Atti Soc. Tosc. Sci. Nat., Mem., Serie A, 122 (2015)
pagg. 79-88, fig. 5; *doi: 10.2424/ASTSN.M.2015.22*

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THE UPPER PLEISTOCENE "ISOLA DI COLTANO SANDS" (ARNO COASTAL PLAIN, TUSCANYITALY): REVIEW OF STRATIGRAPHIC DATA ANDTECTONIC IMPLICATIONS FOR THE SOUTHERN MARGIN OF THE VIAREGGIO BASIN

Abstract - *The Upper Pleistocene "Isola Di Coltano Sands" (Arno Coastal Plain, Tuscanyitaly): Review of Stratigraphic Data Andtectonic Implications for the Southern Margin of the Viareggio Basin.* We present and discuss previously published stratigraphic and chronological (mainly archaeological remains) data about the "Isola di Coltano Sands"(ICS), with the support of unpublished core stratigraphies and taking into account the geological frame of the Arno coastal plain.
ICS outcrops in the southern portion of the extensional Viareggio Basin, forming three isolated small-sized reliefs rising up to 15 m above the present-day Arno coastal plain on both sides of the Arno River.
We document that the deposits outcropping north of the Arno River (Palazzetto site) reasonably belong to the Holocene prograding beach-ridge system to which they are physically juxtaposed. Indeed, both sedimentological and morphological characteristics indicate that the Palazzetto sands were exclusively formed by wind-related processes, likely occurred during the late Holocene according to the presence of Eneolithic artefacts.
Conversely, the common presence of *Mousterian* artefacts at the Castagnolo and Coltano sites, located south of the Arno River, documents an age older than 40 kyr (upper Pleistocene) for these reliefs. Moreover, new stratigraphic data show that ICS are constituted by alluvial deposits with evidences of repetitive fluvial erosion episodes. All these features, indicate that ICS can be reasonably included into the Late Pleistocene Vicarello Formation, widely outcropping along the southern margin of the Leghorn Hills. In this context, an estimated age ranging between MIS 6 and MIS 3 can be hypothesized for the ICS.
However, the occurrence of Upper Pleistocene reliefs formed by alluvial deposits (Coltano and Castagnolo sites) in the southern portion of the Arno coastal plain seems to conflict with the acknowledged interpretation of the area as an extensional, subsiding setting. Moreover, the sharp morphological boundary dividing the flat Holocene coastal plain from the Quaternary Leghorn Hills is roughly coincident with the SW-NE transpressive fault (Sillaro line) that subdivides the subsiding area (Viareggio Basin, to which the Arno plain belongs) from the uplifting area (Leghorn mounts).
Thus, our review of the available stratigraphic and chronological data strongly suggests the occurrence of a geological connection between the southern portion of the Arno coastal plain, specifically of the Castagnolo and Coltano reliefs, and the Leghorns Hills where the Vicarello Formation outcrops. This connection, which may have strong consequences on the geo-tectonic interpretation of the study area, and the formation age of ICS needs to be better investigated in the future with new high-resolution tectonic and absolute chronological data.

Keywords - Facies analysis, sea-level change, Holocene, Late Pleistocene, incised valley, Arno plain, extensional basin, subsidence, Coltano sands, Vicarello Formation.

Riassunto - *Le sabbie del Pliestocene superiore di Isola di Coltano (Pianura costiera dell'Arno, Toscana, Italia): revisione dei dati stratigrafici ed implicazioni tettoniche per il margine meridionale del Bacino di Viareggio.* Nel lavoro sono discussi i dati stratigrafici e cronologici riguardanti le "Sabbie dell'Isola di Coltano" (ISC), con il supporto di stratigrafie di sondaggio inedite e tenendo conto del quadro dell'evoluzione stratigrafico deposizionale della pianura costiera a sud dell'Arno.
ISC affiorano nella porzione meridionale del Bacino estensionale di Viareggio, e formano tre rilievi di piccole dimensioni con un'elevazione fino a 15m sull'attuale piana costiera dell'Arno in entrambi i settori del Fiume Arno.
I depositi affioranti a nord del Fiume Arno (sito di Palazzetto) sono attribuiti al sistema progradante di cordoni costieri olocenici ai quali sono fisicamente giustapposti. Le caratteristiche sedimentologiche e morfologiche indicano con evidenza l'origine eolica delle sabbie di Palazzetto depositatesi in età tardo olocenica, in accordo con la presenza di industrie Eneolitiche. Di contro, la diffusa presenza d'industrie Musteriane nei siti di Castagnolo e Coltano, ubicati a sud del Fiume Arno, documenta un'età non più giovane di 40.000 anni (Pleistocene superiore) per questi depositi. Inoltre, nuovi dati stratigrafici acquisti nell'ambito del progetto CARG alla scala 1/50000 del Foglio Pisa indicano che le ISC sono costituite da depositi alluvionali con evidenze di ripetuti episodi di erosione fluviale. Tutte queste caratteristiche, contestualizzate nel quadro stratigrafico tardo-Quaternario del sottosuolo e degli affioramenti dell'area di studio, indicano che le ISC possono essere incluse ragionevolmente nella Formazione di Vicarello del tardo Pleistocene, ampiamente affiorante lungo il margine meridionale delle Colline Livornesi. In questo quadro può essere ipotizzata per le ICS un'età stimata compresa tra il MIS6 e il MIS3. La presenza di rilievi di origine fluviale di età tardo plesitocenica (siti di Castagnolo e di Coltano) nella porzione meridionale della pianura costiera dell'Arno sembra in contrasto con l'interpretazione largamente condivisa che individua nell'area un'settore estensionale e subsidente. Infatti, il limite morfologico netto che separa la piana costiera olocenica dalle Colline Livornesi pre-Oloceniche è all'incirca coincidente con la nota faglia transpressiva SW-NE (Linea del Sillaro) che suddivide l'area subsidente (Bacino di Viareggio, al quale appartiene la pianura dell'Arno e dunque anche le ICS) dall'area in uplift (Monti Livornesi).
L'analisi dei dati disponibili suggerisce viceversa l'esistenza di una connessione tra la porzione meridionale della piana costiera dell'Arno,

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in particolare dei rilievi di Castagnolo e Coltano, e le Colline Livornesi, dove la Formazione di Vicarello affiora. Il significato di questa relazione, che può avere forti conseguenze sull'interpretazione geotettonica dell'area di studio necessita di ulteriori approfondimenti stratigrafici, tettonici e cronologici.

Parole chiave: Analisi di facies, variazioni del livello del mare, Olocene, Tardo Pleistocene, valle incisa, pianura dell'Arno, bacino estensionale, subsidenza. Sabbie di Coltano, Formazione di Vicarello

INTRODUCTION

According to Fancelli *et al.,*(1986), the"Isola di Coltano Sands"(ICF) forms three small-sized and isolated morphological reliefs rising up to 15 m above the present-day western portion of the Arno coastal plain, on both sides of the Arno river course (Figure 1). Following Lazzarotto *et al.* (1990), the "Isola di Coltano Sands" has been included within the Vicarello Formation (VF), which is Late Pleistocene in age and outcrops widely along the southern margin of the Arno plain, in correspondence of the Pisa and Leghorn foothills. Recently, in the context of the geological mapping (CARG) project of the Pisa Plain to scale 1:50,000 (Sheet 273), the northernmost outcrop of the "Isola di Coltano Sands" (Figure 1, Palazzetto site) has been included in the late Holocene coastal dune unit (Carosi *et al.*, in press). This interpretation is supported by the physically connection between the Palazzetto outcrop and the innermost coastal dune ridge. Furthermore, the Palazzetto succession is exclusively made up of fine sands showing clear evidences of aeolian shaping, such as blow-out and cross stratification, and contains Eneolithic artefacts (Carratori *et al.*, 1994) according to the Etruscan age of the innermost beach-ridge (Pranzini, 2001).

From a tectonic point of view, the occurrence of two late Pleistocene reliefs (Coltano and Castagnolo sites, Figures 1 and 2) seems to conflict with the widely acknowledged interpretation of the Arno coastal plain as an area subject to tectonic-driven subsidence (Mariani & Prato 1988; Pascucci, 2005).

Aim of this work is to furnish a stratigraphic review of the "Isola di Coltano Sands" (ICS) and discuss the tectonic implications deriving by its peculiar stratigraphic-depositional arrangement, focusing on: *i)* the onlap relationships between the Holocene deposits and the "Isola di Coltano Sands", rising up above the Arno coastal plain and *ii)* the mainly fluvial nature of the "Isola di Coltano Sands".

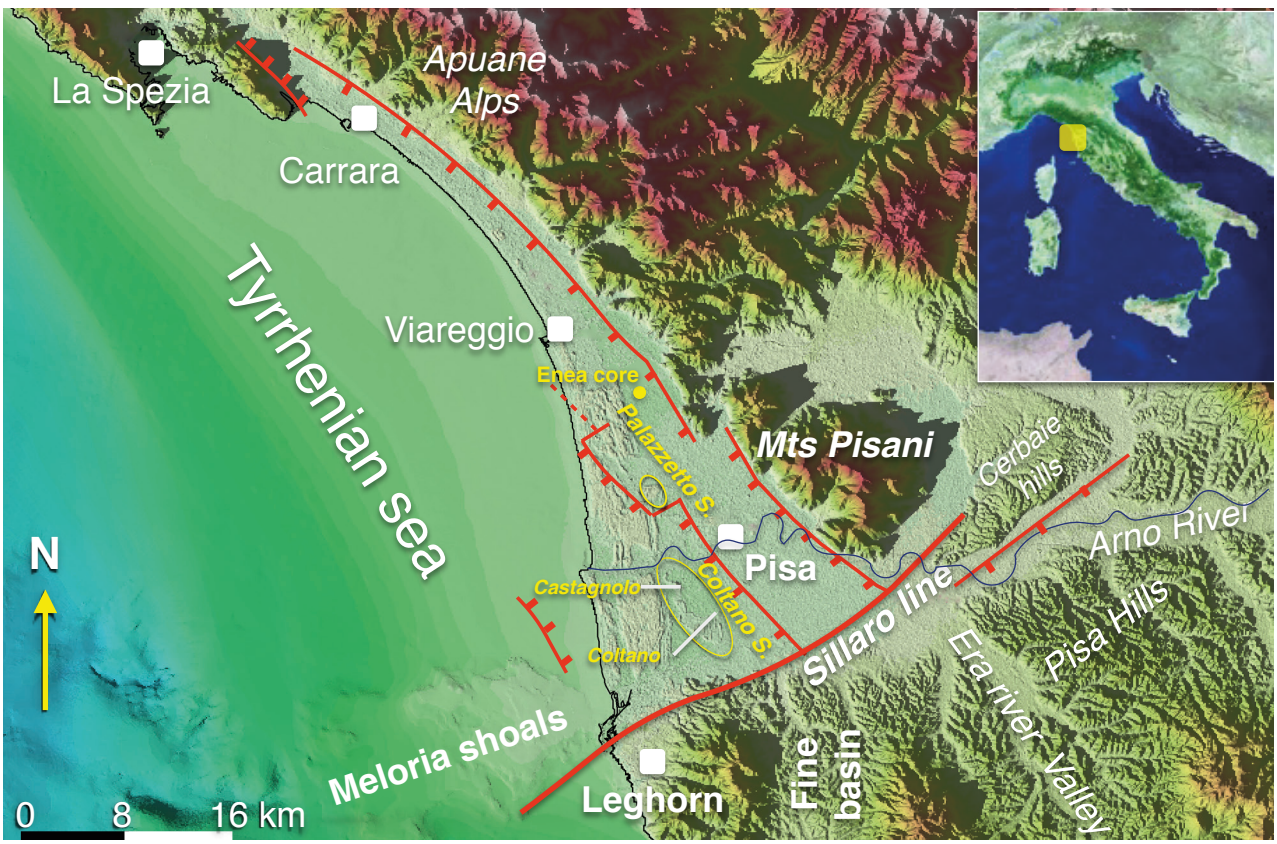

Figure 1 - Location map of the Arno coastal plain and surrounding areas. The main tectonic lineaments connected with the extensional Viareggio Basin are shown (from Pascucci, 2005). ICS reliefs are highlighted by yellow circles. Location of the Enea core is also reported.

Tectonic setting

The Arno coastal plain (Figure 1) constitutes the southern inshore portion of the NW-SE Viareggio extensional basin (Viareggio Basin-VB) that is about 20 km wide and 25 km long. It is bordered by the Pisa Mountains to the northeast, by the Meloria–Maestra shoal to the southwest, and by the Pisa and Leghorn Hills to the southeast.

The VB is one of the several extensional basins that formed since the late Messinian (ca. 7 Ma), in response to the opening of the Tyrrhenian Sea and the counter-clockwise rotation of the Apennine foredeep-foreland system (Malinverno & Ryan, 1986; Patacca *et al*., 1990; Argnani *et al*., 1997; Pascucci, 2005). Seismic analyses, integrated with stratigraphy from several deep-wells, document the occurrence of a 3000 m-thick succession of clays and sands ranging in age between the late Messinian and the Holocene and filling the onshore portion of VB (Mariani & Prato, 1988; Pascucci, 2005).

The southern boundary of the VB is marked by the NE-SW transversal lineament known as Livorno-Sillaro line (Bortolotti, 1966), which runs at the Leghorn and Pisa foothills. Several historical earthquakes, recorded few km seaward of the Leghorn city, testify that the Sillaro line is a still active transpressive fault (Ghelardoni, 1965; Cantini *et al*., 2001; Cerrina Feroni *et al*., 2001).

These data, and particularly the huge thicknesses of the basin-fill sedimentary succession, indicate that the extensional-subsiding nature of the VB mainly generated the sedimentary space-accommodation.

Depositional evolution

The Arno coastal plain is a wide (ca. 450 km2) and flat (05%) low-lying area, faced to the west by the Tyrrhenian Sea and bounded by the Versilia coastal plain and Pisa Mountains to the north, and Pisa and Leghorn Hills to the south.

The overall late Quaternary depositional evolution of Italian subsiding coastal plain areas has been strongly influenced by the Milankovitch-scale glacio-eustatic fluctuations (Fancelli *et al.,* 1986; Aguzzi *et al*., 2005, 2007; Pascucci, 2005; Amorosi *et al*., 2008a,b). A relatively wide set of data, coming from continuous boreholes drilled in the last ten years, shows an alternation of continental and coastal-shallow marine deposits in the uppermost 100 m of the Arno coastal plain. Within this depositional framework two incised-valley systems (IVFs, Sarti, 2012; Sarti *et al*., 2015), 5-8 km wide and more than 30 m depth, represent the most prominent stratigraphic feature (Figure 3). The uppermost incised valley system (IVS) began to form, close to the modern Arno River course, at the transition to the Last Glacial Maximum (MIS 3-2). This incised valley partially cut the post-valley fill deposits of the oldest IVS, which developed in a southern position during the Middle Pleistocene (probably during MIS 8). The incised-valley fill (IVF) sequences accumulated during two interglacial phases (MIS 1 and MIS 7, respectively), and display similar facies architecture. Each IVF exhibits a fining-upward tendency, with a basal lag of fluvial gravels sharply overlain by transgressive, mud-dominated coastal plain and estuarine deposits that progressively onlap onto the valley flanks. Whereas the inundation of the interfluves is almost coincident with maximum marine ingression in both IVSs, a record of the highstand succession is observed uniquely above the uppermost valley fill, due to the erosive processes that followed the MIS 7 interglacial. Around 8000 cal yr BP an extensive surface comprised between the Pisa Mountains and the innermost outcropping beach-ridge was flooded, leading to the development of a 6 km-wide lagoon basin recorded in the subsurface by *Cerastodema*-rich, highly compressible m-thick silty clays (locally known as "pancone"). These lagoon deposits occur between ca. 20-5 m below sea level and show lateral transition to rich-organic swamp silty clays (Benvenuti *et al.,* 2006; Rossi *et al*., 2011). In response to the following phase of decelerated sea-level rise (Lambeck *et al.,* 2004a, 2011), the uppermost prograding portion of the Arno coastal plain has been deposited (Amorosi *et al.,* 2013a; Figure 3). Specifically, a 10-15 m thick fluvio-deltaic succession, composed of predominant clays and silts encasing lenticular sand bodies (Amorosi *et al.,* 2013a), records the siltation of the lagoon and the progradation of the modern Arno delta-coastal plain system under prolonged conditions of relatively stable sea-level (Lambeck *et al.,* 2004a, 2011).

Stratigraphy of "The Isola di Coltano Sands"

At the Coltano site (Figures 2, 4), several hand-man cores driven down to 2 m below the ground surface document a monotonous succession of yellow decarbonated silty clays (Carosi *et al.,* in press), while more sandy deposits are observable moving northward at the Castagnolo site (Figure 2). At both sites no evidences of aeolian shaping are recorded. In contrast, several roughly flat surfaces separated by small escarpments are observed, suggesting repetitive erosional events of fluvial origin (Figure 4c).

On the basis of these sedimentological, stratigraphic and morphological features, we consider not reliable the interpretation of ICS as aeolian deposits (Fancelli *et al*., 1986;Lazzarotto *et al.,* 1990), according to Carosi *et al.* (in press). Indeed, the available data are

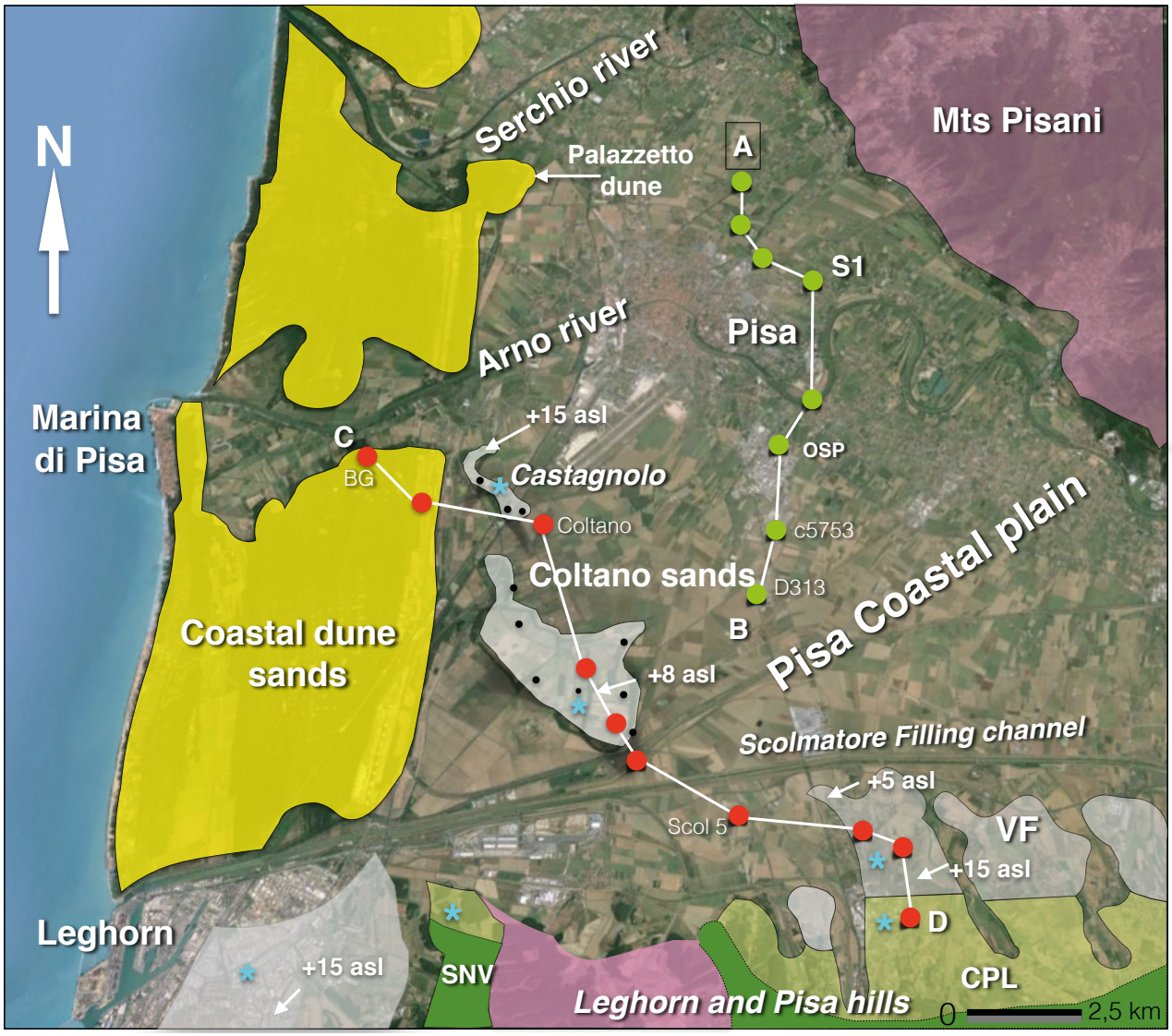

Figure 2 - Simplified geological sketch map of the study area (slightly modified from Carosi *et al.,* in press-CARG Sheet 273). It is worth to note that the Palazzetto relief is included into the late Holocene coastal dune unit, whereas Castagnolo and Coltano outcrops belong to the Upper Pliestocene Vicarello Formation. Location of the continuous cores (red and green circles) and the section traces, both reported in Figures 3 and 4, are also shown.

Keys: CPL, Casa Poggio ai Lecci Conglomerate and Sands, Middle Pleistocene in age. - SNV, Nugola Vecchia Sand, Lower to Middle Pleistocene in age. - In pink are reported the Pre-Quaternary deposits. - Small black circles: hand-man cores; - Light blue stars: *Mousterian* sites.

indicative of overbank and/or channel-related depositional environments similarly to what is suggested for the Late Pleistocene VF sands and silts (Lazzarotto *et al.*, 1990). These deposits unconformably lie onto the Middle Pleistocene deposits of "Casa Poggio ai Lecci" Fm, occurring along the Pisa and Leghorn foothills (Figure 2).

The ICS inferred age

The widespread occurrence of *Mousterian* artifacts (Menchelli, 1984; Grifoni Cremonesi & Tozzi, 1995) within the Coltano and Castagnolo reliefs indicates an age older than 40 ky BP (Grün & Stringer, 1991) and represents the more robust chronostratigraphic data available by now (Marroni *et al.*, 1990; Federici & Mazzanti, 1995; Mazzanti, 2000). *Mousterian* artifacts

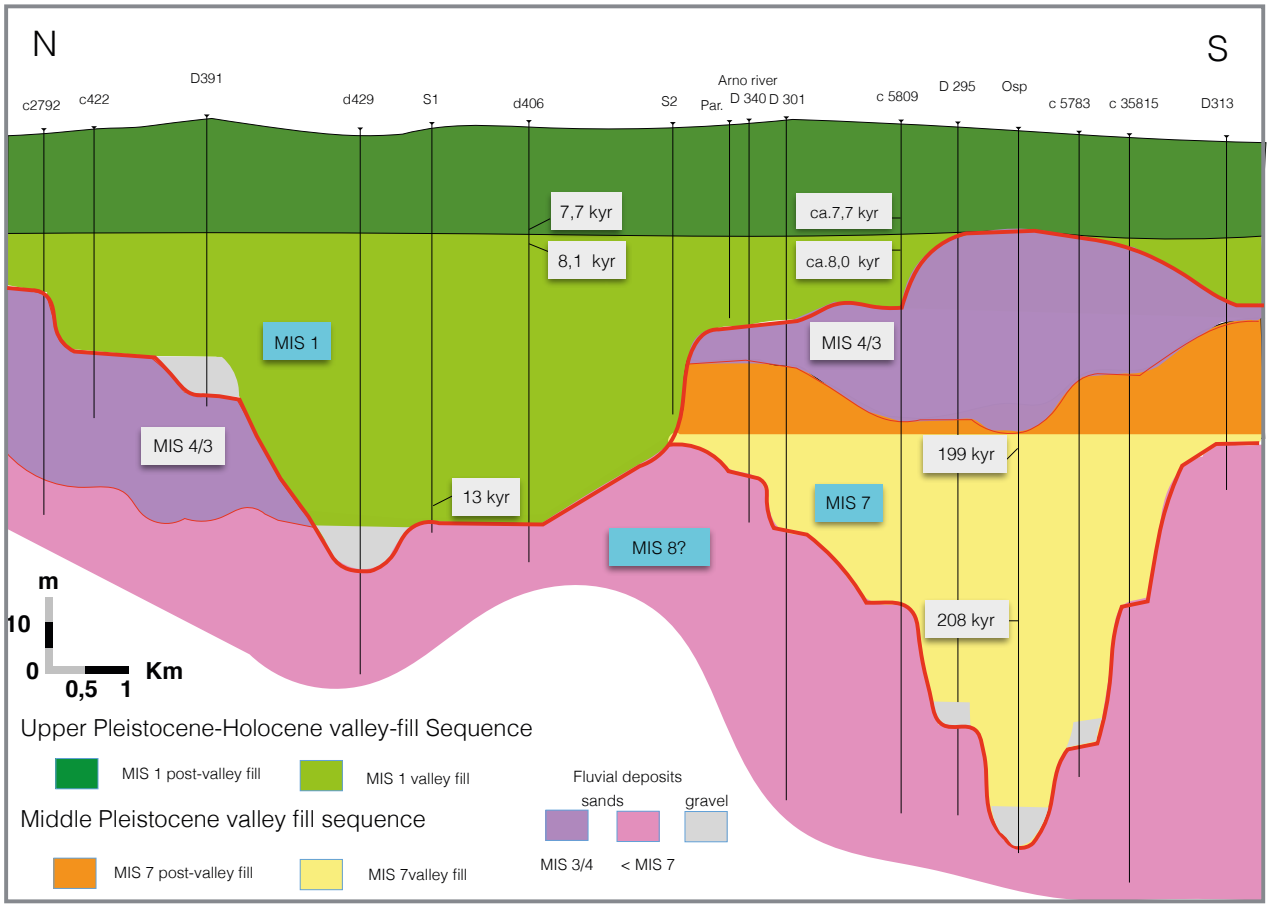

Figure 3 - Representative cross-section of the two incised-valley systems identified within the uppermost 100 m of Quaternary deposits buried beneath the Arno coastal plain. Subdivision into main stratigraphic units and their interpretation in terms of MIS are shown. The radiocarbon ages from the upper Pleistocene-Holocene incised-valley fill are reported as calibrated years BP, while the ages from the middle Pleistocene incised-valley fill are ERS data (dating from Amorosi *et al.*, 2013b, 2014; Sarti *et al.*, 2015). Section traces and sedimentary cores location are reported in Figure 2 (green dots).

(Figure 2) are also found along the Leghorn foothills on the top of the VF deposits, strengthening the belonging of the "Isola di ColtanoSands" to the VF (Lazzarotto *et.al.,*1990)

Other chronological information can be inferred through stratigraphic correlations of ICS with the Arno plain subsurface units.Several authors correlate the "Isola di Coltano Sands" with the "Limi fluviali-palustri" unit that in turn overlies the "Conglomerati dell' Arno e del Serchio da Bientina" attributed to MIS 4 (Fancelli *et al.*, 1986; Della Rocca *et al.,* 1987; Federici & Mazzanti, 1995; Baldacci, 1999). This stratigraphic interpretation seems to agree with the age of the *Mousterian* findings and, according to Federici & Mazzanti (1995) and Mazzanti (2000), refines the age of the VF to the MIS 3 (older than 40 kyr but younger than MIS4; Ciampalini & Sammartino, 2007).

However, the reliability of this stratigraphic framework was criticized by Aguzzi *et al.* (2005), showing that the coarse-grained interval ("Conglomerati dell'Arno e del Serchio da Bientina") used as subsurface stratigraphic marker (Fancelli *et al.,* 1986) is the result of a lithological correlation among conglomerates of different ages (Aguzzi *et al.,* 2007). This fact is relievable in the map reporting the isobaths of the "Conglomerati dell'Arno e del Serchio da Bientina" (see Figure 5 in Fancelli *et al.*, 1986), where the depth of the conglomerates lower boundary broadly ranges from 20 m to more than 200 m below the ground level. Moreover, stratigraphic analysis of continuously cored boreholes performed in the Arno coastal plain confirms the presence of conglomerate layers at different stratigraphic positions partially connected to the IVSs development (Figures 3, 5).

To sum up, in the absence of new specific dates the only reliable ICS chronologicalconstrains are represented by the *Mousterian* artifacts older than 40 ky (the ICS

Figure 4 - The ICF at Coltano southern Hill area (See Fig. 2 for the location). View is from SE. a) panoramic view of Coltano hill and the surrounding coastal plain area; b) particular of the escarpment; c) view from SW of the top of Coltano hill, not the flat morphology.

youngest age limit) and the Middle Pleistocene "Conglomerati di Casa Poggio ai Lecci" Fm, on which the VF rests on(the ICS older age limit). Subsurface date (Figure 5) show that the ICS erode the post-valley fill succession of MIS 7 age. Basing on that the older age limit of ICS can be restricted to MI7/6.

THE "ICS PARADOX": STRATIGRAPHIC AND TECTONIC IMPLICATIONS

In order to discuss the tectonic implications deriving from the occurrence of the ICS reliefs in the Arno coastal plain the following key-points should be keep in mind:

i. the assumed, general subsiding-extensional tectonic framework of the Arno coastal plain;
ii. the ICS depositional age that should be not younger of 40 kyr and not older of Middle Pleistocene (likely younger of MIS 7);
iii. the morpho-stratigraphic position of Coltano and Castagnolo reliefs, which rise up to 15 m above the modern plain that is still aggrading;
iv. the onlap of Holocene deposits onto the ICS reliefs.

As widely documented by both outcrop and subsurface data, the late Quaternary stratigraphy of several coastal and deltaic areas was mainly controlled by the interplay between glacio-eustatic and tectonic signa-

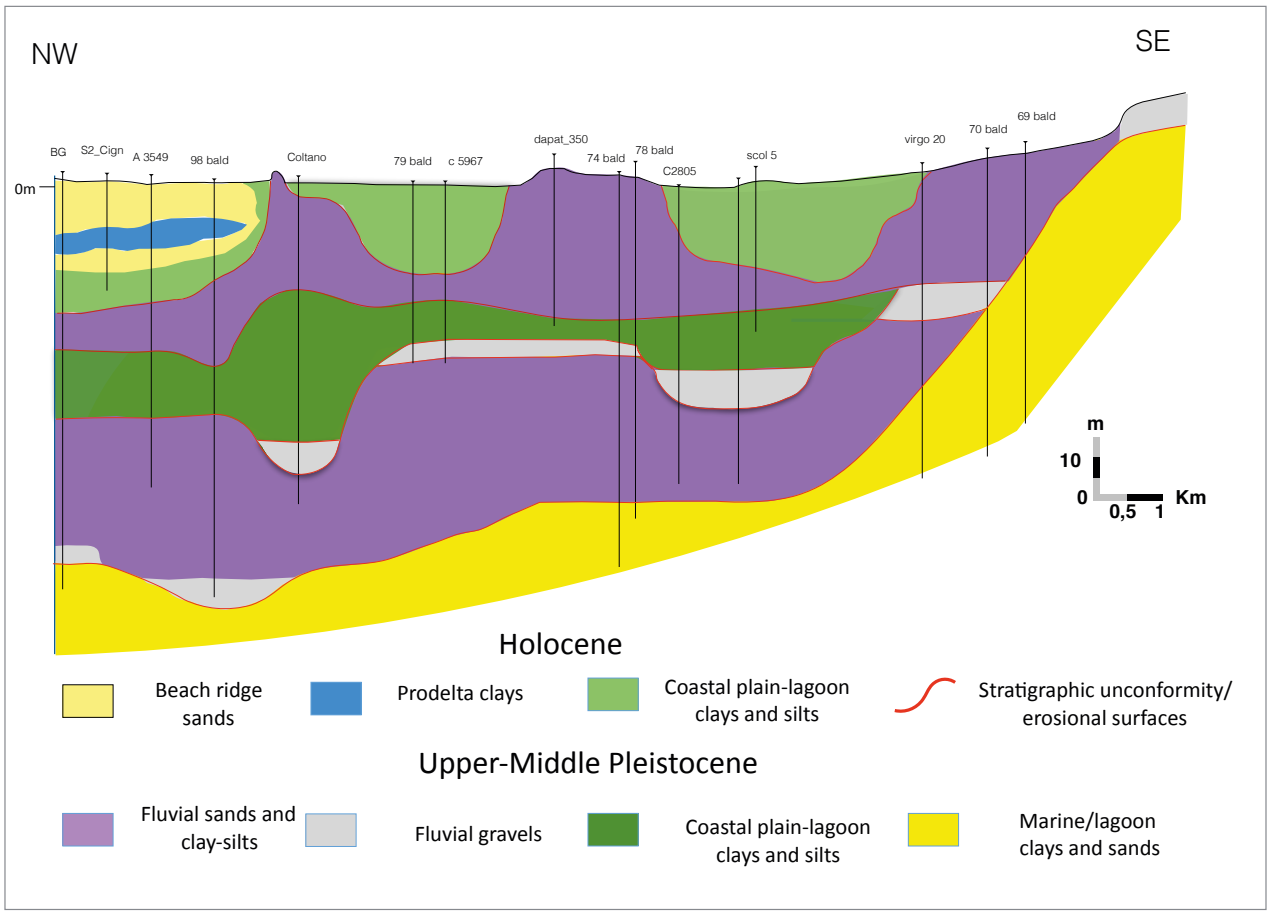

Figure 5 - Stratigraphic section showing the facies architecture of the Holocene-Middle Pleistocene depositional succession, buried beneath the southern portion of the Arno coastal plain. Interpreted stratigraphic relationships between ICS and the formations outcropping along the southern margin of Leghorns Hills are also proposed. Section trace and sedimentary cores location are reported in Figure 2 (red dots).

tures (Mazzini *et al.,* 1999; Amorosi *et al.,* 2008a,b, 2009; Carboni *etal*., 2010; Milli*et al.,*2013; Breda *et al.,* in press). According to the available literature (Ludwigh *et al*., 1996; Waelbroech *et al.,* 2002; Siddal *et al*., 2003; Ferranti *et al.,* 2006) during the MIS3, the age attributed by several authors to the formation of ICS reliefs (Federici & Mazzanti, 1995; Mazzanti, 2000), the sea level was ca. 50-70 m lower than the present-day.
Therefore, the MIS 3 coastline and, consequently, the MIS 3 base level should be shifted tens of km seaward from the modern position even taking into account the relatively low gradient of the Pisa-Leghorn sea platform.
These independent and more generic considerations confirm how much is weak the interpretation of the ICS reliefs as aeolian depositional bodies. Indeed, fossil dunes several meters higher than the present-day aggradational floodplain and detached tens of km from their coeval shoreline would represent a morpho-stratigraphic paradox.
However, the "ICS paradox" is not even resolved by the new facies interpretation of Coltano and Castagnolo sandy deposits as the result of fluvial depositional processes (Carosi *et al.,* in press), because it implies a rate of aggradation so high to still exceed (up to 15 m) the present-day topography. Specifically, MIS 3 fluvial bodies that accommodate to a -50/-70 m base level (Waelbroech *et al.,* 2002) cannot emerge above the modern alluvial-coastal plain formed in equilibrium with the present-day base level.
In this respect, other stratigraphic speculations can be exploited. Following the aforesaid discussion, all chronological attributions related to glacial phases occurring between 40 kyr and the Middle Pleistocene (i.e., MIS 4, MIS 6) should be excluded because their sea-level values are always significantly lower than the present day.
On the other hand, the Mediterranean mean sea-level value attributed to the Last Interglacial -MIS 5e (ca. 6±3 m above s.l.; Lambeck *et al.,* 2004b) could fit with

the altimetric quote of the ICS reliefs. Although a Last Interglacial age for amalgamated fluvial deposits so close to the present shoreline (less than 8 km; Figures 1, 4) is unlikely, we cannot totally rejected this interpretation to date. Indeed, along the N Tuscan coastline MIS 5e deposits show a complex distribution due to different tectonic conditions. A marine terrace containing the MIS 5 Senegalese fauna outcrops few km south respects to Coltano and Castagnolo sites (Leghorn terrace in Figure 1; Ciampalini *et al*., 2006), while marine deposits radiometric dated to the MIS 5 and MIS 7 occur at ca. 65-75 m of depth few km north of the Arno River, in the Serchio coastal plain (Enea Core in Figure 1;Carboni*et al.,* 2010).
In this regard, a new light could be shed on the issue of ICS formation if we reconsider the structural-tectonic context of the southern part of the Arno plain and, specifically, if the two reliefs are considered not detached from the Leghorn hills structural unit, where VF deposits extensively outcrop along the margins at quotes ranging between 5-30 meters (Figure 2). Moving northward from the Leghorn hills, which are subject to a weak uplift since the end of MIS 5e (MIS 5e beach deposits outcrop at 15m; Ciampalini *et al.,* 2006), to the Coltano and Castagnolo reliefs the present-day morphology could be the result of a series of erosional events, mainly related to the last glacial sea-level lowering (MIS 5d-MIS 2; Waelbroech *et al.,* 2002) and to the following transgressive postglacial (MIS 1) valley fill processes.

This interpretation determines strong implications on the tectonic arrangement of the southernmost portion of the VB and on the role of the transpressive Sillaro fault running along the Pisa and Leghorn foothills. Indeed, the transition zone connecting the uplifting Leghorn and Pisa hills and the subsiding Arno coastal plain (VB southernmost sector)seems to not coincide with the morphological hills escarpment, as the ICS morpho-stratigraphic features at Coltano and Castagnolo sites imply that this part of the coastal plain likely belongs to the Leghorn hills structural unit.
The consequent question should be where is the exact location of the area connecting the uplifting or not subsiding zone with the true subsiding one. If our argumentations are correct, this area must be necessarily located north of the northernmost VF outcrops (the Castagnolo site; Figures 1 and 2).
On the basis of these observations, the transition zone may be reasonably shifted northward in correspondence of the present-day Arno river course. However, it is clear that our stratigraphic reconstructions will need to be crosschecked with new absolute dating on ICS deposits (e.g., OSL-Optically Stimulated Luminescence dating on sands) and high-resolution tectonic data, in order to assess the reliability of our hypothesis.

Conclusions

The revision of stratigraphic and depositional features of the ICS, in the context of the late Quaternary subsurface and outcrop stratigraphy, shed new light on the tectonic interpretation of the southern margin of the Viareggio Basin. The following key-points summarize our conclusions:

1) The comparison among Late Pleistocene-Holocene sea-level curves, the fluvial nature of ICS and the ICS estimated age is not compatible with the interpretation of a true subsiding context (southern portion of Viareggio Basin);
2) ICS outcrops at the same quote (about 5-15 m) of the VF that constitutes the Leghorn foothills and the Viareggio Basin southern margin;
3) The ICS is geologically connected to the margin of the Leghorns Hills (VF) and likely formed during the glacial periods occurring between MIS 6-MIS 3;
4) The present-day morphology is the inheritance of Late Quaternary strong erosive processes linked to sea-level fall cycles, as also documented in the subsurface by repetitive incised valley fill sequences;
5) Further subsurface and outcropping stratigraphic data along with new tectonic-seismotectonic data and absolute ages on ICS deposits are needed to resolve the "ICS paradox" and define a more accurate geo-tectonic model for the Arno plain southern area.

Acknowledgments

The authors are indebted with Giancarlo Molli and Gianni Zanchetta for their helpful suggestions.

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(*ms. pres. il 00 mese 0000; ult. bozze il 00 mese 0000*)