1. Introduction

Florence is a city in constant expansion and is immersed in a charming landscape (Fig. 1). Florence counts more than 370,000 inhabitants, with a density of about 3.5/km².

Florence falls into the temperate climatic zone. It has a dry summer and an annual rainfall characterised by a minimum in July and a maximum in November and at the end of winter, with an annual average of 750 mm.

The city of Florence lies in the SE corner of the Florence-Pistoia plain, which appears as an elongated depression with a northwest–southeast direction. It is surrounded by reliefs and the Arno River runs through it. The plain is about 50 m a.s.l. and the surrounding hills reach an altitude of 300–400 m a.s.l.
Fig. 1: View of downtown Florence surrounded by a crown of gentle hills.

Fig. 2: Geological sketch map and cross-section of the Florence area. B (shadowed grey) = bedrock; P = Plio-Pleistocene palustrine and alluvial deposits; A = recent alluvial deposits of the Arno River and its tributaries; Aa = ancient channel deposits of the palaeo-Arno River. Red lines and dotted red lines: faults. The 14th century city-walls ring is shown by a dotted blue line, the Florence Municipality area is circled by a black line. The names are recalled in the text.
The studies, jointly carried out in the last dozen years by the University of Florence, Dipartimento Scienze della Terra, and the Florence Municipality, Direzione Ambiente, resulted in a revision and a more detailed geological knowledge of the entire Florence area and its underground geological setting. This paper summarises the results of more than a dozen years of studies and insights related to both the geological and geomorphic evolution and setting of the Florence area.

2. Geological framework

2.1 Geology


In the Florence area a large number of lithostratigraphic data, referring to 1937 drillings (as of June 2012) is available and allows us to reconstruct the area’s underground geological setting (Fig. 3). These data sets are provided in hardcopy by the archives of the Florence Municipality and the Dipartimento Scienze Terra of the University and include all of the drillings made in the Florence area since the middle of the 19th century. Each drilling has been accurately located onto a georeferenced digital topographic map surveyed at the scale 1:2000 and implemented into a GIS (coordinate system: Monte Mario Italy 1 – ESRI® ArcMap™ 10.0, copyright © 1999–2010 ESRI Inc.). Each hardcopy lithostratigraphic log has been interpreted in terms of Unconformable Boundary Stratigraphic Units (UBSU; ISSC 1994) and Unified Soil Classification System (USCS; ASTM 1988), and this interpretation has been implemented into a GeoDataBase (GDB).

The quality of the data reported in the lithostratigraphic logs is, of course, largely variable. However, by keeping as starting data that of the last twenty years, it has been possible to give a reliable interpretation of the oldest data.

The first 30 m below surface can be considered well documented, but below that, especially where the bedrock lies 100 m below the surface or more, the reconstruction is mainly conjectural and based on geological assumptions (Fig. 3).

This interpretation, a new detailed surface geological map, and a revision of the literature data allowed us to out-

Fig. 3: Territory of the Florence Municipality (black line) with reported location of the 1937 stratigraphic logs available and implemented into the GeoDataBase (GDB). In grey the outcrops of the bedrock. The green intensity resembles the grade of knowledge in the first 30 m below the surface as a function of drilling depth and clustering, distance from the outcrops (<0.2 = scarce; 0.2–0.4 = poor; 0.4–0.6 = fair; 0.6–0.8 = good; >0.8 = reliable). The ring of the 14th century city walls is outlined.
line a new interpretation and a detailed 3D reconstruction of Florence’s geology.

The Plio-Quaternary geological evolution of this area can be divided into three principle evolutionary stages (Fig. 4; Briganti et al. 2003).

During the Early Pliocene there was a long period of tectonic quiescence, with the formation of a low energy relief surface. Towards the Apennines (north–east), the Fiesole master fault system (Late Miocene?) was already present. Its escarpment is still recognisable in the southern slope of the NE reliefs. It constitutes a step-like fault with a total vertical displacement of about 800 m. It is also interrupted by the transverse faults of Castello-Scandicci and Maiano-Bagno a Ripoli. The valley of the Mugnone Creek was also present in this palaeogeographic context (Fig. 4A).

**First stage**

In the Late Pliocene (Fig. 4B) the Northern Apennines were affected by a general uplift. In the Florence area there was a reactivation of the Fiesole Fault with a new vertical slip of about 200 m that caused the tectonic depression where the fluvial-lacustrine basin of Florence–Prato–Pistoia developed. The central area of the basin was characterised by grey-blue lacustrine clayey-silty deposits, which interfingered at the edge of the basin with coarse material related to the creeks’ alluvial fans. As for the coeval deposits of the Valdarno Superiore (Billi et al. 1991, Bertini 1994, Martini & Sagri 1994) we can infer that these deposits were transported in mass by high density turbulent flows. These deposits were also linked to tectonic pulses as well as climatic variations.

**Second stage**

During the Plio-Pleistocene, new tectonic movements along the Castello-Scandicci Fault and the Maiano-Bagno a Ripoli Fault determined an uplift of around 50 m in the Florence area compared to the rest of the Prato-Pistoia Basin and marked the end of the fluvio-lacustrine deposition phase. As a consequence of this uplift, a palustral environment was established, and brown coloured silts and clays with calcrite were deposited in this area, while on the edges of the plain the main tributaries continued to deposit silty-gravelly fan delta sediments. During this period the climate was very hot. During the Middle Pleistocene (Fig. 4C) the reactivation of the Castello-Scandicci and Maiano-Bagno a Ripoli faults caused a new uplift of about 30 m in the area of Florence. These uplifts resulted in the erosion of the previous lacus-
trine sediments (Fig. 4C). During this time the palaeo-Arno made its first appearance following an east–west path and carved out a deep valley. It flowed into the Prato-Pistoia Lake forming a wide alluvial fan, today in the underground of the western suburbs of Florence.

**Third stage**

During the Late Pleistocene (Fig. 4D), the Prato-Pistoia Basin was filled up by fluvial-lacustrine deposits that reached the same level as the fluvial deposits of the Florence area. This event resulted in the formation of a flood plain and residual palustrine conditions. The right tributaries’ alluvial fans pushed the Arno River towards the southern border of the plain causing erosion at the base of the hill where Piazzale Michelangelo is situated today. This lateral erosion formed a nearly flat surface at the top of the bedrock in the historical city centre area. During the Würm Glaciation the deepening of the water gap towards the Tyrrhenian Sea triggered a regressive erosion process along the fluvial grid, resulting in the present day configuration of the drainage pattern and geomorphology (Fig. 4E).

In the Holocene (Fig. 4F) the Arno River continued to flood the plain, forming a gravelly alluvial bed with the exception of the uppermost layer, which was made up of flood silts, while the right bank tributaries formed alluvial fans and smaller river beds, which interfingered with the Arno’s alluvial sediments. The recent deposits of the Arno alluvial bed and its tributaries are ascribed to an upstream accretion phenomenon in a low sinuosity river.

According to the UBSU criterion the interpretation of this geological evolution led Briganti et al. (2003) to group the terrains of the Florence area into three units: Synthem of the Basin, Ancient Deposits and Recent Deposits.

### 2.2 Lithostratigraphy

**Synthem of the Basin**

Terrains formed by massive bodies of bluish to greyish silty clay, deposited in a lacustrine environment, perhaps in cold climatic conditions (Biber and Donau ice ages?). The tributary creeks formed clastic delta and fan delta deposits comprising pebbles and silty gravels, sandy gravels, silty sands or sandy silts. Lobes and channels are interbedded in a complex manner with the lacustrine deposits. Coarse deposits are strongly interfingered with the greyish clays, and can be partly correlated with climatic episodes characterised by strong rainfall. These deposits are thicker and more continuous in the apical areas whereas they become scattered into finer and more diluted clastic layers towards the distal zones. Upward these deposits grade to brown silts of limno-palustrine environments, with peat, carbonate, calcite and palaeosols, with layers and lenses of silty sands and gravels. The sediments of this synthem pinched out on the SW border of the basin and reached their maximum thickness of about 120 m on the NE side along the Fiesole faults; locally its present thickness varies according to the bedrock morphology and the grade of the post-Pliocene erosion.

**Ancient Deposits**

In the Florence city area they are mainly represented by the palaeo-Arno deposits. They consist of well sorted calcareous gravels deposited into an east–west valley eroded in the Synthem of the Basin presently crossing the town area and a large alluvial fan on the town’s western side. This deposit has a maximum thickness of about twenty metres.

Along the northern side of the residual Prato-Pistoia Basin they are constituted by piedmont deposits deriving from the mass transport of the cryogenic detritus of the Plio-Pleistocene ice ages and from the subsequent regularisation of the slopes of the carbonate reliefs of near NE Apennines. Their thickness is several tens of metres; it is made of brown gravelly silt with centimetric angular clasts of mainly carbonate nature.

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**Fig. 5:** 3D reconstruction of the geological assemblages of the Florence underground by means of ESRI® ArcScene™ 10.0 (Copyright © 1999–2010 ESRI Inc.). (a) The bedrock setting (shadowed grey) in relation to the ground surface (shadowed green), dark blue lines represent the drillings; (b) the bottom of the Ancient Deposits (shadowed dark brown) in respect of the bedrock (shadowed grey); (c) the bottom of the Recent Deposits (shadowed light brown) in respect of the bedrock (shadowed grey); vertical = 5x.
The deposits of the residual lacustrine area are represented by brown clayey silt with blue-grey flakes and small carbonate and manganese concretions, with dispersed lenticular gravelly sandy bodies. These deposits onlap the eroded margin of the Florence high along the fault scarp of Castello-Scandicci. These deposits have a variable thickness of up to twenty metres. Tributary creeks deposits are organised according to the stream flows into silty gravels or sandy silts, locally separated by silty clays or laterally interconnected to each other. They have a thickness of up to ten metres. In the western downtown area they present complex relationships of erosion-deposition with the deposits of the palaeo-Arno.

**Recent Deposits**

Terrains formed by the Holocene riverbed and flood deposits of the Arno and its tributaries. Riverbed deposits are mainly made up of pebbles and gravels, from clean to silty, with layers and lenses of locally graded sands. These are referred to a fluvial subaerial environment where the Arno River freely braided on its alluvial bed, but periodically flooded large portions of the plain (Coli et al. 2013). These deposits are extremely variable in thickness: from a few metres up to 20–30 m. They have an average thickness of 15–20 m and lie unconformable over the bedrock in the area of the city’s historical centre and over the Ancient Deposits and Synthem of the Basin in the other areas of the Arno plain.
3. Underground setting

All the available data were implemented into a GDB (Geo-DataBase) and loaded into a GIS (ESRI® ArcMap™ 10.0 – Copyright © 1999–2010 ESRI Inc.) in order to manage all the features in 2D and 3D. By using ESRI® ArcScene™ 10.0 it was possible to reconstruct in 3D the setting of the UBSU of the Florence underground: top of the bedrock, base of the Ancient Deposit, base of the Recent Deposit (Coli & Rubel-lini 2007, Coli et al. 2007, Coli et al. 2003, 2012a, b; Fig. 5).

Recently, it was also possible to reconstruct the 3D complex setting of the USCS units (characterised by unconformable contacts and heteropies) by using a trial licence of LeapfrogGeo3D (® Aranza Geo Ltd.; Fig. 6).

The bedrock surface we reconstructed does not result from a computerised extrapolation but from the authors’ interpretation of all the available data and geological reconstructions. In particular, the bedrock surface was reconstructed on the basis of a few drillings, but mainly on the basis of geological considerations. In accordance with these and with the geological history of the area, the fault scarps were considered subject to subaerial erosion and subsequent onlap sedimentation.

The bedrock (Fig. 7) appears to be at a shallow depth (<20 m from the ground) in Florence’s historical centre, where the Arno River laterally eroded it in the last stage of the recent geological evolution of the Florence area.

To the west, the Castello-Scandicci Fault causes an abrupt lowering of the bedrock of about 100 m. The bedrock lowers westwards towards the plain where it reaches a depth below the ground of about 600 m. Towards the Fiesole master fault system, the bedrock reaches a depth below the

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**Fig. 9:** Landscape changes through the last 20 centuries in the city area of Florence. White/black line: Florence Municipality boundary; the ring of the 14th century city walls is always outlined as reference. Marshlands, the Arno River and its tributaries are reported in order to see their variation in the last twenty centuries. (A) Pre-Roma natural landscape; (B) 3rd century, the Roman City and the “Centuriazione” are outlined; (C) around the 10th century, the City is outlined; (D) renaissance age, Florence is encircled within the 14th century city walls; (E) 19th century, Florence is still encircled within the city walls; (F) 21st century, Florence widens in the plain.
ground of about 120 m; here it is segmented by faults that are transversal to the master faults of Fiesole. The fault of Bagno a Ripoli-Maiano determines a lowering of the bedrock in the southeastern area of only 10–20 m.

The bedrock topography displays traces of the Early Pliocene Mugnone Valley, when the Mugnone Creek supplied a large fan delta in the Pliocene Tyrrenian Sea (Bartolini & Pranzini 1984).

The 3D reconstruction of the bottom of the Ancient Deposits (Fig. 8) derives from the many drilling data available. The proposed reconstruction was made by interpolating the GDB data for the Ancient Deposits according to the IDW (Inverse Distance Weight) criterion.

The resulting surface outlines the eroded valley of the palaeo-Arno River in the Synthem of the Basin and the lacustrine area west of the Castello-Scandicci Fault.

4. Recent anthropic evolution

Basic geological data, geomorphological surveys and historical documentation allowed us to reconstruct the changes of the area surrounding Florence in the last twenty centuries during the development of the city of Florence (Fig. 9; Conedera & Ercoli 1973, Coli et al. 2004, Coli & Rubellini 2007a).

Florence was founded by Julius Caesar in 56 B.C. as a colony for his veterans. Florence was settled following a N–S and W–E street grid, in an upraised area, between the Arno River and the Mugnone Creek. That site allowed the control of the ford on the Arno River, along the main route between the Tyrrenian and the Adriatic coasts.

In those times, the natural landscape, constituted by the wandering Arno River, its tributaries, and by marshlands and bogs, had already been changed by about two centuries of land use by Romans. The Romans used to reclaim marshlands and bogs by means of “centuriazione”: squared grids of ditches and roads that deeply marked the territory.

Traces of the “centuriazione” are still now visible; it drove, and still drives, the organisation of fields and urban outskirts. “Centuriazione” was oriented according to the terrain’s natural configuration (NW–SE and SW–NE). The development of Florence in Roman times (in the 3rd century Florence numbered about 50 000 people, and dropped down to 1000 in the Byzantine age, 6th century) and in the late medieval and renaissance periods (when Florence numbered about 100 000 inhabitants) was along the suburbs. Suburbs were aligned along the outgoing roads, and in order to enclose these suburbs the successive rings of the city walls gave Florence a pentagonal shape. The last city walls (14th century) were mostly destroyed in the late 19th century to make space for a ring of avenues and for new quarters outside the old walls. These new quarters were built parallel to the destroyed city walls. The new outskirts built in the last fifty years around Florence were still settled according to the old traces of the “centuriazione”.

During this time span, the drainage pattern of the Florence plain underwent many important artificial changes (Fig. 10): Originally the Arno River was wandering and braided, as can be inferred by the names of districts such as Bisarno (“Double Arno”), Isolotto (“Little Island”), Cascine dell’Isola (“Farms on the Island”).

After the fall of the Roman Empire, marshlands and bogs again took over areas that were progressively reclaimed from the 11th to the 20th century. Since the late dieval era the Arno River has been progressively banked, narrowed and rectified. These anthropic interventions led to an increase of its gradient, but in the event of large floods the Arno River becomes as large as it used to be and floods the Florence area (Coli et al. 2013; Fig. 11). Creeks became moats and were progressively diverted from their natural path until they were totally channelled or covered.
5. Conclusions

These studies have had the goal to improve the availability of knowledge for the Florence area and its underground. They have also allowed researchers to overcome the gap between the classical studies of regional geology, recently updated with the new regional geological map at the scale 1 : 10 000 (RT 2012), and the needs of planners in terms of urban geology.

The studies developed are being used as the basic data in the planning and designing of the new rail under-pass, the northern underground ring, and the tramway lines, as well as for the development of the urban structural plan and the map of the ground seismic acceleration (Coli et al. 2008a, 2008b).

At present, on the basis of all these acquired data, a comprehensive study on the flood hazard (Coli et al. 2013) has already been presented, and others on the seismic vulnerability of the city of Florence are in progress.

6. References


