Marine and Petroleum Geology 97 (2018) 422–436

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

Research paper

# Late quaternary stratigraphic setting of the Sibari Plain (southern Italy): Hydrogeological implications

Giuseppe Cianflone[a,*], Giuseppe Cavuoto[b], Michele Punzo[b], Rocco Dominici[a], Maurizio Sonnino[a], Vincenzo Di Fiore[b], Nicola Pelosi[b], Daniela Tarallo[b], Fabrizio Lirer[b], Ennio Marsella[b], Salvatore Critelli[a], Rosanna De Rosa[a]

[a] *Department of Biology, Ecology and Earth Science (DiBEST), University of Calabria, Cube 15B, 87036, Arcavacata di Rende (Cs), Italy*
[b] *Institute for Coastal Marine Environment (IAMC), Italian National Research Council (CNR), Calata Porta di Massa-Naples Harbour, 80133, Naples, Italy*

ARTICLE INFO

*Keywords:*
Ibari plain
Stratigraphy
Electrical resistivity tomography
Crati delta

ABSTRACT

The aim of this study is the reconstruction of the late Pleistocene-Holocene stratigraphy of the Sibari Plain (southern Italy) aimed to obtain information about hydrogeological framework. A multidisciplinary approach combining boreholes data and Electrical Resistivity Tomography, allowed us to recognize three electro-stratigraphic units, which consist of upper Pleistocene fluvial and floodplain-littoral facies (deep aquifer), passing upward to Holocene marine-transitional deposits (aquiclude) evolving toward continental sediments (shallow aquifer) related to the Crati delta progradation. The late Quaternary-Holocene plain evolution took place in a tectonic-controlled setting and was driven by the interaction between sea-level variations and local factors. The presence of a NE-SW fault zone controlled the facies and thickness of Holocene sediments along strike of the fault. This active fault zone contributed to determine the plain stratigraphic architecture, the arrangement of the depositional environments, and consequently the stratigraphic pattern.

## 1. Introduction

Coastal and deltaic plains represent vulnerable environments affected by natural and/or anthropogenic processes, e.g. land subsidence, sea level rise, saltwater intrusion, marine intrusion, often exacerbated by the low-lying morphology and seismicity. The knowledge of the late Quaternary stratigraphic architecture plays a key role for understanding different processes, such as hydrogeology.

Worldwide, the late Pleistocene-Holocene delta plains are characterized by a comparable stratigraphic architecture (Stanley and Warne, 1994) composed generally by a basal lowstand alluvial wedge passing upward to transgressive and highstand sediments marked by transitional facies changes from marine/estuarine to coastal plain and prodelta deposits testified by retrogradational, aggradational and progradational trends. Comprehensive stratigraphic dataset are available for the major Italian rivers (Fig. 1) as Po (Amorosi and Milli, 2001; Stefani and Vincenzi, 2005), Arno (Aguzzi et al., 2007; Rossi et al., 2011), Ombrone (Bellotti et al., 2004), Tevere (Bellotti et al., 1995; Amorosi and Milli, 2001), Volturno (Amorosi et al., 2012) and Sele (Amato et al., 2013; Barra et al., 1999). Unlike other parts of Italy, no detailed stratigraphic studies of the post- Last Glacial Maximum (LGM) sequence are available in the Calabria region (southern Italy). During the Holocene, several Calabrian coastlines have been submerged, as testified for e.g. by the presence of old millstone quarries below the present sea level (Lo Presti et al., 2014). The Sibari Plain (SP) is located in the northeastern sector of the region and has a surface of about 470 $km^2$. It is important for the agricultural production (citrus, peaches, rice, vegetable) and the cultural appeal due to the ancient town of Sybaris.

The plain is affected by a general subsidence; the average downlift rate for the last 40 ka is 0.7–0.8 mm/yr with a peak during early to mid-Holocene, mainly related to the compaction of the fine-grained compressible sediment deposited in the early Holocene (Ferranti et al., 2011; Zecchin et al., 2011), and present rates up to 20 mm/yr due to a concurrence of natural and anthropogenic processes like tectonics, groundwater withdrawal, compaction of younger deposits amplified by urban-induced loading (Cianflone et al., 2015a; b).

The SP is characterized by a shallow (−20/-30 m asl) and deep (−50/-60 m asl) aquifers separated by a aquitard consisting of clayey and silty-clayey layer (Polemio and Luise, 2007). In the Crati Delta area, groundwater shows high salinity ascribed to seawater intrusion due to water pumping, groundwater long age and interactions with salt

* Corresponding author.
*E-mail address:* giuseppe.cianflone@unical.it (G. Cianflone).

https://doi.org/10.1016/j.marpetgeo.2018.07.027
Received 4 June 2018; Received in revised form 23 July 2018; Accepted 25 July 2018
Available online 26 July 2018

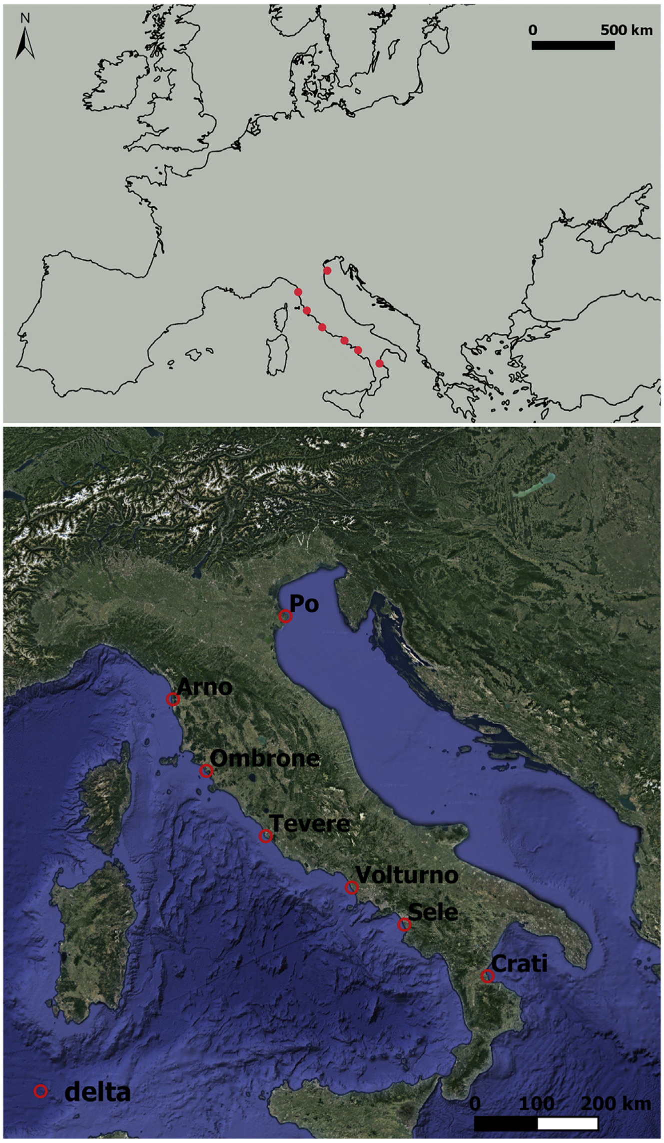


**Fig. 1.** Location of the Po, Arno, Ombrone, Tevere, Voltuno and Sele Deltas and of the investigated Crati one.

rocks (Guerricchio and Ronconi, 1997; Vespasiano et al., 2015).

Most of the aquifer systems in late Pleistocene-Holocene coastal plains (like that of the SP) are characterized by complex hydro-stratigraphy resulting from the high spatial variability of the depositional units. Therefore, both sedimentological and stratigraphic concepts are basic to investigate the arrangement of the hydraulic parameters (Fraser and Davis, 1998). For example, paleo channels filled by permeable sediments represents preferential pathways for groundwater flow (Owen and Dahlin, 2010); in coastal area they can facilitate the seawater intrusion acting as hydraulic connection between freshwater aquifers and the sea (Mulligan et al., 2007). For this reason, the modeling of the three-dimensional, complex, heterogeneous and anisotropic sedimentary aquifers has to based on the stratigraphic pattern reconstruction and sedimentological studies useful to define spatial variations of facies.

Our goal is the reconstruction of the stratigraphic architecture of the SP and its relationship with late Quaternary plain evolution, which represents a basic tool to better understand the hydrogeological pattern and groundwater salinization sources and mechanisms.

We propose a multi-disciplinary approach comparing boreholes analysis and Electrical Resistivity Tomography (ERT) to define the subsurface structure of the Sibari Plain and to constrain interpretations of available data. The good efficiency of ERT to model the subsurface resistivity changes in depth used to obtain stratigraphic information about the shallow subsurface has been shown by Baines et al. (2002) and later used by different authors (Beresnev et al., 2002; Froese et al., 2005; Kilner et al., 2005; Bersezio et al., 2007; Pellicer and Gibson, 2011; Chambers et al., 2013). In the last decades, the ERT, often associated with other shallow geophysical techniques, has commonly been used to investigate the subsurface features and mapping active faults (Suzuki et al., 2000; Caputo et al., 2003, 2007; Nguyen et al., 2005, 2007; Improta et al., 2010; Giocoli et al., 2011) and also for investigation of geometry of the aquifer system (Amaya et al., 2016).

## 2. Geological setting

The SP is located in the northeastern Calabria Terranes (Fig. 2). The latter represents a fault-bounded continental fragment within the western Mediterranean orogen. Its tectonic evolution is related to subduction and rollback of the Ionian oceanic lithosphere and the slow convergence between the Eurasian and African–Adriatic continental plates (Malinverno and Ryan, 1986; Critelli and Le Pera, 1995, 1998; Faccenna et al., 1997; Gueguen et al., 1998; Wortel and Spakman, 2000; Jolivet and Faccenna, 2000; Rosenbaum and Lister, 2004; Critelli et al., 2011, 2013; 2017; Critelli, 2018).

Cello et al. (1981) analyzed a deep-crust seismic profile passing in the middle of the plain, and recognized that the Calabrian terranes form only the thin superficial portions of the chain, which is prevalently composed by Apenninic terrenes. The latter, cropping out along the northwestern side of the SP, include Mesozoic-Tertiary carbonatic succession and deep-marine siliciclastic turbidite strata overlapped by Plio–Pleistocene clastics (Selli, 1976; ISPRA, 2009). Instead, the Calabrian terranes, occur along the southern margin of the SP, and consist of igneous, metamorphic and Mesozoic sedimentary rocks (Spadea et al., 1976).

The SP stays between Sila Massif to the South and Pollino Massif to the North. The SP represents a tectonic subsiding area bounded by Pliocene-to-Holocene high-angle faults. The activity of these faults during the Quaternary time is still debated (Lanzafame and Tortorici, 1981; Knott and Turco, 1991; Cucci, 2004; Molin et al., 2004; Ferranti et al., 2009).

Ferranti et al. (2009) suggests the existence of WNW–ESE shallow-crustal folds, which involve late-Middle Pleistocene sediments, grown within a recent and still active transpressional field. Recently, Ferranti et al. (2014) detailed the presence of an active oblique-contractional belt in the Corigliano Gulf (Fig. 3), which testifies the major active horizontal compressive stress present in this portions of the Calabrian sector inferred by the focal mechanism of recent earthquakes in the area (Pondrelli et al., 2006).

Also sea-level variations are well recorded in the SP. In fact, marine terraces widely occur along the Sibari Plain outer limit: seven-order of terraces are identified by Cucci and Cinti (1998) which estimate an average uplift rate, active during Holocene, of 0.67 mm/yr; Cucci (2004) maps 5 orders of marine terraces and calculates an average uplift rate of ~1 mm/yr. The marine terraces are 11 in Santoro et al. (2009) which evaluate uplift rates, since middle Pleistocene, variable from > 3.5 mm/yr to 0.5 mm/yr.

In the area of the Crati Delta (therein after CRD), Lanzafame and Tortorici (1981) suppose the existence of NE-SW normal faults, which are considered as active and capable faults (Comerci et al., 2013) (Fig. 3). Recently coseismic evidences of these structural lineaments are observed in the *Sybaris* archeological sites; they consist of fractures with relative displacements, paleoliquefaction phenomena with surface evidences, rotation of walls and complete walls tearing down (Cinti et al., 2015).

Holocenic morphological evolution of the plain is strictly related to the CRD progradation (started about 6 kyr B.P.). Toward NW the main