important in a time of widespread river flooding. The ancient fortification site still stands out as the "highest" point of the town (present geoidal elevation 9.6 m; Figs. 3b, 5). The southern side of the fortified structure was about 240 m long, its area 35,000 squared metres (Phase 1 in Fig. 5). The nucleus was surrounded by a wood palisade and was the site of at least one church (San Pietro) and of about two dozens of wood houses, with associated kitchen-gardens and stalls. The detailed architectural investigation of the area reveals that the present-day brick building structure still preserve a good memory of these ancestral wood structures (DALLA NEGRA *et al*., 2009).

3.4.3. Linear growth of the town on both the northern and southern levees of the Po River

The early expansion of the build up area was confined to the levee crest, protected from long lasting flooding (Fig. 3b). About 700 m at the north-west of the primary nucleus, a small village colonised the San Michele channel body (1a in Fig. 5). The attraction between these two nuclei triggered the expansion of the proto-urban tissue, along the interposed levee road (Phase 2 in Fig. 5). In a text dated to the 757 AD, the name *Ferraria* is for the first time documented, as a former Byzantine site occupied by Longobard forces; in a 936 AD manuscript, Ferrara is already referred to as a town (*Civitas*; CASTAGNETTI, 1985). During Carolingian times, the Po River acquired a growing transportation importance. The upstream transport of sea salt crossed the flow of agricultural and hunting products and of the Alpine Pennidic serpentinites, out of which containers for liquids were produced. The river port activity triggered the development of a triangular market square on levee deposits (Figs. 1b, 5), to the west of the original fortified area (*Platea Publica Maior*, quoted in 972 AD; BOCCHI, 1974). Archaeological investigation (ADD & WARD PERKINS, 1991; CREMASCHI & NICOSIA, 2010) has revealed, in 10th and 11th centuries levels, the intercalation of crevasse deposits and anthropic materials, producing fast ground aggradation.

During the Middle Ages, the urban tissue grew in an almost symmetrical way, on both the northern and southern banks of the Po River. The urban structures on the southern levee are however now largely obliterated by the widespread man induced destruction, occurred since the 16th century (Paragraph 3.8). During early Medieval times, the first cathedral of San Giorgio was built, at the junction of the right levee of the Po di Volano, of the left levee of the Po di Primaro. The Episcopal church is well documented in this site at the middle of the 10th century. In the early 11th century, churches and houses were thread along the southern levee road of the Po di Ferrara, facing the developing northern nucleus (FRANCESCHINI, 1981). The southern urban area then constantly grew through the Middle Ages, to give origin to two large districts (Borgo di San Giacomo and Borgo di San Luca), elongated through the bent levee structure (Figs. 3b, 5).

On the northern bank of the Po di Ferrara River, at the beginning of the 11th century, upstream of the older *Castrum* nucleus, a feudal castle was built (Castel Tedaldo, Fig. 1b). During the first half of the 11th century, the urbanised area on the northern levee broadly stretched over a distance of about 2300 m, with a width of often less than 100 m (Phase 2 in Fig. 5). The discontinuously built area covered a surface of about 30 hectares. Between the 11th and 12th centuries, the town expansion slowly reached the base of the northern levee sedimentary body (Phase 3 in Fig. 5), consolidating there a continuous defensive line, associated to small drainage canals (via Garibaldi and via Contrari, Fig. 1b). In the meanwhile, the Po River pathway and the port works polarised the commerce activity along the sandy river-bank southern border of the town (via Ripagrande = main riverbank road).

3.5. Late Medieval fluvial reorganisation and discrete expansion episodes of the town

3.5.1. Origin of the modern Po River channel and expansion events of the town

During the 12th century, the new distributary channel of the Po River developed, which led to the formation of the present-day Po di Venezia channel, flowing just at the north of Ferrara (Figs. 1c, 4b). The new channel diverged about 30 km upstream from the town. The slowly subsiding Casaglia anticline area (Paragraph 1.2) acted as a repulsion region for the river flow, in such a way that the Po River bifurcated at Ficarolo, into the new Po di Venezia and the older Po di Ferrara channels (Fig. 4b). During the 13th century, the new northern channel still had a minor importance, and the southern flows of the Po di Volano and Po di Primano remained active, fed by the Po di Ferrara. The new Po di Venezia channel however progressively funnelled northward the main river flow, gradually draining out the older southern fluvial structures. Marshes initially expanded both at the north and south of the town. During the later Middle Ages, the climate became warmer and dryer (VEGGIANI, 1986), the fluvial drainage structures stabilised, and land reclamation works and protective dam construction were built to allow the town to grow out of its original levee location.

In the first half of the 12th century, the town became politically independent (*Libero Comune*, 1116 AD). An early decision of the new political entity was the building of a majestic cathedral, on the distal portion of the Po di Ferrara levee, at the northern border of the town. The five naves church building was cleverly adapted to the poor geotechnical properties of the cohesive sediments, through the structure load reparation onto the external walls.

During the 13th century, the urban development style gradually shifted from a "spontaneous" growth of the urban tissue, through individual building cells rooting into the geomorphological template, to the planning of discrete town expansion episodes (*Addizioni)*, fore-run by hydraulic and land reclamation works. The two growth styles often coexisted during late Middle Ages. A long protective earth dam (Argine del Traversagno, Fig. 1c) was built at the north-west of the urban centre, connecting the northern embankment of the Po di Ferrara with the southern levee of the Po di Venezia (Fig. 1c) and protecting the town from flooding. Between the 12th and 13th centuries, a new district (*Borgo Novo*) was developed at the north of the new cathedral under construction; on comparatively low laying argillaceous land (Phase 4 in Fig. 5). During the latter century, Dominican and Franciscan convents were placed at the opposite side of the new northern urban expansion, on a silty mud interfluvial substratum. At the same time, the brick building progressively pervaded and hardened the previous wood cell tissue, while the street framework experienced extensive reorganisation, with the closing of many roads and the opening of several others.

3.5.2. Flux reduction in the southern channels of the Po and urban colonisation of river deposits

During the late Middle Ages, the progressive reduction of the water flow through the southern Po di Ferrara channel induced the accumulation of sand islands, rapidly colonised by buildings, as it was the case of the San Antonio Monastery on the homonymous island (Phase 5 in Fig. 5). The lateral growth of the river sand beaches allowed a moderate expansion of the town toward the river axis, at the south of via Ripagrane (Paragraph 3.4). During the 13th and 14th centuries, the expanding urban nucleus was surrounded by brick town-walls. The southern fortifications were characterised by a peculiar concave geometry, following the river bank shape (phase 5 in Fig. 5). The southern wall structure is still followed by ancient drainage structures (Fig. 3c). The northern walls were built at the margin of the interfluvial depression, in a more morphologically uniform framework, and therefore they were more rectilinear. During the 14th century, the town had reached a length of about 2400 m and a surface extension of 140 hectares (Phase 5 in Fig. 5). The Estense Castle of San Michele was founded in 1385, at the northern town-wall line, on the ancient San Michele channel body (Figs. 1b, 2b, 5).

At the end of the 14th century, the further reduction of the water flow in the Po di Ferrara enabled the joining of the San Antonio Island to the town area. This portion of town still preserves clear evidence of the river channel morphology (Fig. 3b). Large sandy islands accumulated upstream to the town (Boschetto and Belvedere islands, Figs. 1b, 2c). Built-up districts were further growing both along the southern levee body of the Po di Ferrara (*Borgo di San Giacomo, Borgo di San Luca, Borgo della Misericordia*, Fig. 5) and on the northern one. On the latter sedimentary body, districts were developing upstream (*Borgo di Mizzana*) and downstream (*Borgo della Pioppa*) of the walled town. More buildings were constructed toward the north-east, on the winding sediment body of the San Michele channel (*Borgo di San Guglielmo*, Figs. 3b, 5). The interfluvial argillaceous depressions remained largely unbuilt. Despite the land reclamation works and the river embankment effort, flooding remained commonplace in the urban area (flooding documented in 1328, 1362, 1365, 1419, 1470, 1480, 1481, 1493, 1498; Bondesan *et al*., 1995).

3.6. Land reclamation works and Renaissance town expansion into interfluvial depressions

The middle of the 15th century marked a change in the attitude of the Estense ruling family toward the regional management. Discontinuous local intervention gave way to large geometric planning and massive land reclamation works, co-ordinated at the regional scale. Advanced topographic survey techniques were developed and large economic resources utilised. In the process, the natural patterns rooted in the geological substratum were often overlooked and obliterated. The marsh region at the north-west of the town (*Bonifica della Diamantina*, Fig. 1c) was dried, at the middle of the 15th century. Further embankment were built along the Po di Ferrara channel and the district surrounding the former San Antonio Island was surrounded by new town-walls, at around 1450 (*Addizione di Borso d'Este*; Phase 6 in Fig. 5). A new castle (Castel Nuovo) was built on the Po di Ferrara channel body, upstream to the former San Antonio Island. In the meanwhile, new building progressively colonised the argillaceous interfluvial depression, at the north of the Medieval town of Ferrara (Church of Santa Maria degli Angeli, Villa of Belfiore, Monastery of San Cristoforo, Fig. 1b). These edifices fore-run a massive town expansion and new fortification building, made possible by the regional land reclamation works. An urgent need of an expansion and modernisation of the town fortification was at the time prompted by the southward expansion of the Venice Republic, which reached the Po di Venezia channel, just a few kilometres to the north of Ferrara, following the 1484 victory in the "War of Salt". At the end of the 15th century, the town surface was more then doubled, through the construction of a very large addition (*Addizione Erculea*), occupying interfluvial argillaceous depressions (Fig. 3b). Topographic lows of less than 4 m of elevation were incorporated into the enlarged town that reached a surface of more than 440 hectares and a population between 40,000 and 50,000 people. Ferrara therefore joined the number of the largest town of Europe. Large unbuilt areas were however to persist within the town-walls until the present (Fig. 1b). The new fortifications were important also for protecting the urban area from the recurrent flooding, such as the 1522, 1579, and 1585 ones. This protection remained affective for a long period of time, as for instance documented by the 1705 flooding episode. The poor geotechnical properties of the organic rich mud supporting the new edifices induced significant construction problems, witnessed by large building deformation (for example the church of San Cristoforo, Fig. 1b). The new leaving on low permeability mud sediments reduced the water availability and prevented the phreatic well exploitation. Water reservoirs were therefore realised, with artificial sand infilling of under-

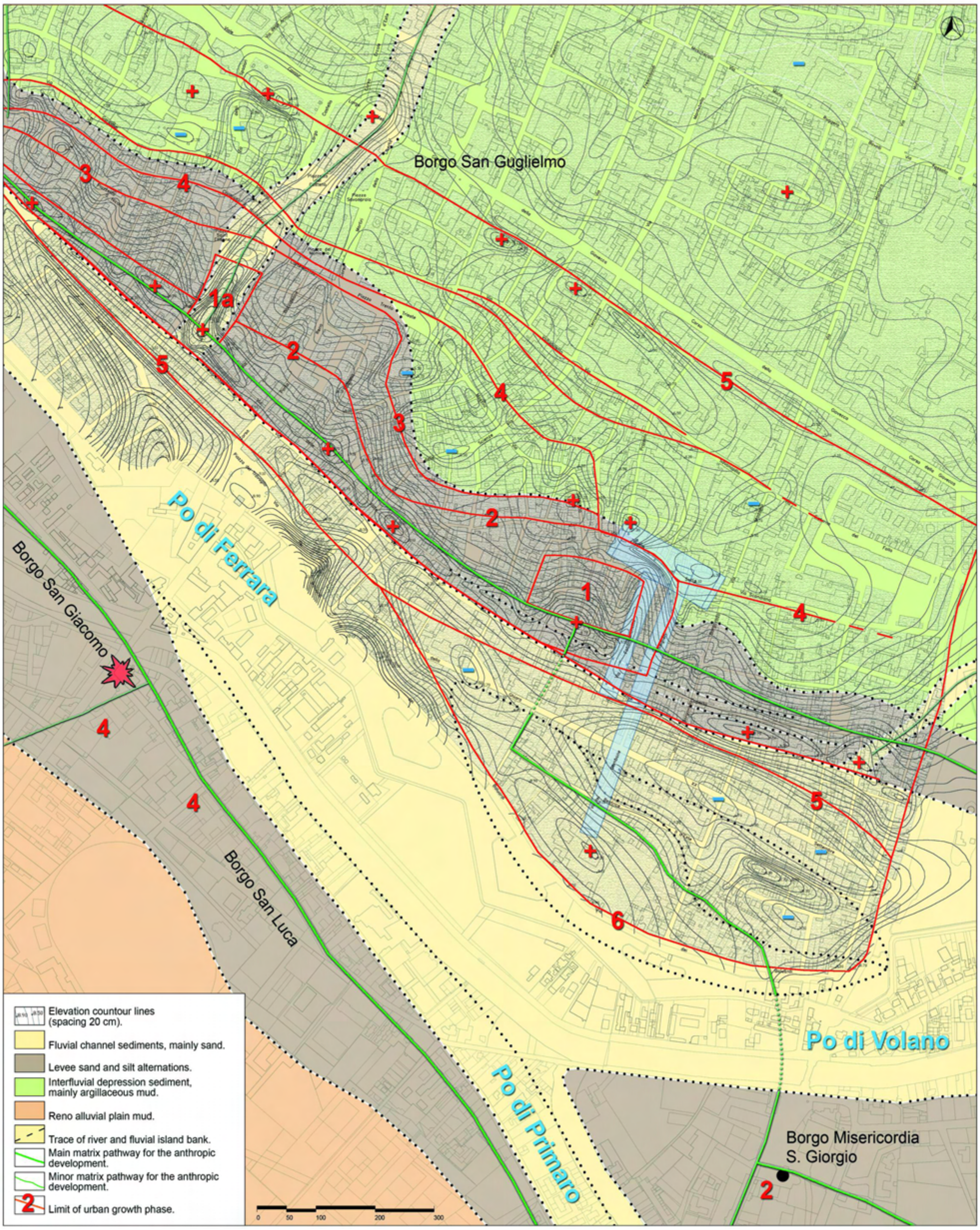

Fig. 5 - Synoptic representation of the relationship linking (1) sedimentary substratum, (2) topographic framework, (3) route pathways, and (4) urban growth phases. (1) Colours lines depict the different sedimentary facies; (2) contour lines describe the digital elevation model, with a 20 cm spacing; (3) the green lines illustrate the regional roads framework, (4) the red boundary-lines and red numbers correspond to the Medieval growth phases of the town; the red mark indicates the probable confluence site of the Roman time Reno River into the Po channel. The light blue boxes indicate the trace of the stratigraphic-architectural profiles of Fig. 6. For the regional framing of the map, see Fig. 2. The Po di Ferrara sedimentary body bifurcates into the Po di Volano and Po di Primano distributary channel deposits. The adjacent natural levee units supported the development of the Medieval town, which nucleated on a crevasse splay (1) and then grew in an elongated way on the levee crest (2), to then slowly expand toward more distal portions of the levee body (3-4). Fluvial island and channel units were colonised only at later times (5), following a river flux decay

Rappresentazione sinottica dello stretto legame esistente fra (1) composizione sedimentologica del substrato stratigrafico, indicato dalle diverse campiture cromatiche, (2) il contesto topografico, descritto da isoipse continue con equidistanza di 20 cm, (3) l'andamento dei percorsi antropici regionali, indicato dalle tracce verdi, e (4) le fasi di nucleazione e crescita del tessuto urbano in età medievale, indicate dai confini e dai numeri in rosso. Il segno arancione indica il probabile sito di confluenza del Reno di età romana con il Po. I rettangoli azzurri indicano la localizzazione dei profili stratigrafico-architettonici di Fig. 6. Per la collocazione regionale della carta, vedere la Fig. 2. Il corpo di canale fluviale del Po di Ferrara si biforca presso la Punta di San Giorgio nei depositi del Po di Volano e del Po di Primaro. Questi corpi sono fiancheggiati da depositi di argine naturale, su cui si svilupparono gli insediamenti medievali. Il nucleo iniziale della città (1) si insediò su di un ventaglio da rotta parte dell'argine naturale destro del Po, lungo cui la città si espanse poi in modo lineare (2); solo dopo il XII secolo la città si espanse lentamente verso la depressione interalvea (3-4). L'isola fluviale di San Antonio in Polesine e le sponde del fiume poterono essere colonizzate solo durante il basso Medioevo (5), grazie ad una riduzione del flusso fluviale.

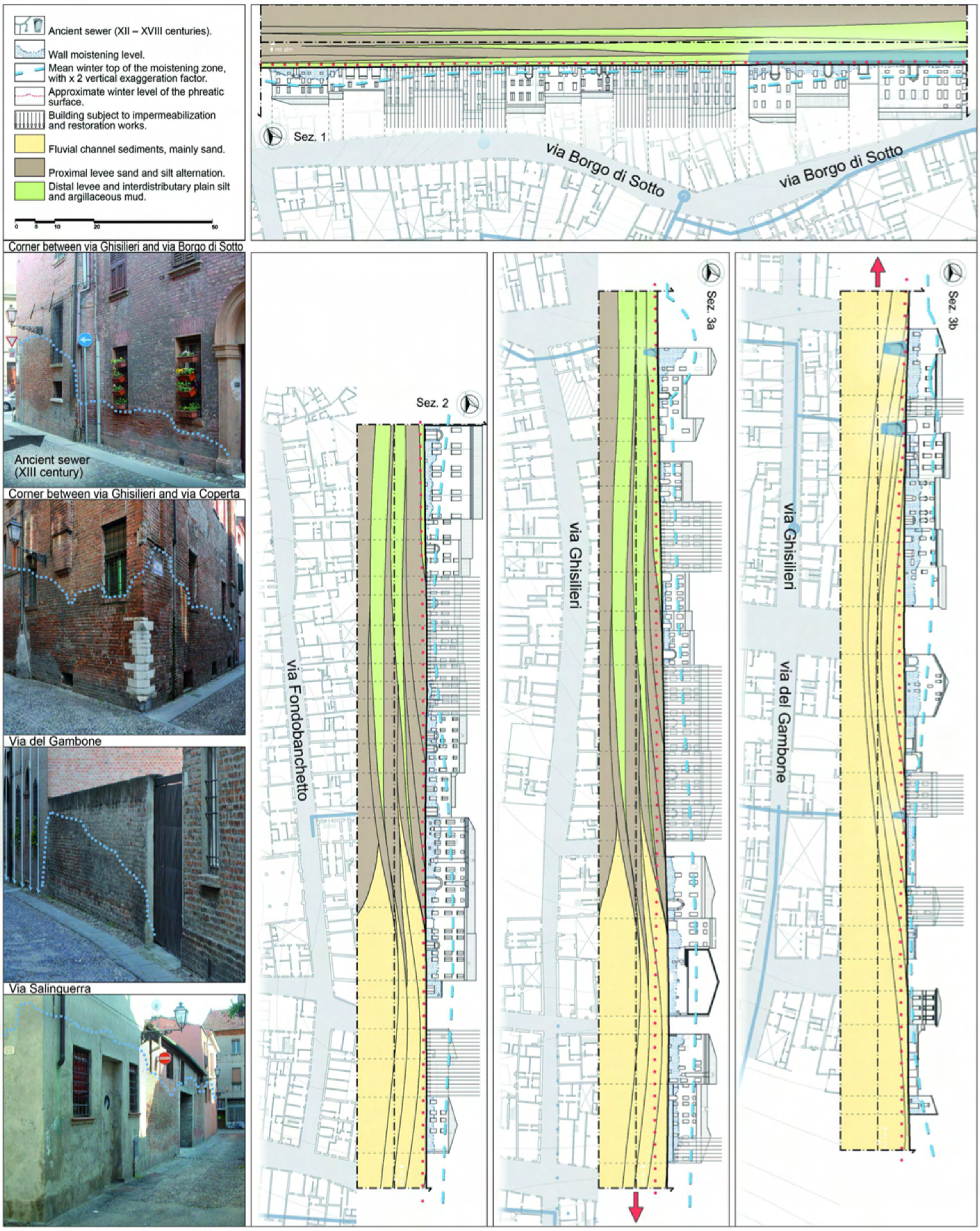

Fig. 6 - Geological-architectural profiles illustrating the strong genetic connection of the stratigraphic substratum, the surface morphology, the building structures, and the present day degradation state of the brick walls. Substratum stratigraphy derived form cone penetration tests, stratigraphic coring, and trench examination; building data from architecture surveying. Profiles location in Fig. 5. Structures built on permeable fluvial sand are characterised by very high levels of water impregnation and wall degradation, whereas building on low permeability mud are comparatively dry, despite their low topographic placement.

Profili stratigrafico-architettonici che illustrano i legami genetici esistenti fra composizione sedimentologica del sottosuolo, morfologia della superficie topografica, strutture architettoniche storiche e lo stato di degrado delle murature laterizie. La ricostruzione di sottosuolo deriva dalla correlazione di prove penetrometriche, carotaggi stratigrafici e dall'esame di trincee di scavo; i dati sugli edifici dal rilievo architettonico. Le strutture costruite sui corpi permeabili di sabbie fluviali mostrano livelli di imbibizione idrica e degrado molto più accentuati di quelli fondati su terreni argilloso-limosi coesivi, a bassa permeabilità e ad alta tensione osmotica, nonostante che questi ultimi affiorino alle quote topografiche più basse. Posizione delle sezioni in fig. 5.

ground brick walled cistern, dug into the argillaceous sediments (Stefani & Zuppiroli, 2010). Visionary hydraulic works were also performed. Salty waters from the Casaglia anticline structure were brought into an Estense court spa (*Delizia del Belvedere*), and fresh water was pumped from the Po di Ferrara stream, at the south-western corner of the town, using an hydraulic wheel, and brought to the central court square, near the cathedral (Zuppiroli, 2008).

3.7. Death of the southern Po channels and seismic damage of the town

The southern distributary channels of the Po River (Po di Ferrara, Volano, Primaro) eventually experienced a sudden demise, triggered by an ill-fated attempt (1522) to force the Reno River water to reach the Adriatic Sea through them. The reduced morphological gradients and the large sediment load of the Reno River suddenly silted up the Po di Ferrara channel, preventing any further water flow to the sea. The Reno River input formed a large shallow water lake (*Valle della Sammartina*), which was to be progressively filled by Apennines-derived sediments.

An earthquake significantly affected the town in the year 1570, (Boschi *et al*., 1997). Large edifices built on interfluvial depression mud suffered minor damage (for example: San Benedetto and San Cristoforo churches; Palazzo dei Diamanti, Fig. 1b), whereas buildings on fluvial sands, with maximum grain size in the mm order, suffered catastrophic collapses, as it was the case of Castel Nuovo and of the church of San Paolo (Fig. 1b). These collapses were possibly related to co-seismic thixotropic fluidification of water saturated river sands.

3.8. Widespread re-flooding and urban structure decay

The ending of the 16th century brought major alteration to the urban structures, triggered by both fluvial dynamic modification and political change. The silting up of the southern Po River channels (see previous paragraph) and the danger produced by the new artillery menaces prompted the building on fluvial sands of bastion fortification at the southern side of the town during the 17th century (Figs. 1b, 5) and, at the beginning of the 17th century, of a large, star-shaped fortress (*Fortezza Pontificia*, Fig. 1b), incorporating part of a former fluvial island (*Belvedere*, Fig. 1b). This large works induced massive geomorphic modification, obliterating the riverine morphology and destroying the peripheral districts previously surrounding the town (*Borghi di Mizzana, San Giacomo, San Luca, Pioppa*, Figs. 1, 5).

Several environmental and anthropic factors combined during the following centuries to generate a long lasting socio-economic decay of the town, which was to persist into the early 20th century.

(a) In the 16th century, the drying up of the Po di Ferrara channel brought an end to any port activity into the town. The Apennines-derived rivers fed large fresh water environments between Bologna to the southern border of Ferrara, reducing the agricultural space and preventing inland communication.
(b) During the 17th century, sediment compaction subsidence and the fast progradation of the man-induced modern Po delta severely disrupted the drainage system of the region, thus inducing the re-flooding of the previously reclaimed lands, through large areas to the east of the town. This re-flooding also severely reduced the agricultural potential of the region.
(c) During the 17th and 18th centuries, a shift toward moister and cooler climate condition ("small ice age"; Veggiani, 1984) supported catastrophic fluvial flooding episodes (for example, the 1705 one). The climate change reduced the agriculture production of the region and induced the marginalisation of the grape.
(d) The new large marsh areas were supported the spreading out of endemic malaria and the area was also affected by severe plague episodes.
(e) The papal rule of the town (1598-1859) made the region a marginal one in the Church State. These factors combined together to induce long-lasting socio-economic stagnation, Ferrara population halving to less than 25,000 persons (18th century), urban structures decay and fossilisation, and thinning out of the town building tissue.

3.9. The artificialisation of the fluvial system and the modern urban evolution

During the 18th century, massive hydraulic works eventually succeeded into bringing the Reno water stream to the Adriatic Sea, through long artificial canals and the reactivation of the previous southernmost distributary channel of the Po River (Po di Primaro; Angelini, 1993). Wetlands however remained commonplace in the town vicinity, until the steam-supported land reclamation works, performed during the second half of the 19th century. After the long period of economic and demographic decay, massive urban expansion restarted only after the Second World War, disregarding any geological and environmental constrains, and therefore exposing the town to significant environmental hazards from river flooding, seismic damage and underground water pollution (Bondesan, 1989). The sediment distribution in the shallow subsurface affects the local response to seismic wave acceleration, the circulation of pollutants, and the moistering of building structures. Structures built on low permeability, high osmotic tension mud are generally comparatively dry, despite their being built into topographic low area, whereas building on permeable fluvial channel sand are characterised by elevated level of water impregnation and wall degradation (Fig. 6). A close relationship therefore links the depositional evolution of the area, the stratigraphic architecture of the close subsurface, the historic evolution of the town and the present degradation state of the town buildings.

4. CONCLUSIONS

Stratigraphy, sedimentology, geomorphology, historiography, and architecture investigations were integrated to generate an interdisciplinary understanding of the dynamic interaction between natural and anthropic processes shaping the urban structure of Ferrara and the environmental evolution of the surrounding plain. Intervals of drainage system stability were punctuated by episodes of fluvial avulsion, drainage disorganisation, and widespread flooding, leading to palaeogeography innovation events. During these events, renewed fluvial stability repeatedly emerged from the down- and up-stream interconnection of river channels. The fluvial reorganisation episodes were controlled by both allocyclic factors, like climate change, and local autocyclic processes, like the instability induced by the depositional rising of the river channels. In the Ferrara area, the depositional processes were significantly affected by both the large late Quaternary climatic fluctuations and the ongoing compressional deformation of the foreland basin. The punctuated nature of the fluvial equilibria induced repeated episodes of human colonisation and urban site development, terminated by widespread abandonment. Through proto-historic and historic times, at least three main cycles of human settlement and urban growth can be detected, a Bronze Age cycle, a massive Roman colonisation of the area, and an early Medieval to modern time cycle, during the early development of which Ferrara nucleated. The study was therefore particularly focused on the later one.

The fluvial sands inherited form the glacial phase affected the depositional dynamics even in historic times, supporting the cannibalistic development of meander point bars. In the study area, meander river deposition progressively gave way to lower alluvial plain and inner delta plain deposits. During Roman times, a comparatively warm and dry climate scenario was associated with a long-lasting stabilisation of the delta system, helped by massive anthropic intervention. The fall of the Roman Empire structures and a climate shift toward cooler and moister conditions was matched with a massive river reorganisation, the diffuse abandoning of Roman site and the nucleation of new villages and towns. During early Medieval times, the converging of fluvial and terrestrial routes suggested the sitting of a small fortification, which was to provide the nucleus to the future Ferrara urban growth. Until the 12th century, the town grew linearly, over the northern natural levee of the Po River. During later Middle Ages, the town slowly colonised base of levee and former fluvial channel settings. The Medieval urban tissue was largely influenced by the underlying depositional and geomorphic structures. In late Medieval and Renaissance times, large land reclamation works were performed, enabling the design of a majestic urban expansion onto interfluvial depression argillaceous sediments. The water flux through the southern channels of the Po River was stopped during the 16th century, by the silting up induced by an ill-fated attempt to force the Reno River water into reaching the Adriatic Sea through these distributaries. The 1570 earthquake produced different effects according to the various stratigraphic substrata. During the following centuries, large fresh water marsh surrounded the urban area that experienced a sever decay. The urban structures started to expand again at a faster pace only after the Second World War, disregarding the geological, ecological, and historic features of the area and thus leaving the town exposed to dangers like floods, earthquake and pollution.

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