DOTTORATO DI RICERCA IN SCIENZE DELLA TERRA

Università degli Studi di Firenze

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"Facies analysis, depositional architecture and paleogeography of the fluvio-lacustrine Upper Valdarno Basin (Plio-Pleistocene, Northern Apennines, Italy)"

settore scientifico disciplinare: GEO-02

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XXIII CICLO

Firenze, 31 Dicembre 2010

AKNOWLEDGMENTS

First of all I want to thank my supervisors Prof. Ernesto Abbate at the University of Florence and Dr. Massimiliano Ghinassi at the University of Padua for their support and for providing me freedom in research during these three years. I wish to thank Prof. Ernesto Abbate for the autonomy he gave me, for the exiting experiences he involved me in and for his critical review of this thesis. Especially I'm very grateful to Dr. Massimiliano Ghinassi for his guidance during fieldwork, his restless help and patience and for permitting me to learn new things every day: this work wouldn't have been the same without his enthusiasm. I can't forget to mention a number of my colleagues and friends of the Department of Earth Sciences, whose helpful discussions and scientific assistance were fundamental for my education: Dr. Mauro Papini, Prof. Mario Sagri, Dr. Adele Bertini and Prof. Marco Benvenuti. A special thank to Dr. Marianna Ricci and Dr. Elena Menichetti (which shared this 3-year experience with me) for their invaluable support in laboratory. Last but not least I wish to thank Prof. Wojtek Nemec (University of Bergen) for his unlimited knowledge, for his exquisite way to share it and for his inestimable friendship.

Naturally I wish to thank my father, Andrea, for motivating me to follow my aspirations and my girlfriend, Agnese, for her love, trust and support: “you made me a better man”.

During these three years I had the possibility to work with several excellent researchers, to know fantastic people from many parts of the world and to travel a lot. I felt welcome everywhere and this memory will be with me forever.

My wish is this would be only the beginning.

Francesco Fidolini — Firenze, November 2010

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PREFACE

The Upper Valdarno Basin stands out from the Neogene-Quaternary basins of the Northern Apennines because of its exceptional fossil mammal record and good quality of natural and artificial outcrops. The Valdarno Basin attracted a large number of scientists since the past centuries. The well-preserved fossil mammals were studied by George Cuvier, and the suggestive exposures of alluvial deposits located along the NE margin of the basin gave to Nicholas Steno a base in formulating the principles of the modern stratigraphy. During the first half of the past century, the basin was largely explored in order to plan the exploitation of subsurface resources, which significantly contributed to the socio-economical development of the area. The basin has been the focus of a huge number of palaeontological, sedimentological and stratigraphic studies, culminated in 2004 with the CARG Regione project, which allowed a lithostratigraphic review of the basin stratigraphy and provided solid bases for further detailed geological investigations.

The present PhD dissertation stems from a research project carried out at the Department of Earth Sciences of the University of Florence (January 2008 – January 2011) and focused on the whole alluvial-lacustrine, basin-fill succession. The Valdarno basin was selected among the numerous Neogene-Quaternary basins of the Northern Apennines because of its good natural and artificial outcrops, plentiful of literature and the detailed chronostratigrafic frame. The principal aim of the present study has been to improve our understanding on basin stratigraphy through a review of the basin-fill succession following the modern facies analysis and physical stratigraphy principles.

AIM OF THE STUDY AND METHODS

Facies analysis of sedimentary successions is a powerful tool for paleoenvironmental and paleogeographic reconstruction. The present report aims to re-consider the historical lithostratigraphy-based models for the basin with the support of the new data collected, with the purpose to provide a new stratigraphic model, funded on the modern concepts of physical stratigraphy. To do this a detailed sedimentological investigation was carried out, using the facies analysis principles.

According to the recent ratification of the Quaternary System/Period with a base at 2.58 Ma, proposed by of the International Commission on Stratigraphy and formally accepted by the IUGS Executive Committee, this report adopts the new chronological timescale for the Quaternary (Gibbard et al, 2010).

SYNTHESIS

This report is organized in 6 chapters; each of them focuses on a main theme, because it has been thought to be the nucleus for a forthcoming publication, with the exception of the introductive and final ones.

Chapter 1 is an introductive section summarizing the present knowledge on Northern Apennines basins. It describes the main models concerning development of these basins, from the “traditional graben model” (linking the basins to high-angle normal faults) to the more recent, scar-basin model (considering the basins as a surface expression of a crustal megaboudinage), passing through the thrust-top basin model (interpreting the basins as bowl-shaped depressions developed in a compressional tectonic regime).

Chapter 2 summarizes the main part of this study and concerns the basin stratigraphy and depositional environment. A brief review of the main steps in understanding the basin stratigraphy, from the milestone paper of Sestini (1936) to the last edition of the CARG project (Foglio 276 Figline), are provided. In this chapter, the spatial and temporal distribution of the main sedimentary units, which was inferred from a detailed field mapping at 1:10.000 scale, is outlined using the principles of physical stratigraphy. Fining- and coarsening-upward depositional trends are discussed in terms of accommodation space formation or subtraction. Furthermore a detailed description of the sedimentary features characterizing the sedimentary units of the basin-fill succession is provided and the units are interpreted and referred to a specific depositional environment using the facies analysis principles.

Chapter 3 focuses on the lacustrine deltaic deposits formed in a shallow and protected lake in the SE part of the basin during the Late Pliocene. In this peculiar framework, where absence of wave reworking allows preservation of flood-generated deltaic deposits, different types of mouth-bars have been distinguished and compared with classical and modern examples. Moreover, the role of climate and tectonics in controlling development of the internal architecture of the deltaic succession is discussed.

Chapter 4 describes alluvial fan and fluvial deposits developed along the NE margin and in the central areas during Early and Middle Pleistocene. In this chapter, the role of local tectonics in the development of alluvial-fan depositional trends (i.e. coarsening- and fining-upward successions) will be analysed. Moreover, alternation between aggradational and erosional phases in alluvial fan systems will be discussed in terms of the interaction with fluvial axial system.

Chapter 5 summarizes the main results of palinological investigations carried out in a key interval of the basin-fill succession. The methodologies used for samples preparation are illustrated and the main palynological assemblages are briefly described.

Chapter 6 consists in the synthesis of the main results. Here the major steps of basin development are highlighted considering the influence of tectonics and climate on depositional and erosional phases.

Chapter 1

INTRODUCTION

1.1 GENESIS AND EVOLUTION OF THE NORTHERN APENNINES

The Northern Apennines is a NW-SE oriented thrust and fold orogenic belt, formed starting from the Late Cretaceous due to the interaction between the Adria microplate and the European plate (Vai and Martini, 2001 and references therein). The orogenic pile involves sedimentary successions originally deposited on the Adria continental margin, as well as oceanic rocks and sedimentary successions accumulated in the Mesozoic Ligurian-Piedmont Ocean. The Ligurian-Piedmont Ocean developed during the Jurassic, when the opening of the Central Atlantic Ocean led to the left lateral transcurrent movement of the African plate with respect to the European one.

At that time four major paleogeographic domains could be distinguished within the Neo-Tethys:

- Ligurian Domain (oceanic) formed by Jurassic ophiolites and their Cretaceous-Eocene pelitic-arenaceous sedimentary cover.
- Sub-Ligurian Domain (transitional) formed by Cretaceous-Oligocene calcareous-argillitic and arenaceous sediments.
- Tuscan Domain (continental) formed by Late Triassic evaporites, Early Jurassic-Early Cretaceous calcareous sediments, Early Cretaceous-Oligocene argillitic deposits and Late Oligocene arenaceous deposits.
- Umbro-Marchigian Domain (continental) formed by Late Triassic evaporites, Early Jurassic-Eocene calcareous sediments, Eocene-Miocene argillitic deposits and Late Miocene Arenaceous deposits.

During the Late Cretaceous, contemporaneously with the Northern Atlantic spreading, the African plate changed its movement and started to migrate towards Europe. This resulted in the closure of the Ligurian-Piedmont Ocean with the development of a west-verging subduction (Treves, 1994).

During the Late Eocene the continental margins of the two plates started to collide (Boccaletti et al, 1980), causing the vertical stacking of tectonic units belonging to different paleogeographic domains. At the same time turbiditic sedimentation started in the foredeep area, due to erosion of the uplifting margins (Ricci Lucchi, 1986; Boccaletti et al., 1990).

After the Miocene esialic collisional phase the Northern Apennines have been affected by the development of many NW-SE oriented tectonic depressions, which have been filled by Miocene-to-Quaternary deposits. Those basins located in the most external part of the chain show clear compressional-tectonics related geometries (piggy-back basins; Ori and Friend, 1984). On the other hand, the genesis of the basins lying on the internal part of the chain is still matter of discussion. Classical models consider the post-late Miocene evolution of the hinterland sector of the Northern Apennines as the result of an extensional tectonic regime (Merla, 1952; Sestini, 1970; Patacca and Scandone, 1987; Boccaletti et al., 1971; Boccaletti and Guazzone, 1974; Dewey et al., 1973; Barberi et al., 1973; Locardi, 1982; Wezel, 1982; Lavecchia, 1988), accompanied by crustal thinning (Decandia et al., 1998 and references therein), a regional positive Bouget anomaly (Locardi & Nicolich, 1988) and diffuse magmatism (Serri et al., 1993 and references therein). In this hypothesis, related to the opening of the northern Tyrrhenian Sea, the basins, controlled by normal faults at their margins, become younger from west to east, following the migrating extensional wave (Martini and Sagri, 1993; Martini et al., 2001 and references therein).

1.2 THE NEOGENE-QUATERNARY BASINS OF THE NORTHERN APENNINES

The Neogene-Quaternary basins of the Northern Apennines (Fig. 1.1) developed during the latest stages of interaction between the Adria and Corso-Sardinian microplates, within the collisional belt between Africa and Eurasia.

In a well established and accepted model, sedimentary basins have been related to an extensional regime affecting the orogen during the latest stage of its formation, and structurally referred to *graben* and *half-graben* (Martini and Sagri 1993; Pascucci et al. 1999). This extensional stage resulted in the collapse of the western side of the neo-formed chain and the basins widening was controlled by progressive activation of backstepping normal faults (Carmignani and Kligfield, 1990; Carmignani et al.,1994; 1995; Jolivet et al., 1998; Carmignani et al., 2001). According to this model, the

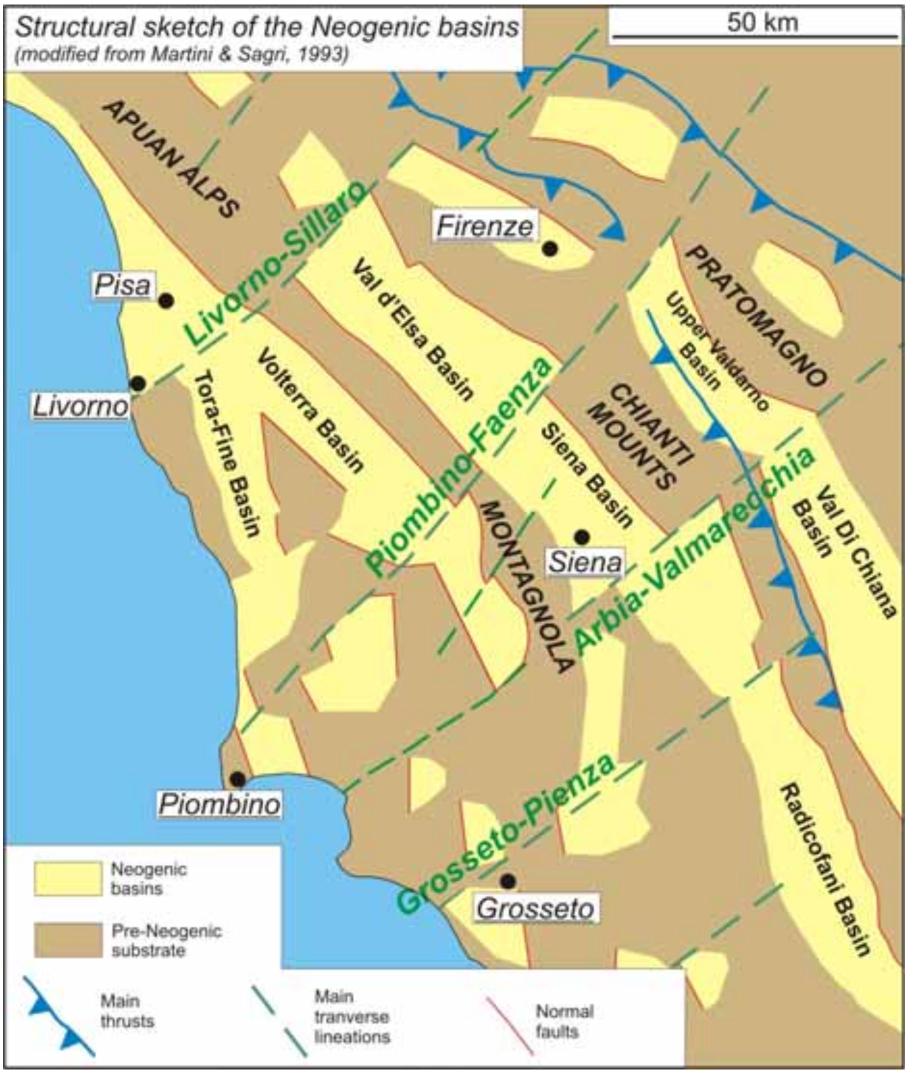

Fig. 1.1 – Spatial distribution of the main Neogenic-Quaternary basins within the inner sector of the Northern Apennines.

collapse of the tectonic pile occurred between the Oligocene and the Tortonian as a consequence the isostatic re-equilibration of the orogen, causing the shift from a compressional to an extensional tectonic regime (Fig. 1.2). In the areas characterized by minor crustal thickness this extensional regime induced rifting (i.e. Sardinian rift) or drifting processes (i.e. Balearic Ocean). In those areas with high crustal thickness, such as the Tuscan area, the isostatic re-equilibration resulted in the exhumation of the deeper parts of the tectonic pile (core complex model, Carmignani and Kligfield, 1990), causing crustal delamination within the sedimentary cover (“serie ridotta”, Trevisan, 1955; Giannini et al., 1971; Bertini et al., 1991; Decandia et al., 1993) and East-verging emplacement of tectonic units in the eastern part of the chain.

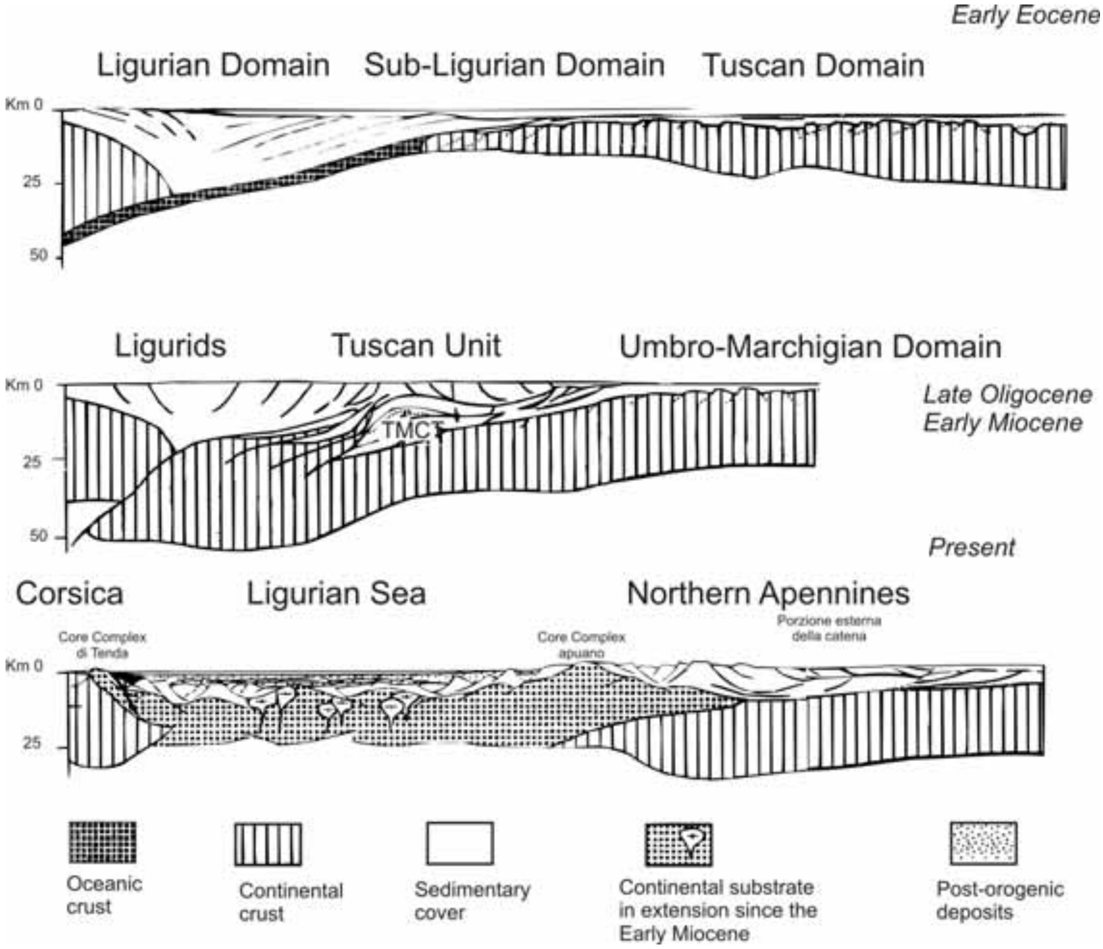

Fig. 1.2 – Northern Apennines evolution from Eocene and basins development accordig to the extensional model (modified from Carmignani et al., 2001).

After this phase, during Tortonian to Quaternary time, a new extensional stage led to the development of NNW-SSE and N-S oriented high angle normal faults. During this phase, related by some Authors to the opening of the Southern Tyrrenian basin, the inner part of the chain was affected by the development of several *graben*- and *half graben*-like tectonic depressions (Carmignani al.,1994; 1995; 2001; Elter and Sandrelli, 1994) bounded by syn-sedimentary high-angle normal faults (Martini and Sagri, 1993; 2001; Bossio et al., 1993; Bossio et al., 1998).

On the other hand, structural evidences of compressional tectonic deformation in the basin fill deposits led some Authors to introduce an extensional scenario interrupted by pulses of compression (Bernini et al. 1990), or a scenario of tectonic compression persisting until Pleistocene time (Boccaletti and Sani 1998; Bonini and Sani 2002; Sani et al., 2009). In this framework the Neogene-Quaternary tectonic depressions of the Nothern Apennines are interpreted as *thrust-top basins* (*sensu* Bulter and Grasso, 1993). According to this theory, after the ensialic collisional phase, the northward movement of the African plate induced the creation of a NNW-SSE oriented stress field, responsible for the Tyrrenian *rifting* and causing the east-verging extrusion of the Apenninic chain (Boccaletti and Sani, 1998) (Fig. 1.3). This tectonic regime caused the activation of new thrusts and the reactivation of older structures (out-of-sequence thrusts) during high convergence rate periods, and the development of extensional structures during periods of low convergence rate (Boccaletti and Sani, 1998).

The resistance exerted by the tectono-sedimetary pile (*marginal loading*) in the most external part of the chain (*foreland*) is thought to be a fundamental controlling factor for the development of these extensional phases. During periods characterized by high marginal loading, thrust development and reactivation in the inner parts of the chain is favored; when marginal loading is low, thrust propagate in the external sector, causing extension in the inner part (Bonini and Sani, 2002).

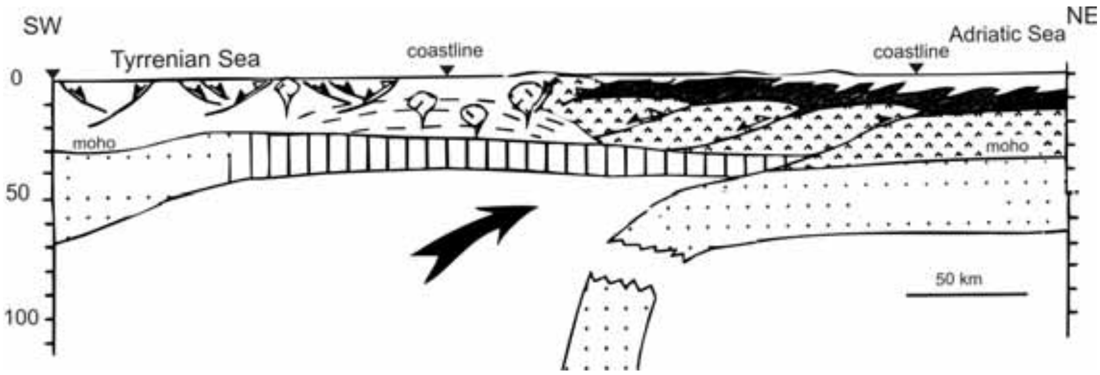

Fig. 1.3 – Northern Apennines evolution and basins development according to the compressional model (modified from Boccaletti and Sani, 1998).

A new model has been recently proposed to explain the genesis of extensional Middle-Late Miocene basins (Brogi 2004 a, b, c; Brogi and Liotta 2005). According to this model, low-angle normal faults, due to post-collisional rapid extensional strain rate, caused a megaboudinage in the upper crust. Progressive unconformities developed close to the margins during the main tectonic phases. High-angle normal faults affected the basins since the Late Miocene/Early Pliocene (Brogi, 2004a).

Chapter 2

STRATIGRAPHY AND FACIES ANALYSIS

2.1 INTRODUCTION

The outstanding fossil mammal record, along with the good quality of natural and artificial outcrops and the peculiar tectono-stratigraphic framework, allows the Upper Valdarno basin to stand out from the numerous Neogene-Quaternary basins of the Northern Apennines (Martini et al. 2001 and references therein). The well-preserved fossil mammals stored in the Geological and Paleontological Museum of Florence and in the Paleontological Museum of Montevarchi were studied by George Cuvier and many other researchers. The spectacular exposures located along the NE margin of the basin, locally known as “balze”, fascinated Leonardo da Vinci and provided to Nicholas Steno a noteworthy base in formulating the basic principles of modern stratigraphy. In recent years, the Valdarno Basin was used as case study to formulate new hypothesis on the latest phase of the Apenninic chain evolution and the formation of the Neogene-Quaternary intermontane depressions. Moreover, the exploitation of the abundant subsurface resources contributed to the socio-economical development of the area, which, at the present, is one of the most populated of the Florence surroundings. The S. Barbara lignite quarry was one of the largest open-air mines in Europe during the 1970s. Several quarries of siliceous sand offered the raw material for a flourishing glass manufacture.

During the past decades, a good knowledge of the basin stratigraphy offered a solid base both for academic researches and economic activities such as mining, building, and offered a significant support for geohazard prediction.

The sedimentary succession of the Upper Valdarno basin is characterized by a wide spectrum of depositional environments, which spans from lacustrine to eolian (Albianelli et al., 1995). Such a wide variety of depositional environments implies a flourishing of different geological and geomorphological sceneries. A significant variability of depositional environments causes accumulation of different sediments, which are distributed in space and time according with dynamics affecting their depositional setting. Such a temporal and spatial distribution, in turn, is strictly related with the development of different geomorphological processes acting on the modern landscape. As a consequence, both in the frame of geological and geomorphological studies, a proper management of the landscape requires a deep knowledge of sedimentary units lateral variability, which derived from changes in depositional dynamics.

Although the Upper Valdarno Basin was the aim of numerous sedimentological and stratigraphic investigations (Abbate, 1983; Sagri and Magi 1992; Albianelli et al., 1995; Napoleone et al; 2003), and a recent detailed geological mapping (CARG and Carta Geologica Regione Toscana) offered the possibility to re-evaluate the spatial distribution of the main sedimentary units, most of these researches dealt with basin scale stratigraphy, and only few studies were focused on a bed-by-bed facies analysis (Billi et al., 1987; 1991; Ghinassi et al., 2004).

This Chapter aims to provide a detailed description of the basin succession using the principles of physic stratigraphy, identifying and tracing the most representative key surfaces (e.g. unconformities) at the basin scale. The main sedimentary units will be analysed in terms of their spatial and temporal distribution. In particular, the fining and coarsening upward trends, defined by the vertical stacking of deposits formed in different depositional settings, will be discussed in terms of accommodation space formation or subtraction (Martinsen et al., 1999). Furthermore the main stratigraphic units forming the basin-fill succession will be described in detail and interpreted according to the modern principles of facies analysis (Nemec, 1996; Posamentier and Walker, 2006), according to their sedimentary features, such as grain size, sedimentary structures, bed attitude and stratal architecture. This work aims to provide a base for forthcoming sedimentological and stratigraphic academic studies, but it also will offer a support for matters of applied geology strictly connected with subsurface prediction and lateral variability of sedimentary bodies (e.g. exploration of aquifers).

2.2 GEOLOGICAL SETTING AND HISTORICAL BACKGROUND

The Upper Valdarno Basin is located 35 km SE of Florence, between the Chianti Mountains and the Pratomagno Ridge (**Fig. 2.1**). It is a 15 km wide asymmetric tectonic depression elongated 35 km in a NW-SE direction and drained from SE to NW by the Arno River. This depression has been filled by up to 550 m of alluvial and lacustrine deposits during the Plio-Pleistocene time span.

Although during the past centuries the basin–fill succession was described and discussed by several Authors (Ristori, 1886; Lotti, 1910; Sestini, 1929; De Castro and Pillotti, 1933), with a particular attention to the basal lignitiferous deposits, the first significant contributions to define the basin stratigraphy were provided by Sestini (1934; 1936). Sestini, who ascribed a tectonic origin to the basin, recognised and older lignitiferous, muddy succession (*formazione argilloso-lignitifera* in Sestini, 1934) unconformably overlain by a sandy-gravelly succession (*complesso villafranchiano* in Sestini, 1934).

The basing stratigraphy was improved in 1967 by Merla and Abbate, with the second edition of the Carta Geologica d'Italia (Foglio 114, Arezzo). The sedimentary succession was divided into three main units, splitting the *complesso villafranchiano* defined by Sestini into two portions, separated by an unconformity surface. These Authors provided the first structural interpretation of the basin, which was classified as an *half-graben*, with the main normal fault located along the NE margin.

On the basis of Merla and Abbate's work, Azzaroli and Lazzeri (1977) produced the first detailed geological map (1:50.000 scale) of the basin highlighting the spatial distribution of the main sedimentary bodies and providing the bases for studies of the following decades.

A turning point in understanding the basin stratigraphy came with Abbate (1983) and Sagri and Magi (1992) (**Fig. 2.2**) who defined the main features of the three sedimentary successions (Castelnuovo, Montevarchi and Monticello-Ciuffenna successions). The Castelnuovo succession was described as made of basal fluvio-deltaic gravel and sand, grading upward into lacustrine clay with intercalations of lignite levels,

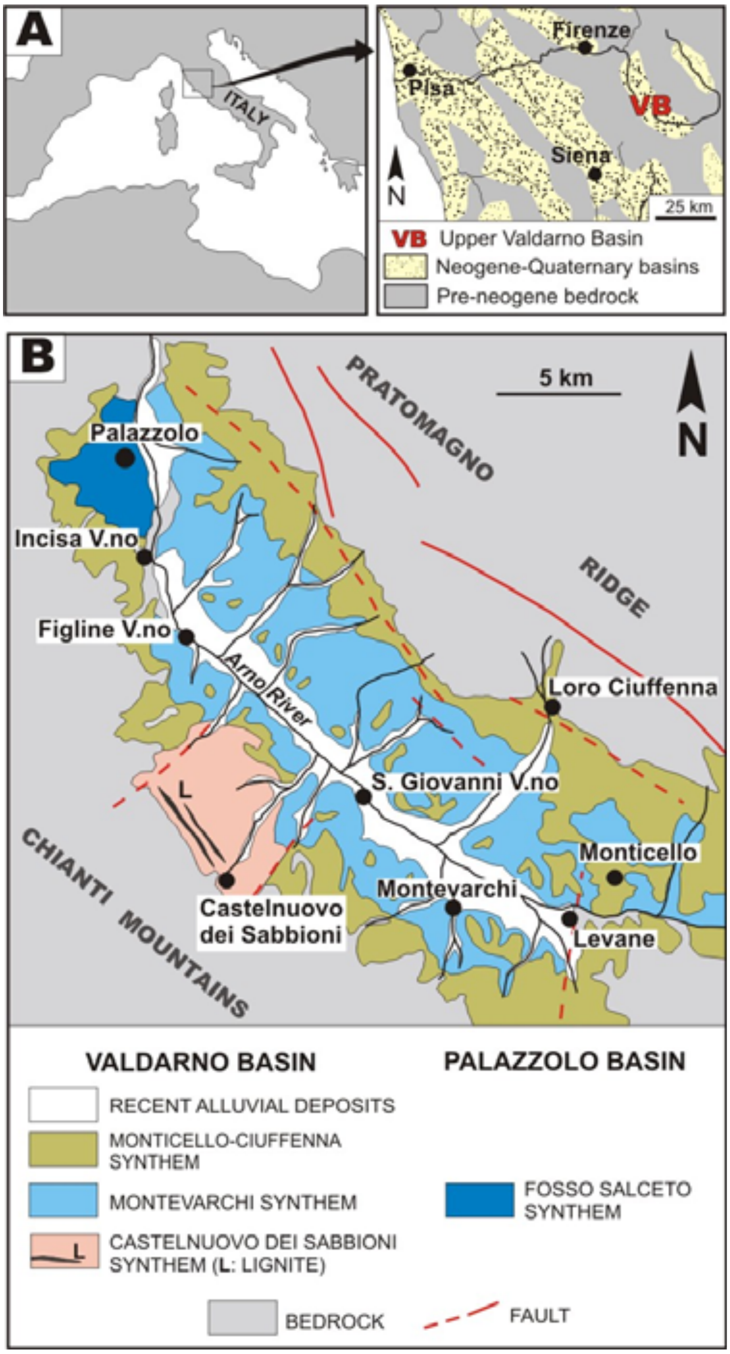

Fig. 2.1 - (A) Geographic location of the Upper Valdarno Basin. (B) Geological sketch map of the basin.

in turn overlain by fluvio-deltaic sand. The Montevarchi succession was divided in an axial muddy palustro-lacustrine portion, bearing an organic-rich, muddy horizon in its central part, interfingering with gravelly fan-delta deposits accumulated along the basin margin. In the Monticello-Ciuffenna succession they distinguished fluvial gravel and sand in the central portion of the basin, and gravel of alluvial fans along the margins.

During the nineties the extensional structural model was criticized by Boccaletti et al. (1995; 1999), which interpreted the Upper Valdarno as a piggyback or thrust-top basin associated with an east verging compressional tectonics.

Albianelli et al., (1995) identified ephemeral stream deposits erosionally overlaying the fluvio-deltaic sand at the top of the Castelnuovo succession (**Fig. 2.2**). In particular, they provided the first detailed chronological framework of the basin-fill succession. The magnetic event Kaena (3.2 Ma) was identified at the top of the basal lignite levels, and the Gauss-Matuyama transition (2.6 Ma) in the middle part of the newly defined ephemeral stream deposits. Those Authors also characterized the palinological content of the different units, highlighting the presence of subtropical taxa in the Castelnuovo succession, steppic floras in the ephemeral stream deposits and alternation between cold and warm conditions in the Montevarchi succession.

Ghinassi and Magi (2004) focused their work on the transition between the first and the second depositional phase linking the ephemeral stream deposits with the Montevarchi Synthem and locating the main unconformity at the top of deltaic sand capping the Castelnuovo Synthem (**Fig. 2.2**). These Authors divided the Montevarchi Synthem in two portions through the identification of a minor unconformity. The lower part included the ephemeral-stream sand grading upwards into mollusc-rich alluvial sand. The upper part comprised the “classical” muddy, palustrine and fan-delta deposits of the Montevarchi succession defined by Sagri and Magi (1992).

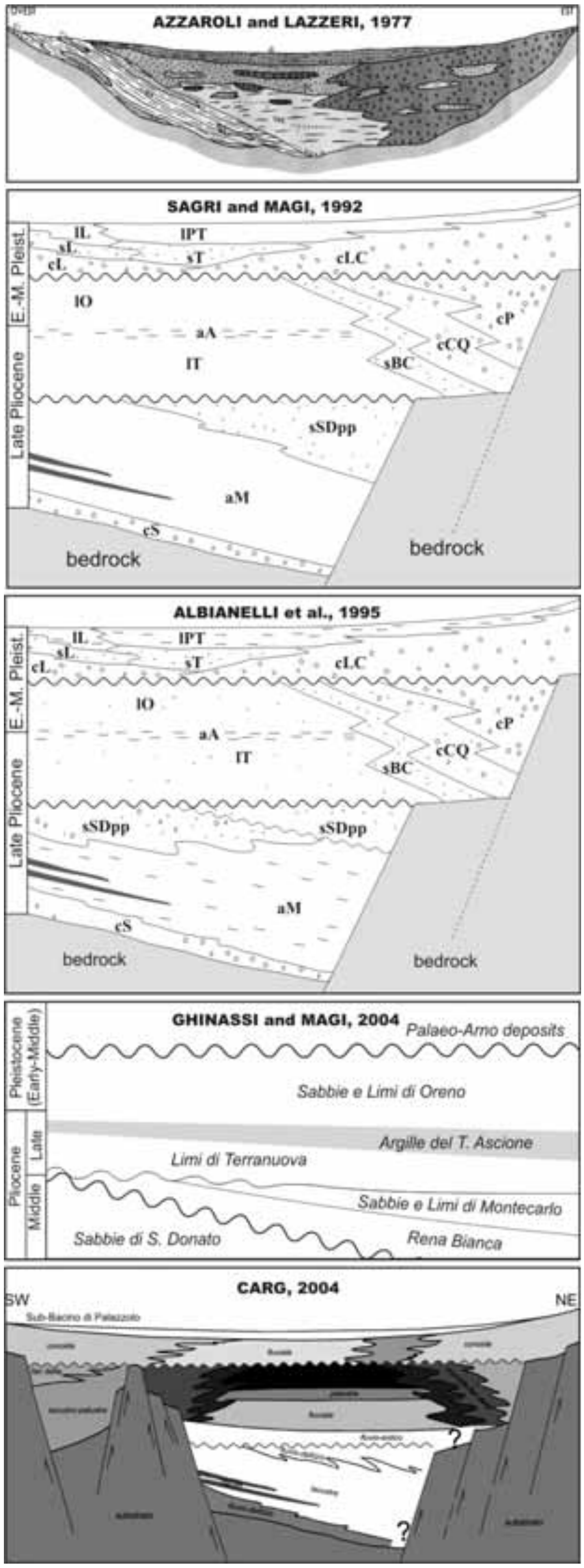

Fig. 2.2 - Stratigraphic schemes of the Upper Valdarno Basin proposed since 1977.

Other papers, published during the past decade, improved the knowledge on the basin. Napoleone et al. (2003) identified the Brunhes magnetochron in the middle part of the Monticello-Ciuffenna Synthem. Mazza et al. (2004) and Bertini et al. (2010) described the sedimentary and pedological features of a bone-bearing interval in the Montevarchi Synthem. Mazza et al. (2006) studied the mammal remains and an exceptionally preserved tar-hafted stone tool in the Monticello-Ciuffenna Synthem succession. Moreover, during the past decade, the CARG (Foglio 276 Figline) and Carta Geologica Regione Toscana (1:10.000, fogli Figline e Montevarchi) projects provided a 1:10.000 geological maps of the whole basin and refined the sedimentological and stratigraphic characterization of the main sedimentary units (**Fig. 2.2**).

2.3 BASIN-FILL SUCCESSION AND SEDIMENTARY UNITS

The stratigraphic scheme proposed in this paper (**Fig. 2.3** and **2.4**) for the Upper Valdarno Basin considers the spatial distribution of the axial and transverse sediment supplies and the main CU (Coarsening-Upward) and FU (Fining-Upward) depositional trends. It is based on the "classical" partition of the basin fill succession into three synthems (Benvenuti, 1992): Casteluovo, Montevarchi and Torrente Ciuffenna Synthem.

This section provides a detailed description of the sedimentary units forming the basin-fill succession in terms of spatial distribution, stratigraphic attitude, thickness and age. Furthermore a description of the main sedimentological features for each unit is provided and deposits are discussed and interpreted in terms of grain size, sedimentary structures, beds attitude and stratal architecture.

MAGI and SAGRI, 1992 and ALBIANELLI et al., 1995			GHINASSI and MAGI, 2004		CARG (Foglio 276 Figline) and Carta Geologica Regione Toscana (1:10.000, fogli Figline e Montevarchi)			THIS WORK		
					VALDARNO BASIN			VALDARNO BASIN		
3° phase	margin	Limi di Pian di Tegna (IPT)	MONTICELLO-CIUFFENNA SYNTHEM	unstudied	SINTEMA DEL TORRENTE CIUFFENNA (UFF)		limi di Pian di Tegna	SINTEMA DEL TORRENTE CIUFFENNA (UFF)		UFF.c
		Sabbie del Tasso (sT)					limi di Latereto			
		Ciottolami di Loro Ciuffenna (cLC)				margin	sabbie del Tasso e sabbie della Loccaia		margin	UFF.b
	basin	Limi di Latereto (IL)					ciottolami di Loro Ciuffenna			
		Sabbie di Levane (sL)				basin	sabbie di Levane		basin	UFF.a
		Ciottolami di Laterina (cL)					ciottolami di Laterina			
2° phase	margin	Ciottolami della Penna (cP)	MONTEVARCHI SYNTHEM	unstudied	SINTEMA DI MONTEVARCHI (VRC)	margin	ciottolami di Leccio	SINTEMA DI MONTEVARCHI (VRC)	margin	VRC.g
							ciottolami della Penna			
		Ciottolami e Sabbie di Casa la Querce (cCQ)					formazione di Casa la Quercia			
	basin	Sabbie di Borro Cave (sBC)					sabbie di Borro Cave			
		Limi e Sabbie di Oreno (IO)		Limi e Sabbie di Oreno		basin	limi del T. Oreno		basin	VRC.f
		Argille del T. Ascione (aA)		Argille del T. Ascione			argille del T. Ascione			VRC.e
		Limi di Terranuova (IT)		Limi di Terranuova			limi di Terranuova			VRC.d
1° phase		Sabbie di S. Donato (sSDpp - conoide terminale)		Sabbie e Limi di Montecarlo			sabbie di Palazzetto			VRC.c
				Sabbie della Rena Bianca						VRC.b
										VRC.a
		Sabbie di S. Donato (sSDpp - fluvio deltizie)	CASTEL SYNTHEM	Sabbie di S. Donato	SINTEMA DI CASTELNUOVO DEI SABBIONI (CSB)		sabbie di S. Donato	SINTEMA DI CASTELNUOVO DEI SABBIONI (CSB)		CSB.c
		Argille di Meleto (aM)		unstudied			argille di Meleto			CSB.b
		Ciottolami di Spedalino (cS)					ciottolami di Spedalino			CSB.a

Fig. 2.3 - Comparative table of the main depositional units described in literature and correlation with the units discussed in the present work.

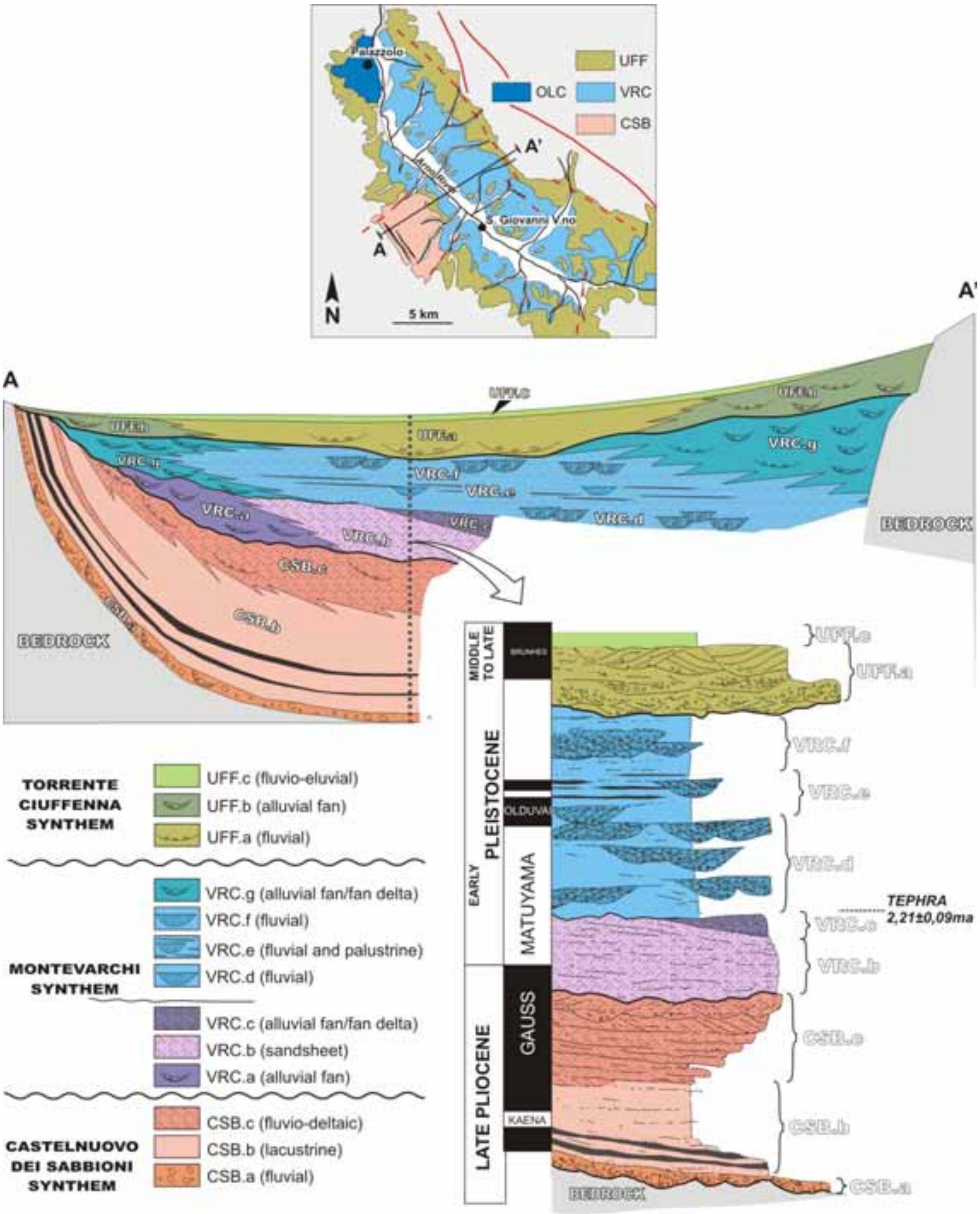

Fig. 2.4 - Stratigraphic scheme of the Upper Valdarno Basin.

2.3.1 Castelnuovo Synthem (CSB)

The Castelnuovo Synthem consists of three vertically stacked units (**Fig. 2.5A**), labelled here as CSB.a, CSB.b and CSB.c (**Fig. 2.4**). The Castelnuovo Synthem deposits, up to 200 m thick, are exposed in the Castelnuovo dei Sabbioni area, along the SW margin of the basin. These deposits are almost vertical close to the basin margin, and decrease their dip to about 10° moving basinward. In the S. Martino and Spedalino areas, where the basin margin is made of argillaceous rocks, the older deposits of the Castelnuovo Synthem are strongly deformed, locally overturned, and, in one site, are covered by the argillaceous bedrock. These deformations has been interpreted as due to gravitational collapses of the margin (Lazzarotto e Liotta, 1991) or, alternatively, as induced by compressive tectonics (Bonini, 1999).

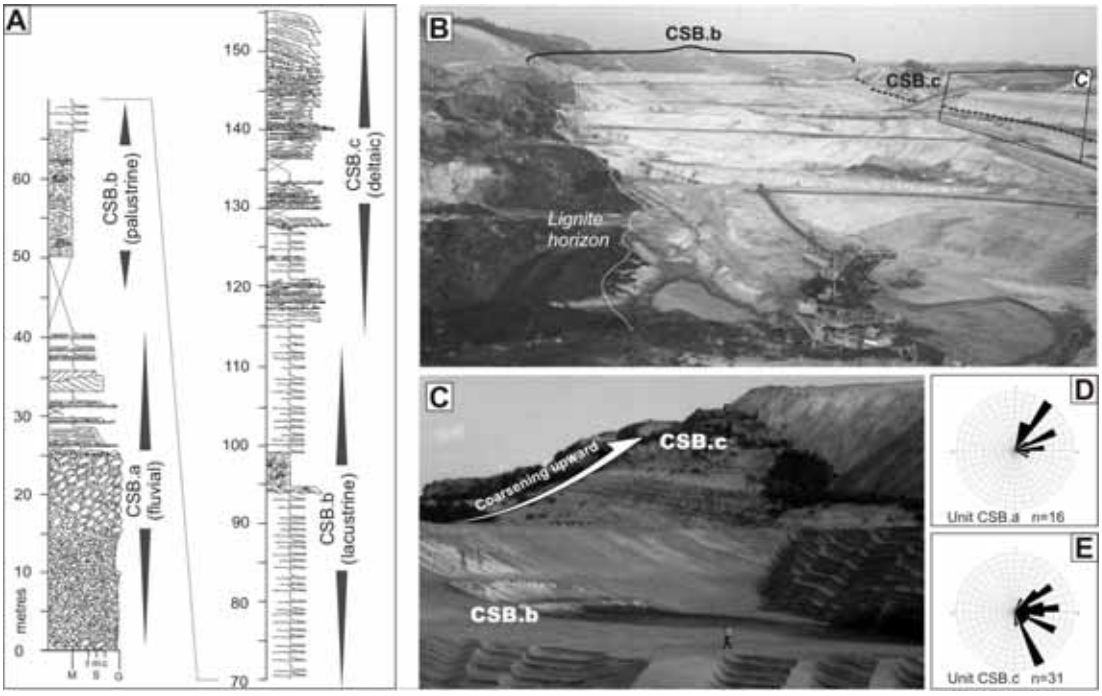

Fig. 2.5 - (A) Schematic log across the Castelnuovo Synthem (modified after Fialdini, 1988). (B) The Castelnuovo Synthem deposits in the S. Barbara quarry during year 1985. (C) close view of B showing the gradual transition from unit CSB.b to CSB.c. (D-E) Rose diagrams showing paleocurrent directions for units CSB.a and CSB.c respectively.

Deposition of the lower part of this synthem occurred in subtropical to warm-temperate climatic conditions. Unit CSB.b deposits record an expansion of cool-temperate forest taxa, indicating a cooling trend lacking of significant variations in humidity, as attested by the subordinate presence of herbaceous taxa. The uppermost part of the succession records a dramatic decrease of the warm and humid forest taxa, substituted by boreal conifers (Albianelli et al., 1995; Sagri et al., in press; see Chapter 5). The magnetochron Kaena has been identified in the lower portion of unit CSB.b (Albianelli et al., 1995) and dates the succession to the Late Pliocene, according to the new scale for the Quaternary (Gibbard et al, 2010).

2.3.1.1 Unit CSB.a

Unit CSB.a (Ciottolami e Sabbie di Spedalino, *Auctt.*) is exposed in small, discontinuous outcrops in the Cavriglia area. with a maximum thickness of 50 m close to Spedalino. This unit is made of coarse gravels (Albianelli et al., 1995) forming three main elongated bodies that show a concave base and flat top in sections transverse to their long axis. These bodies, up to 50 m thick and few hundreds of meters wide, directly overlay the pre-Neogene bedrock between Castelnuovo dei Sabbioni and Spedalino (**Fig. 2.6**). The axes of these bodies are NE-SW oriented (i.e. transverse to the basin) and paleotransport direction was to NE (**Fig. 2.5D**). Transition from unit CSB.a into CSB.b (Argille di Meleto, *Auctt.*) occurs through a marked increase in sand content (**Fig. 2.5A**).

Description

The lower portion (~25 m) of CSB.a succession consists of clast-supported, amalgamated, plane-parallel bedded gravels. Beds, up to few meters thick, are locally poorly distinguishable and made of rounded to well-rounded arenaceous gravels ranging in size from pebbles to cobbles, containing blocks up to 1 m in diameter (**Fig. 2.7**). Beds are massive or poorly stratified and contain abundant sandy matrix. Locally a(p)a(i) gravel imbrications have been observed, showing a plaleotransport direction to NE. The intermediate part of the succession, up to 20 m thick, is mainly made of amalgamated, lensoidal bodies (i.e. channel forms), with concave base and flat top, up to 30 m wide and 4 m deep, cutting subordinate vertically stacked tabular sandy and muddy beds.

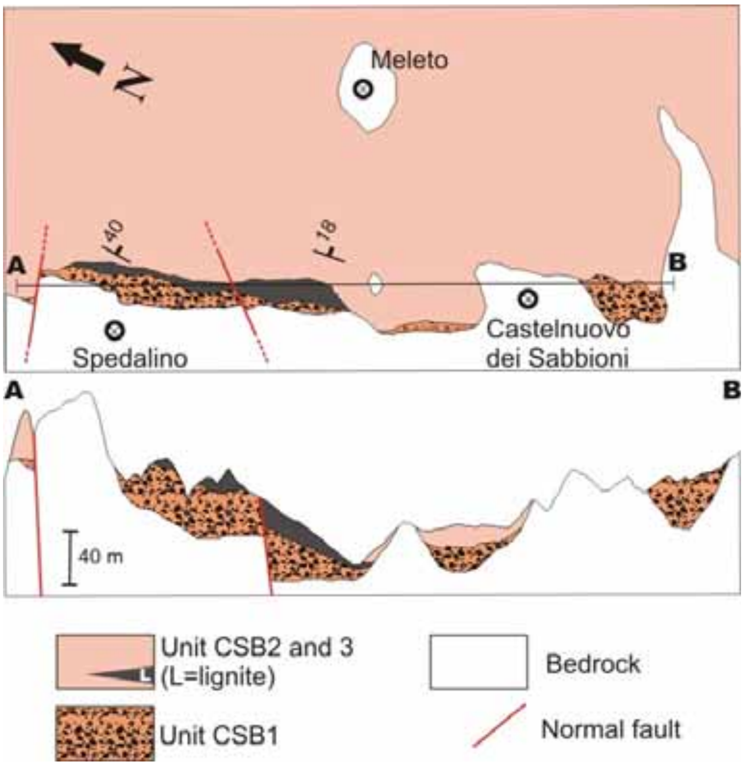

Fig. 2.6 - Geological sketch map, and relative cross-section, of the Castelnuovo dei Sabbioni area (modified after Fialdini, 1988). Note the concave base of CSB.a gravelly bodies which are interpreted as infill of fluvial valleys.

These lens-shaped bodies are filled with well rounded, clast-supported pebble to cobble size gravels at the base passing to sandy deposits and giving rise to clear FU trends. Individual lenses show an erosional basal surface, typically floored by a(t)b(i) imbricated gravels, giving an overall paleocurrent direction towards NE. Overlying conglomerates are arranged in crudely plane-parallel-stratified CU packages up to 60 cm thick. Gravels are typically capped by 10-50 cm thick beds of normally graded, massive sand passing to silt with abundant plant debris. Tabular sandy beds, typically 50-100 cm thick, are medium to coarse grained, massive, plane-parallel stratified or ripple-cross laminated. Subordinate muddy intervals, ranging in thickness between 10 and 50 cm, are massive or crudely laminated and rich in plant debris. The uppermost part of the CSB.a unit is characterized by a dramatic increase in sand content. Sand ranges from medium to coarse (**Fig. 2.8A**), with scattered gravels, and form rippled-cross laminated to plane-parallel stratified beds up to 1 m thick. Sandy beds can be normally graded, with a marked erosional base, or inversely-to-normally graded with a sharp, poorly erosional base (**Fig. 2.8D**). These beds, which are almost parallel and tabular at the outcrop scale, are rich to very rich in plant debris and don't show evidence of a significant subaerial exposure. Rare massive muddy layers, up to 10 cm thick, can be locally interbedded within the sandy deposits. The horizontally bedded deposits are locally truncated by lens-shaped bodies, up to 1 m thick and few meters wide, showing a FU trend from pebbly sand to fine silty sand. These deposits are massive in their coarsest basal portion and plane-parallel stratified in the upper part, where root traces and mottling are present.

Fig. 2.7 – Unit CSB.a conglomerates in two small outcrops close to the Neri village.

Interpretation

The lowermost to intermediate portion of unit CSB.a represents fluvial deposits confined in valleys. The mainly disorganized, horizontally bedded conglomerates forming the basal portion of the succession are interpreted as hyperconcentrated-flow deposits (Nemec and Muszyński, 1982; Smith, 1986; Benvenuti and Martini, 2001). The lensoidal units dominating the intermediate part of the succession represent channel-fill deposits (Bridge, 2003). Within these, the basal imbricated gravel pavement is interpreted as channel lag, whereas the CU packages of stratified gravels represent the product of the downstream migration of longitudinal bars hosted in the axial part of the channel (Boothroyd and Ashley, 1975; Nemec & Postma, 1993). These packages, elongated in a downstream direction, have been emplaced starting from a cluster of coarse material, forming the head of the bar, and a wedge of finer grained gravels accumulated in the downstream part of this cluster, forming the bar tail (Boothroyd and

Ashley, 1975). As the bar head moves downstream as successive bed-load sheets, it climbs on the tail causing the CU packages accumulation. Sandy graded deposits capping the channel-fill succession are interpreted as channel-abandonment deposits, accumulated in low energy conditions during the last phases of channel infill, as attested by the frequent presence of a plant-debris cap on top (Bluck, 1980). Horizontally bedded sand and mud are interpreted as interchannel deposits: sandy beds represent the products of expanding spill-over flows, while muddy intervals accumulated by fines fallout during the last stages of flood events (Miall, 1996).

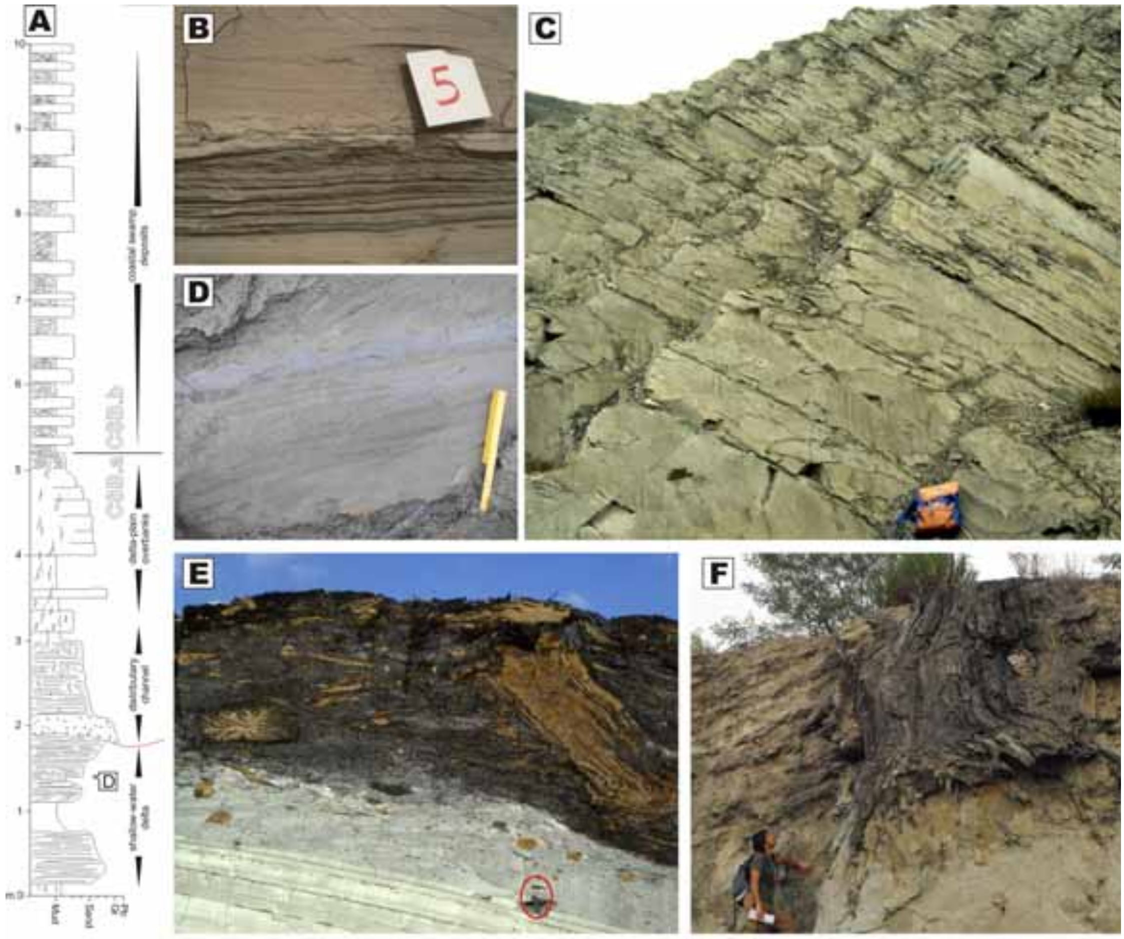

Fig. 2.8– Gradual transition between units CSB.a and CSB.b in the Castelnuovo dei Sabbioni area. A) Sedimentological log. B) Laminated sandy bed within unit CSB.b muddy succession. C) Unit CSB.b muddy deposits. D) Erosively based, normally graded sandybed cutting an inversely graded, plane-parallel stratified sandy bed in the uppermost part of unit CSB.a. E) and F) Basal Lignite horizon of unit CSB.a bearing tree trunks in life position.

The uppermost part of the succession, almost entirely made of sandy deposits, is characterized by remarkable different facies associations. The overall absence of evidences for subaerial exposure, the abundance of plant debris and the tabular geometry of these deposits suggest the accumulation by unconfined, point-sourced, expanding flows in a subaqueous environment (Wright, 1977). On the other hand, the lack of clinoforms or avalanching fronts indicates relative shallow-water conditions (Postma, 1990). Inversely-to-normally graded beds, as well as normally graded beds with erosional base, are interpreted as hyperpycnal-flow deposits fed by a shallow-water deltaic system (Mulder & Alexander, 2001). Muddy interlayers accumulated by sediment fallout during periods of low sediment supply (Colella, 1988). Lens-shaped sandy bodies are interpreted as distributary-channel deposits, as they represent the only deposits affected by pedogenic processes, (i.e. root traces and mottling).

According to this interpretation, the sedimentary succession of unit CSB.a represents the transition from a fluvial setting to a shallow-water deltaic environment.

2.3.1.2 Unit CSB.b

Unit CSB.b (Argille di Meleto, *Auctt.)* outcrops are delimited to SE and NW by the Vacchereccia and Cesto Creek respectively. This unit consists of a basal 15 m thick lignite layer covered by a muddy succession (**Fig. 2.5A**). The overlying muddy succession is up to 65 m thick (**Fig. 2.5A, B** and **C**), even if a thickness of about 180 m is reported by Gullotto (1983) for the southernmost reaches of the mine. Within the middle part of the muddy succession, a second, thinner lignite horizon is present. The two lignite layers show their maximum thickness close to the Chianti margin. Unit CSB.b lays conformably over unit CSB.a along the SW margin of the basin, while in the Meleto area it covers directly the pre-Neogenic bedrock (**Fig. 2.6**). Transition from unit CSB.b into CSB.c (Sabbie di S. Donato in Avane, *Auctt.*) occurs through a gradual increase in sand content (**Fig. 2.5A**).

The lignite layers of unit CSB.b have been followed toward NE (**Fig. 2.9**) for about 2 km through subsurface investigations, whereas the exposures of the Castelnuovo Synthem are bounded by rocky substratum along the Vacchereccia and

Cesto Creek, suggesting a limited NW-SE extent of the lacustrine basin. On the other hand, Lotti (1910) refers about two explorative wells in the Montevarchi area. The first well started at 147 m above the sea level and stopped after 115m without encounter the basin floor. The second well reached the depth of 74 m finding lignitiferous layers. More recently, in the subsurface of the S. Giovanni Valdarno area (**Fig. 2.9**), borehole data highlighted the presence of 40-60 m thick organic-rich mud passing upward into 50 m thick sand. Although the basal part of the mud layer was not explored, since the wells didn't reach the rocky bedrock, this 100 m thick, CU succession reasonably resembles the CSB.b-c package. Along the Caposelvi Creek, the occurrence of the oldest Montevarchi Synthem deposits above the rocky substratum suggests that the Castelnuovo Synthem deposits did not certainly extent south-eastward further than Montevarchi.

Description

Unit CSB.b (Argille di Meleto *Auctt.*) unit is 80 m thick and is exposed between the Vacchereccia and Cesto Creek, and consists of a monotonous muddy succession (**Fig. 2.8C**) bearing two lignitiferous layers in its lower part.

The lower lignitiferous horizon, located at the base of the unit, is 15 m thick and is separated from the uppermost one, that is 5 m thick, by sandy to muddy deposits. These organic-matter rich layers (**Fig. 2.8E** and **F**) consist of chaotic accumulations of plant debris both as small branches and metric trunks. Isolated metric trunks belonging to genus *Taxodium* (**Fig. 2.8E**) are preserved in live position and rooted in the underlying deposits. Discontinuous tabular sandy or muddy massive layers, up to few decimeters thick and rich in plant debris, can be locally interbedded within the lignitiferous layers. Muddy beds are massive to gently laminated and range in thickness from 10 to 50 cm. Sandy layers, up to 50 cm thick, are commonly ungraded and massive, although a primary stratification could be indicated by subtle changes in grain size. Both muddy and sandy layers lack evidence for a marked subaerial exposure, while the locally show root traces. Siderite ($FeCO_3$) nodules can occur within the sandy intercalations. Fluitated trunks up to 6 m long can locally occur within the silty sand deposits.

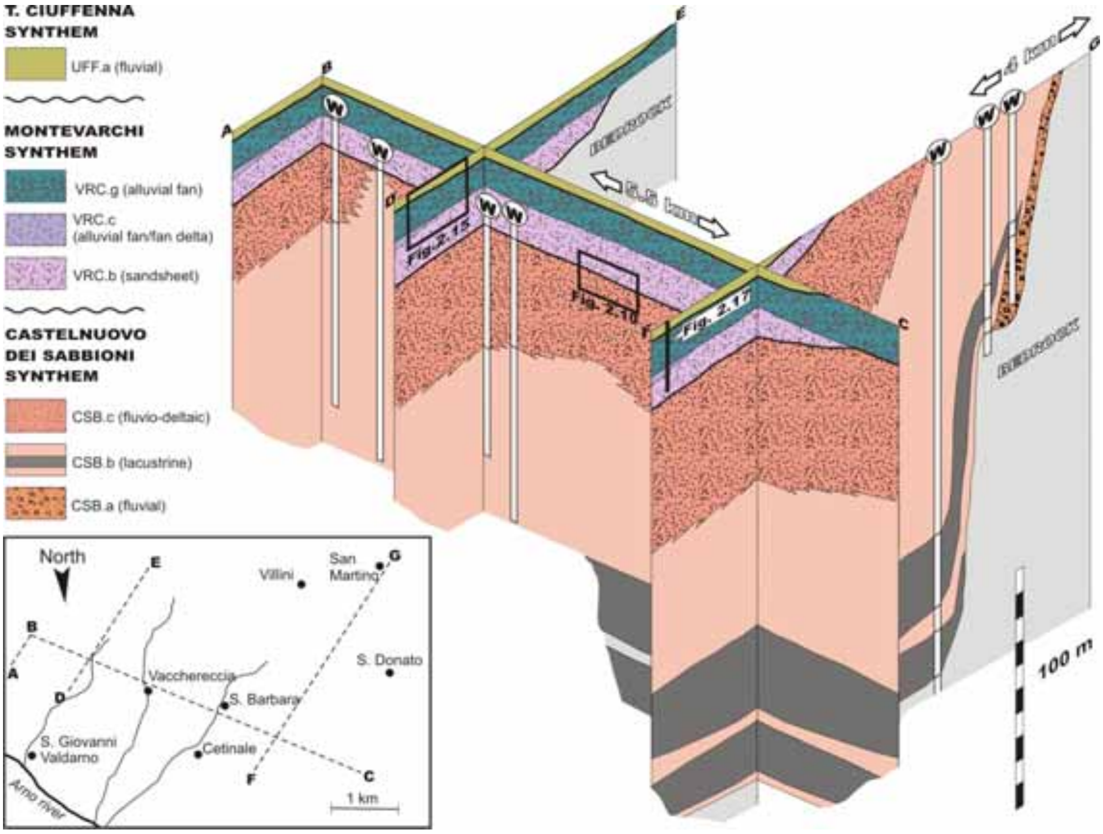

Fig. 2.9 - Outcrop and subsurface data from the S. Giovanni Valdarno - S. Martino area. Note the subsurface continuation of the CSB deposits moving toward SE.

The muddy succession shows a well defined bedding (**Fig. 2.8C**) and mainly consists of vertically stacked horizontal graded beds. These beds, 5-30 cm thick, are characterized by a lower plane-parallel stratified or ripple-cross laminated sandy portion (2-10 cm thick) and by an upper part made of silty mud and rich in well preserved vegetal remains. Nodules and layers of siderite ($FeCO_3$) are common within these deposits.

Towards the top, unit CSB.b shows a clear increase in sand content and the sandy-to-muddy graded beds are commonly interbedded with 10-200 cm thick sandy layers. The sandy intercalations consist of single or stacked tabular beds of fine to coarse sand with scattered gravels. Sandy beds show a wide spectrum of depositional trend and associated sedimentary structures. Normally, these beds are up to 50 cm thick and show a normal or inverse-to-normal grading. Normal graded beds are characterized by an erosive basal surface covered by a massive division passing upward into a stratified interval, which can be rippled or plane parallel-stratified. Inverse to normal graded beds are commonly well stratified and show repeated changes from rippled to plane-parallel stratified intervals, which can be associated or not with changes in grain size. Plant debris is common in the upper part of both types of sandy beds, which can bear ripple forms preserved on their top surface (**Fig. 2.8B**). Both muddy and sandy deposits lack evidence for a significant subaerial exposure. In the uppermost part of the succession lens-shaped bodies, locally floored by fine pebbles and filled with sandy-to-muddy graded beds, cut the underlying tabular deposits (Fialdini, 1988).

Interpretation

The described facies associations for CSB.b unit suggest a lacustrine-palustrine environment characterized by variable amounts of clastic sediment supply. Lignite horizons accumulated in a coastal palustrine setting where noteworthy volumes of wood were accumulated both through *in situ* growth and debris deposition, as attested by the widespread presence of tree trunks in life position. The lack of oxidation features due to subaerial exposure and the occurrence of siderite nodules and root traces within the thin sandy layers, interbedded with the lignite, together with the absence of bioturbation, testify anoxic conditions in a shallow subaqueous environment (Hamblin, 1992; Basilici, 1997).

The overlaying muddy succession accumulated in an offshore lacustrine setting occasionally affected by the emplacement of sandy layers from river-generated turbidity currents. The thinly bedded deposits made of sandy-to-muddy graded beds are interpreted as the products of low-density turbidity currents (Lowe, 1982). The lower stratified sandy portion of these beds accumulated in tractional conditions, while the muddy interval emplaced by sediment fallout, as attested by the presence of well preserved, plant debris laminae. The thicker sandy beds that become more common in the upper part of the succession, represent the accumulation by delta-fed, sustained and pulsating, turbulent hyperpycnal flows running on the basin floor (Mulder and Alexander, 2001; Mulder et al., 2003; Zavala et al., 2006). In this framework, lens-shaped, erosively based bodies can be interpreted as subaqueous channels (Mutti et al., 1996).

In its lower part the succession records an overall rising of the water level, passing from the first lignite horizon to the graded ritmites. A subsequent shallowing, indicated by deposition of the second lignite horizon, was followed by a new deepening episode.

2.3.1.3 Unit CSB.c

Unit CSB.c (Sabbie di S. Donato in Avane, *Auctt.*) is exposed in the S. Barbara area and is about 70 m thick. The succession shows a clear CU trend form very fine, muddy sand grading upward into medium to coarse sand. Paleocurrent derived from stratified sands indicate a main transport direction towards SE (**Fig. 2.5E**). In the S. Cipriano area unit CSB.c is unconformably overlain by the VRC.b unit (**Fig. 2.10**).

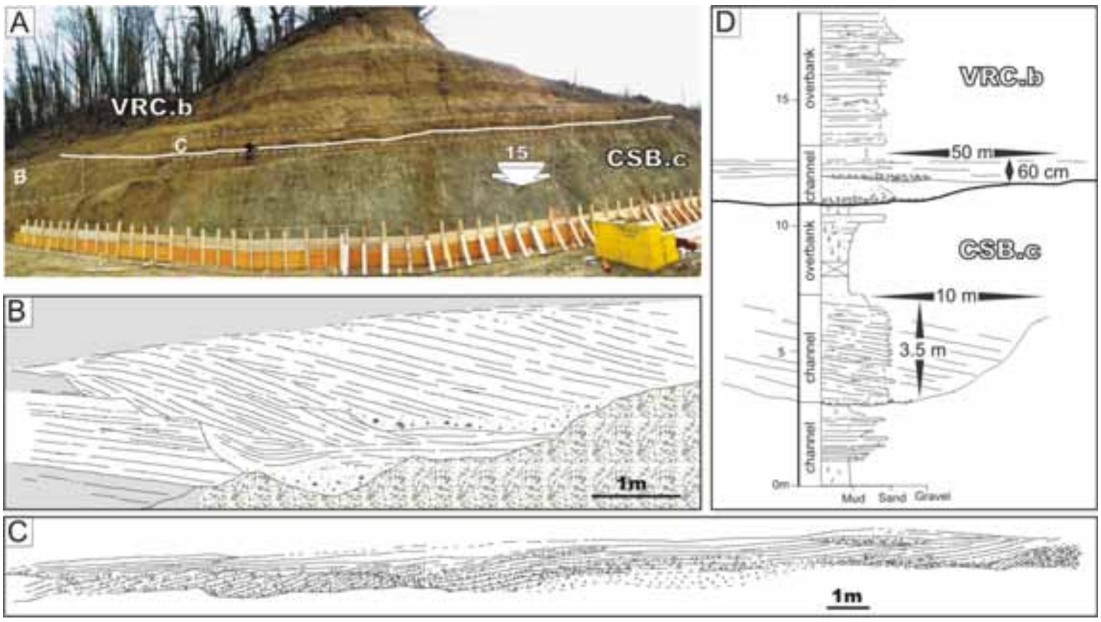

Fig. 2.10 - The unconformity capping the Castenuovo Synthem in the S. Cipriano area. (A) VRC.b deposits unconformably overlaying the CSB.c unit. VRC.b deposits are almost sub-horizontal (apparent inclination is due to the photo) whereas CSB.c beds dip into the outcrop about 15° (see white arrow). (B) Linedrawing of a sandy channelized body in the upper part of unit CSB.c. (C) Linedrwaing of a gravelly sand channelized body at the base of the VRC.b unit. (D) Sedimentological log across the unconformity surface. Note the difference in W/D ratio between the VRC.b and CSB.c channelized bodies.

Description

This sandy lithosome consists of stacked 2-6 m thick CU subunits (**Fig. 2.11A**), which are, in turn, made of three main stacked portions. The lower portion is made of sub-horizontal, tabular beds, which are 15-40 cm thick and range in grain size from mud to medium sand. Sandy beds can be normally graded, ungraded or inversely-to-normally graded. They are commonly ripple-cross laminated to plane-parallel stratified and contain abundant plant debris in their uppermost portion (**Fig. 2.11D**). Bases of sandy beds can be erosional, mainly where a 2-4 cm thick layer of massive sand forms the basal part of the layer. Muddy intervals are faintly laminated or massive and bear evidences of intense bioturbations. In extensive outcrops those beds form compensationally-stacked, mounded bodies 0.5-1 m thick and 10-15 m wide. The middle portion of the CU sub-units consists of sandy clinoforms (15°-20°) characterized by well-defined sigmoidal bedding (**Fig. 2.11E**). Beds are up to 25 cm thick, normally graded and commonly massive, although a crude plane-parallel stratification occurs in places. Discontinuous, massive muddy layers up to 3 cm thick are present. Cross-bedded units form mounded, fan-shaped bodies spanning around ~180°. The upper portion of the CU sub-units is made of FU sandy bodies (up to 2 m thick and 15 m wide) with concave erosional base and flat top (**Fig. 2.11B**). These units are often floored by pebble-size mud clasts, which in turn are covered by inclined beds (10°-20°) of coarse- to medium-grained sand. Sandy beds, up to 25 cm thick, are plane-parallel and cross-stratified. Paleocurrent directions, inferred from cross-stratified sands and basal scours, are mainly transverse to the beds dipping. The complete succession, made of these three vertically staked portions, is rare. Commonly the upper part is missed where the basal part is overlain by the middle portion. Where the upper part is present, it erosionally overlay the lower part, and the middle one is missed (see Chapter 3 for further details).

In the S. Cipriano area, the uppermost stratigraphic part CSB.c unit is mainly made of muddy deposits containing many sandy intervals (**Fig 2.11F**). Muddy deposits

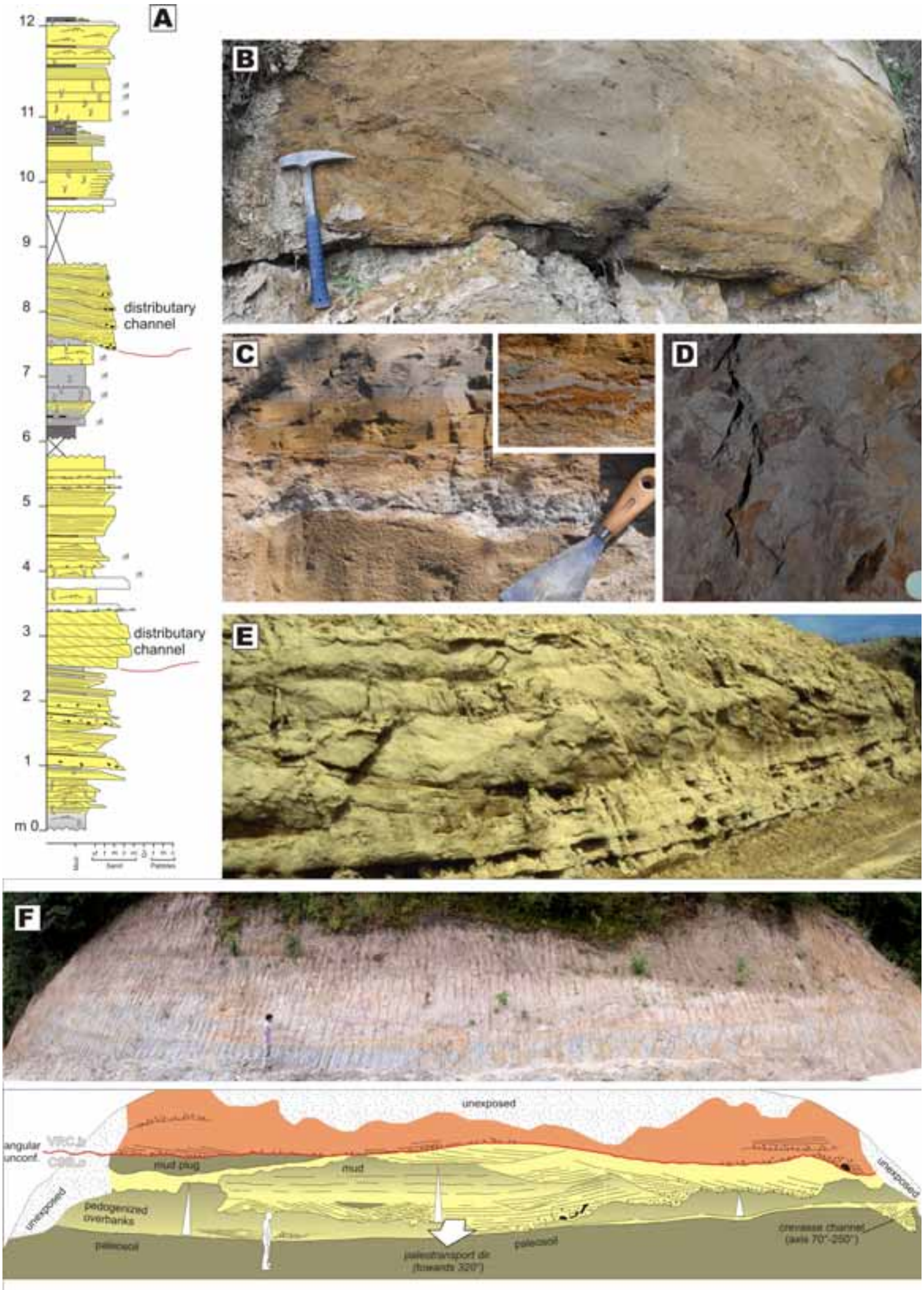

Fig. 2.11 – Fluvio-deltaic deposits of unit CSB.c. A) Sedimentological log measured through the upper part of the succession north of S. Cipriano. B) Distributary channel cutting muddy deltaic deposits. C) Well sorted, wave-worked sands showing symmetrical trough-cross lamination. D) Top surface of muddy bed bearing leaves and plant debris. E) Sigmoidal cross-bedded mouth-bar deposits. F) Fluvial deposits of unit CSB.c in the S. Cipriano area.

are massive, bear root traces and show hydromorphic pedogenetic features. The most common sandy deposits are mainly represented by lensoidal bodies (up to 3.5 m thick and 10 m wide) with concave erosional base and flat top (i.e. channel forms) (**Fig. 2.11F**). These bodies show a clear FU trend, from pebbly, coarse sand to very fine sand, and consist of cross-bedded units dipping toward the channel axis of about 15°. Beds show trough-cross stratification in their lower portion, while they are plane-parallel stratified in their upper part. Palaeotransport direction from cross strata is oblique to beds dip direction (**Fig. 2.11F**). Locally these cross-bedded units are plugged by muddy deposits that are slightly pedogenized to the top. Subordinate sandy deposits are represented by laterally continuous beds of medium to very fine sand that can be massive, plane-parallel stratified or ripple-cross laminated, locally showing root traces and pedogenic features to the top, and by U-shaped units, cutting the tabular sands, made of pebbly and coarse to medium grained sandy beds showing trough-cross stratification in the lower part and plane-parallel stratification in the upper part.

Interpretation

The overall lack of oxidation features due to sub-aerial exposure suggests that the lower part of unit CSB.c emplaced in a subaqueous environment. In particular these deposits represent the products of the accumulation by a shallow-water delta (*sensu* Postma, 1990). The described CU sub-units represent mouth-bar deposits. Their lower portions mainly consist of river-fed, expanding low-density turbidity current deposits, as attested by the tabular geometry, the graded nature and internal stratification of these beds (Mulder and Alexander, 2001; Mulder et al., 2003; Plink-Björklund and Steel. 2004; Petter and Steel 2006; Zavala et al., 2006). These are interbedded with muddy layers accumulated by fallout of fines during low sediment supply periods, as confirmed by the occurrence of plant debris laminae and bioturbation. The fan-shaped geometry of the medial parts of CU sub-units suggests sediment accumulation on a lobe fed from a stable entry point (Bates, 1953; Hoyal et al., 2003; Wellner et al, 2005; see Chapter 3) in a subaquesous setting. High-density turbulent flows represent the dominant process on the delta front, but no avalanching evidences are present. These deposits accumulated during flood peaks, when a significant amount of sediment is dropped down in the proximal areas due to flow expansion and deceleration (Wright, 1977). The lensoidal sandy bodies, with concave erosional base and flat top, forming the upper portions of the CU sub-units are interpreted as distributary channel deposits. Mud-clasts flooring the base represent channel-lag deposits, eroded from the banks and accumulated in the deeper part of channels, which is mainly affected by sand bypass (Collinson, 1986). The overlying clinoforms accumulated by migration of bank-attached bars, as attested by paleocurrent directions and bed attitude (Bridge, 2003).

The uppermost part of the succession, cropping out in the San Cipriano area, mainly consists of channelized sandy bodies hosted within a muddy succession. Cross-bedded units forming the channel bodies accumulated by lateral migration of bars, as attested by beds attitude, internal stratification and paleocurrent directions (Bridge, 2003). Mud units plugging the clinoforms are interpreted as channel abandonment deposits accumulated by fallout of fines (Bluck, 1980). Tabular, laterally persisting sandy beds interbedded within the muddy succession are interpreted as the product of unconfined, expanding flows (i.e. crevasse splays; Ethridge et al., 1981) occurring during flood events. In these framework the U-shaped, erosively based bodies represent crevasse channels (Ethridge et al., 1981; Allen et al., 1983). The abundance of oxidation and pedogenetic features suggests a sub-aerial environment for this part of the succession, while the hydromorphic nature of the paleosols implies that the water table was close to the ground surface (Wright and Marriot, 1993). These data indicate a fluvial environment for these deposits.

2.3.2 Montevarchi Synthem (VRC)

The Montevarchi Synthem is made of two portions separated by a minor unconformity which grades basinward into a depositional surface (Ghinassi & Magi, 2004). The lower portion of the Synthem crops out along the SW margin, it is at least 40 m thick and shows a gentle dip (about 5-10°) toward NE. This portion consists of three units labelled here as VRC.a, VRC.b and VRC.c (**Fig. 2.4**). Palinological content of unit VRC.a points to humid conditions (see Chapter 5), whereas samples from unit VRC.b show a clear expansion of herbaceous elements, indicating the development of arid conditions (Albianelli et al., 1995; Sagri et al., un press; see Chapter 5). This dramatic shift has been calibrated close to the Gauss-Matuyama boundary and correlates with the onset of glacial/interglacial (G/I) cycles due to the maximum expansion of the ice-cap, occurred at 2.6 Ma (Albianelli et al., 1995; Napoleone et al., 2003; Ghinassi et al., 2004; Sagri et al., in press), dating the middle part of unit VRC.b to the Plio-Quaternary boundary (Gibbard et al., 2010). Unit VRC.c testifies a new expansion of warm-forest taxa, indicating the transition to more humid conditions (Sagri et al., in press).

The upper portion of the synthem is exposed at the basin scale and is sub-horizontal. It is about 30 m thick along the Chianti margin and thickens up to 100 m moving toward the NE margin, where the base of the succession is never exposed. This portion is made of axial muddy and sandy deposits, belonging to units VRC.d, VRC.e and VRC.f, interfingering with margin-attached gravelly to sandy deposits belonging to unit VRC.g. This succession accumulated under variable climatic conditions, related to alternating glacial and interglacial phases and showing a progressive reduction of subtropical/warm-temperate taxa (Albianelli et al., 1995; Sagri et al., in press; see Chapter 5). The Olduvai palaeomagnetic event has been identified within unit VRC.e (Albianelli et al., 1995), and a tephra from the base of unit VRC.d provided an age of about 2.2 ma (Ghinassi et al., 2004). According to this data, the Montevarchi Synthem deposition occurred during Middle Pleistocene time (Gibbard et al., 2010).

2.3.2.1 Unit VRC.a

Unit VRC.a (Ciottolami e Sabbie di Caposelvi and Sabbie di Palazzetto *p.p.* in Carta Geologica Regione Toscana 1:10.000, foglio Montevarchi) is exposed close to the Caposelvi village, where mainly covers the rocky substratum, and in the Borro del Cesto area, where unconformably overlies the CSB.c units and the bedrock. The succession, up to 50 m thick, consists of coarse gravels grading upward to gravelly sands.

Description

This unit, up to 50 m thick consists of a basal gravelly interval grading upward and basinward into sandy/gravelly deposits. The gravelly interval (up to 30 m thick) consists of multistorey lensoid units of moderately rounded clast-supported pebble to boulder size gravels with rare sandy intercalations. Individual lenses have an erosional basal surface, typically floored by imbricated a(t)b(i) clasts (**Fig. 2.12D**). A variety of gravelly beds constitute the lensoid bodies. The most common beds are massive, poorly sorted pebble to boulder gravel tabular beds up to 40 cm thick, bearing a variable amount of interstitial sandy matrix (**Fig. 2.12B**). These beds are in general erosively based (**Fig. 2.12A**), disorganized to crudely normally graded with a common a(i)a(p) clasts imbrication, and seldom inversely graded, with an a(p) or a(p)a(i) fabric of elongate clasts. Plane-parallel stratified, clast-supported, gravelly beds (10-20 cm thick) are, in places, stacked vertically to form coarsening upward packages, typically up to 1 m thick (**Fig. 2.12D**). Paleoflows, as suggested by a(t)b(i) gravel imbrication, are parallel to the sediment bodies axis, along which these deposits show a downstream fining. Subordinate normal graded, cross-stratified, clast-supported gravels form packages up to 1 m thick. These strata dip about 30° parallel or gently oblique to the sediment bodies axis.

The sandy/gravelly interval (Sabbie di Palazzetto - Membro di Ricasoli in Carta Geologica Regione Toscana 1:10.000, foglio Montevarchi) is up to 20 m thick and consists of vertically stacked tabular sandy beds truncated by sandy or, less frequently, gravelly lensoid bodies with erosive concave base and flat top (**Fig. 2.13H**). Tabular sandy deposits are medium-to-coarse grained with occasional pebbles, dispersed or concentrated in strings (**Fig.2.13A**). They typically show plane-parallel stratification or ripple-cross lamination (**Fig. 2.13D**). Bedding is sometimes faintly observable due to extensive bioturbation, root traces and pedogenetic processes. The sandy lensoid units, up to 1 m thick and few meters wide, are often floored by pebble-size gravels and mud clasts and show a fining upward trend (**Fig. 2.13H**). Overlying deposits consists of inclined beds (5°-10°) of coarse- to medium-grained sand. Sandy beds, up to 15 cm thick, are plane-parallel and ripple-cross stratified. Paleocurrent directions are mainly oblique to the beds dipping direction. The gravelly lensoid units are similar to those forming the basal gravelly portion of the units, but show a higher W/D ratio (0.5 m thick and 10 m wide). Massive deposits are rare, and most of the beds show a diffuse plane-parallel stratification. These beds, up to 10 cm thick, are commonly tabular and vertically stacked into form coarsening upward packages, typically up to 50 cm thick. In

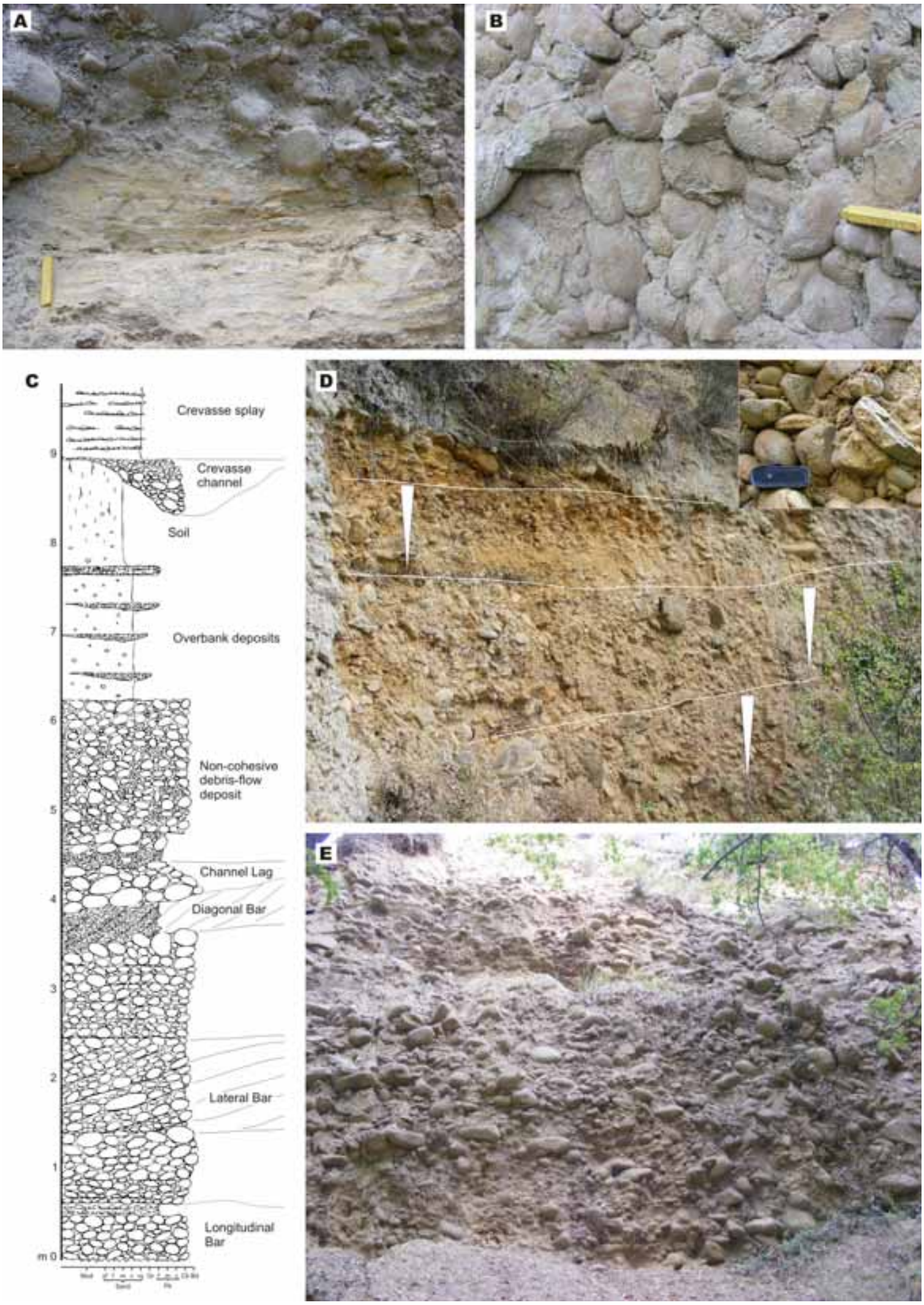

Fig. 2.12 – Gravelly deposits of unit VRC.a south of Montevarchi. A) Erosional base of a gravelly channel cutting horizontally stratified sandy overbanks. B) Poorly sorted, massive gravel. C) Sedimentological log measured in the lowermost part of the succession. D) CU packages of horizontally bedded gravel deposited by downstream migrating longitudinal bars.
E) Base of the succession shown in the log.

places, gravelly beds are gently inclined (10°-15°) toward the axis of the lensoid body (**Fig. 2.13H**).

Interpretation

Unit VRC.a represents alluvial fan deposits. Multistorey lensoid bodies of the gravelly portion of the unit are interpreted as channel bodies, as testified by the erosional nature of their base and by their geometry. The channel base is floored by channel-lag deposits, discontinuously moved by the current as lower-stage plane bed and causing clasts orientation by rolling around their longer axis. Massive, poorly sorted, matrix-rich, tabular gravelly beds are interpreted as hyperconcentrated-flow deposits (Nemec and Muszyński, 1982; Smith, 1986; Benvenuti and Martini, 2001) in case they show evidences of turbolence, such as erosional base and normal grading, as cohesionless debris-flow deposits (Nemec and Steel, 1984) when they show non-erosional base and are ungraded or inversely graded. Plane parallel-stratified, clast-supported gravelly beds arranged in CU packages are interpreted as longitudinal bars (Boothroyd and Ashley, 1975; Nemec & Postma, 1993). Gravelly cross-bedded units dipping parallel or slightly oblique to the channel axis are the product of successive accumulation on the avalanching faces of migrating transverse or diagonal bars respectively (Miall, 1977; Bridge, 2003).

Tabular sandy beds of the sandy/gravelly interval of the succession have been emplaced by unconfined, rapidly expanding, sheet-like turbulent flows, as attested by their lateral persistence and by the presence of tractional bedforms. Lensoid units are interpreted as channel deposits. The sandy ones consist of a pebbly basal lag and a clinostratified upper portion accumulated on lateral accretion bars (Lewin, 1976; Bridge, 1993; 2003). Horizontally bedded, CU packages of conglomerate and gently inclined gravels are interpreted as longitudinal bars and lateral accretion bars deposits respectively (Boothroyd and Ashley, 1975; Bridge, 2003).

The architectural assemblage of facies and their relative abundance suggest a proximal alluvial fan setting for the gravelly portion of the succession, while the predominant sheet-like geometry of sediments and the significant presence of pedogenic features indicate a distal fan environment for the sandy/gravelly portion.

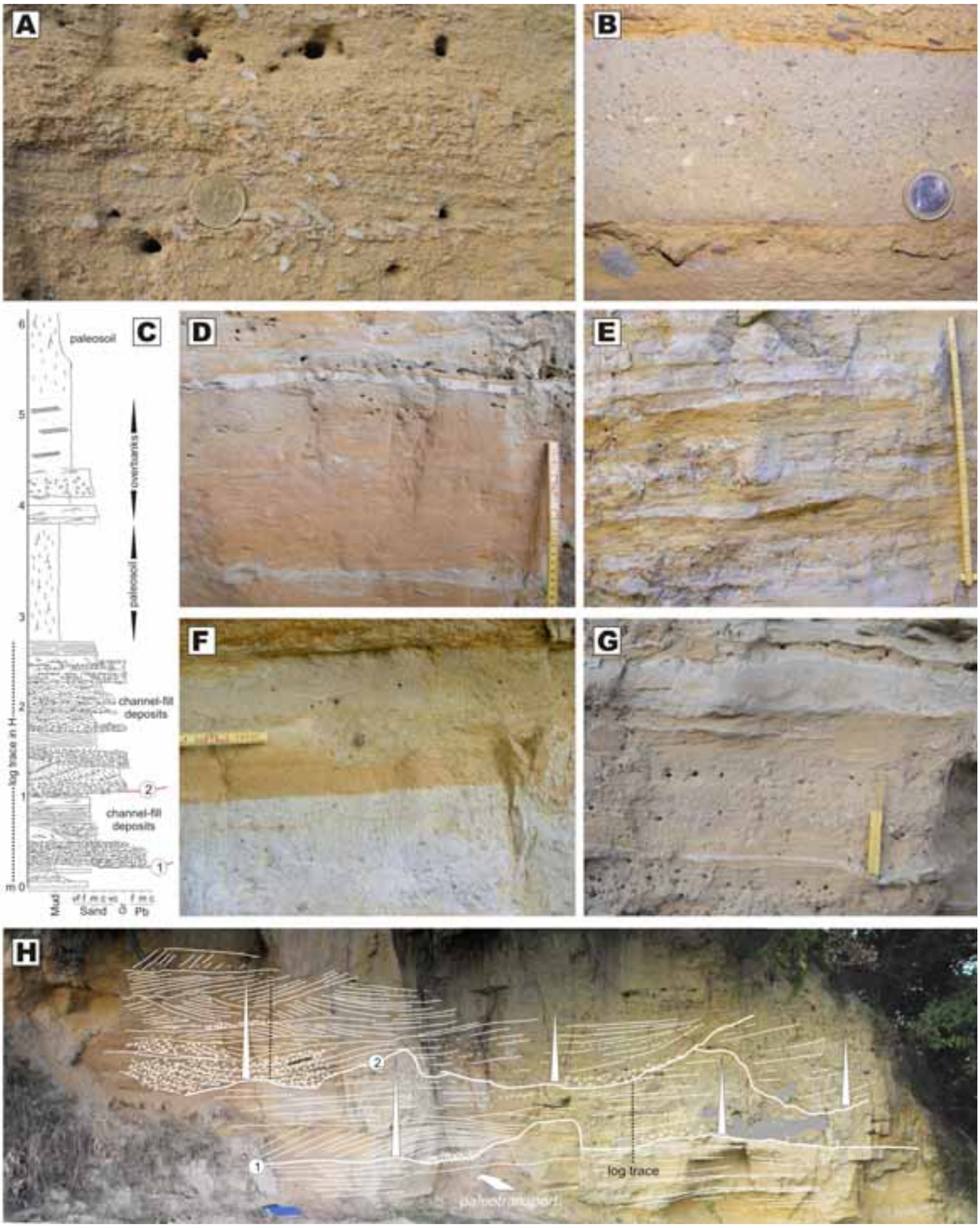

Fig. 2.13 – Sandy/gravelly deposits of unit VRC.a cropping out close to the Ricasoli village. A) Plane-parallel laminated sands with strings of fine pebbles. B) Massive sandy bed showing coarse-tail inverse grading and bearing mud-clasts. C) Sedimentological log measured in the autcrop shown in H. D) Plane parallel laminated tabular sandy beds alternating with thin mud drapes. E) Interbedded sandy and muddy tabular beds. F) Granules-filled small scour cutting a sandy bed. G) Plane-parallel stratified sandy bed capped by a muddy layer. H) Transverse W-E oriented section showing multistorey channels cutting tabular sandy to muddy beds.

VRC.a gravels, were emplaced by two main alluvial-fan systems sourced from south (**Fig. 2.14**) and west respectively (i.e. Chianti margin) and separated by a topographic paleo-high located in the S. Cipriano area (**Fig. 2.14A**). The Caposelvi fan was larger than that developed in the Borro del Cesto area, and gave rise to a well-developed FU sedimentary succession, which can be clearly recognised both in its distal and proximal areas (**Fig. 2.14B**).

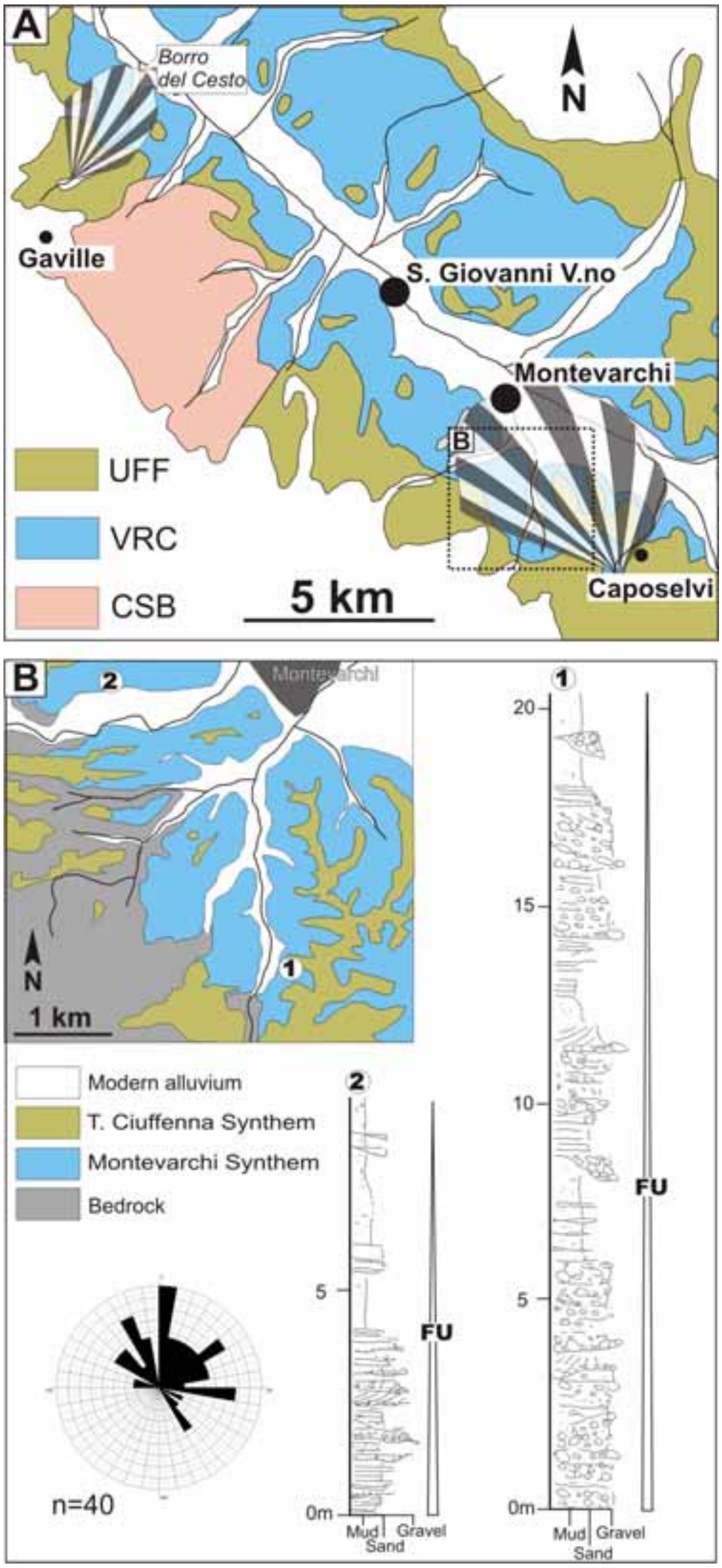

Fig. 2.14 - (A) Geological sketch map of the Valdarno basin highlighting the distribution of the alluvial fans of unit VRC.a. (B) Simplified geological map of the area indicated in A. Note the well-defined FU trend in the proximal and distal parts of the alluvial-fan system.

2.3.2.2 Unit VRC.b

Unit VRC.b (Sabbie di Palazzetto *p.p.* in Carta Geologica Regione Toscana 1:10.000, foglio Montevarchi) is mainly exposed between Montevarchi and S. Cipriano, with subordinate outcrops in the Figline area. It is a least 40 m thick and consists entirely of sand, locally characterized by a high textural and compositional maturity (Rena Bianca in Ghinassi et al., 2004). In the S. Giovanni Valdarno area, where VRC.b sands have been intensely quarried, these deposits show an internal cyclicity of climatic origin (Ghinassi et al., 2004) and evidences of syn-depositional tectonics. This unit onlaps both the rocky substratum and the VRC.a unit between Montevarchi and S. Giovanni Valdarno, whereas it unconformably overlays the Castenuovo Synthem deposits in the Vacchereccia - S. Cipriano area (**Fig. 2.10**). Close to the Chianti ridge, the VRC.b deposits are capped by an unconformity surface (**Fig. 2.15**), whereas moving north-eastward (i.e. basinward) VRC.b unis grades upaward into VRC.c unit (Sabbie e Limi di Montecarlo in Ghinassi and Magi, 2004; **Fig. 2.15**).

Description

URC.b unit is entirely made of vertically stacked tabular sandy beds (**Fig. 2.16A** and **C**), which, in a few places, are cut by lensoid sandy lithosomes. Tabular beds, up to 1 m thick, are made of fine to medium sand, which can vary from moderately to very well sorted. Moderately sorted sandy beds show a sharp base and can be ungraded or normally graded. Plane-parallel and cross stratification, along with ripple-cross lamination, are very common and locally disturbed by fluid-escape structures. Rare massive, normally graded beds with scattered pebbles at the base are present. Well-sorted sandy beds show a marked lateral persistence and are associated with brownish encrustations cemented by iron oxides. Sandy beds are characterized by a diffuse planar stratification (**Fig. 2.16I**). Single strata range from horizontal to very gently inclined (3°-5°) and, locally, show an internal inverse grading (**Fig.2.16B**). In places, isolated ripple forms (**Fig. 2.16G**) are preserved with the coarser sand grains concentrated in the crest zone. Well sorted sand can also show an internal cross stratification, both at the ripple and dune scale. Occasionally, the high textural and compositional sorting prevents the

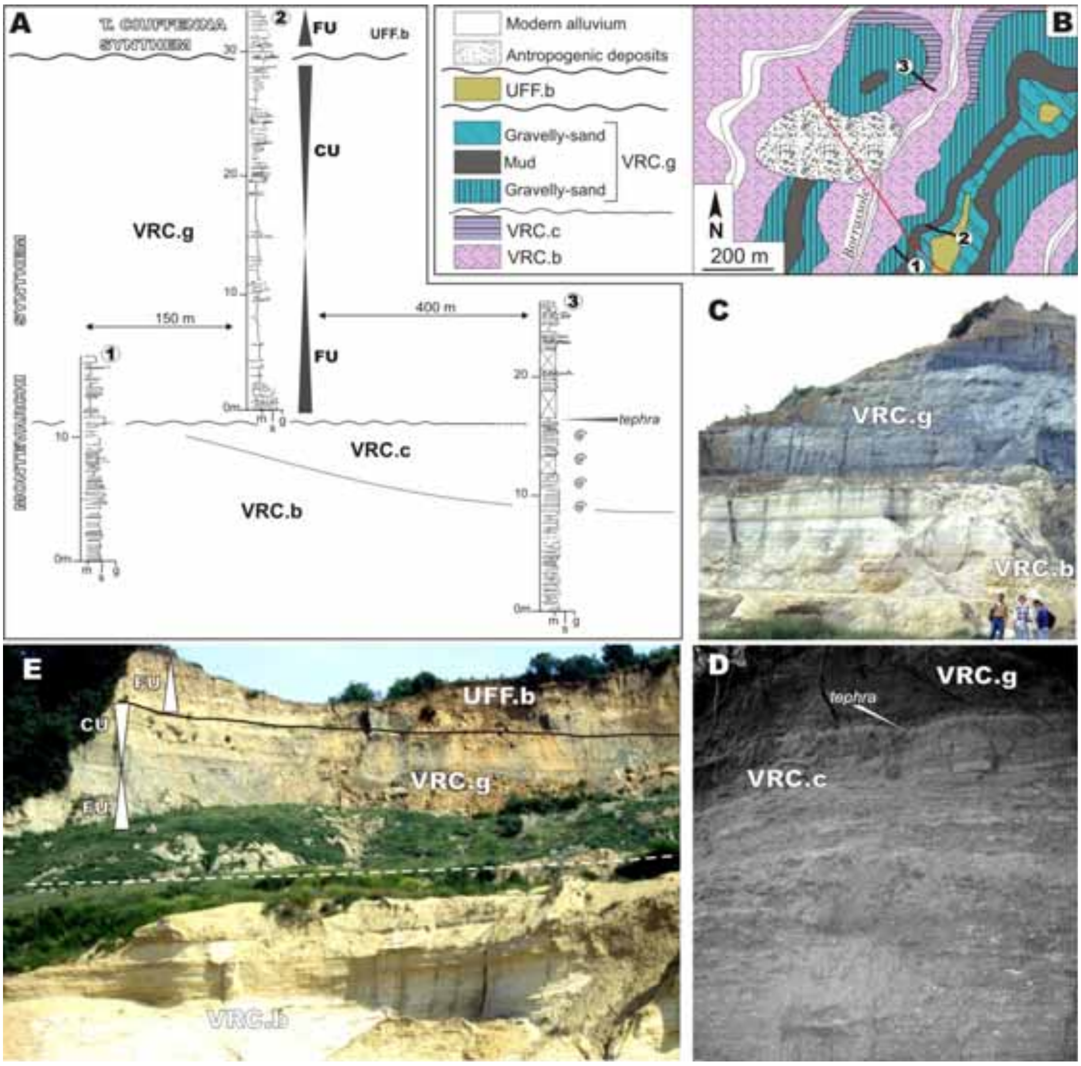

Fig. 2.15 - (A) VRC and UFF Synthem in the Borrassole area (1.5 km SW of S. Giovanni Valdarno). The lower part of the VRC Synthem is separated from the upper part by an unconformity passing basinward into a depositional surface. (B) Geological sketch map of the Borrassole area showing location of logs of inset A. (C) Alluvial-fan deposits of VRC.g unit abruptly overlaying eolian-reworked VRC.b sand (Cava Silva). (D) Mollusc-rich sand of unit VRC.c passing upward into muddy deposits of unit VRC.g. Note the whitish tephra layer few decimetres in the lowermost part of unit VRC.g. (E) Francalanci Quarry photographed in 1985. Note the angular unconformity between VRC.b and overlying deposits.

detecting of sedimentary structures. The iron incrustations show a remarkable lateral persistence and can be up to 50 cm thick. The top surface of these crusts can be smoothed or characterized by complex dendritic geometries (**Fig. 2.16I**). Sandy deposits associated with these crusts are characterized by a diffuse crinkly lamination, which varies from sub-horizontal to gently inclined (10°-15°). Lensoid sandy units (**Fig. 2.16F**), up to 1 m thick and 15-20 m wide, are commonly associated with moderately sorted deposits. These units show a concave upward base and flat top and are characterized by a fining upward trend. The lowermost part of these lenses is commonly floored with fine pebbles and subangular, pebble-size mudclasts. This basal gravelly interval is covered by gently inclined beds (5°-10°) dipping toward the lens axis. Inclined beds are erosively based, and consist of plane-parallel stratified medium to coarse sand with scattered gravels. Muddy layers can occur within these sandy beds.

Interpretation

Moderately sorted, tabular sandy beds are interpreted as accumulated by expanding unconfined turbulent flows, ranging from hyperconcentrated (massive, normally graded, pebble floored) to tractional (ripple-cross laminated, plane-parallel or cross stratified). These deposits alternate with well sorted, tabular sandy beds that show evidence of small-scale eolian bedforms migration (Hunter, 1977; Irmen and Vondra, 2000), as attested by the gently inclined inversely graded strata, while larger scale cross strata are the product of accumulation on small eolian dunes. The occurrence of iron incrustations represent episodes of ground water rise (Ghinassi et al., 2004); the internal lamination of these horizons have been produced by wind-blown sand accumulating on the wet ground surface as adhesion ripples, laminae or warts (Kocurek and Fielder, 1982; Olsen et al., 1989). Lensoid sandy units, associated with moderately sorted sands and interpreted as channel deposits, are floored by channel-lag deposits covered by clinoforms representing deposition on lateral accretion bars (Bridge, 2003).

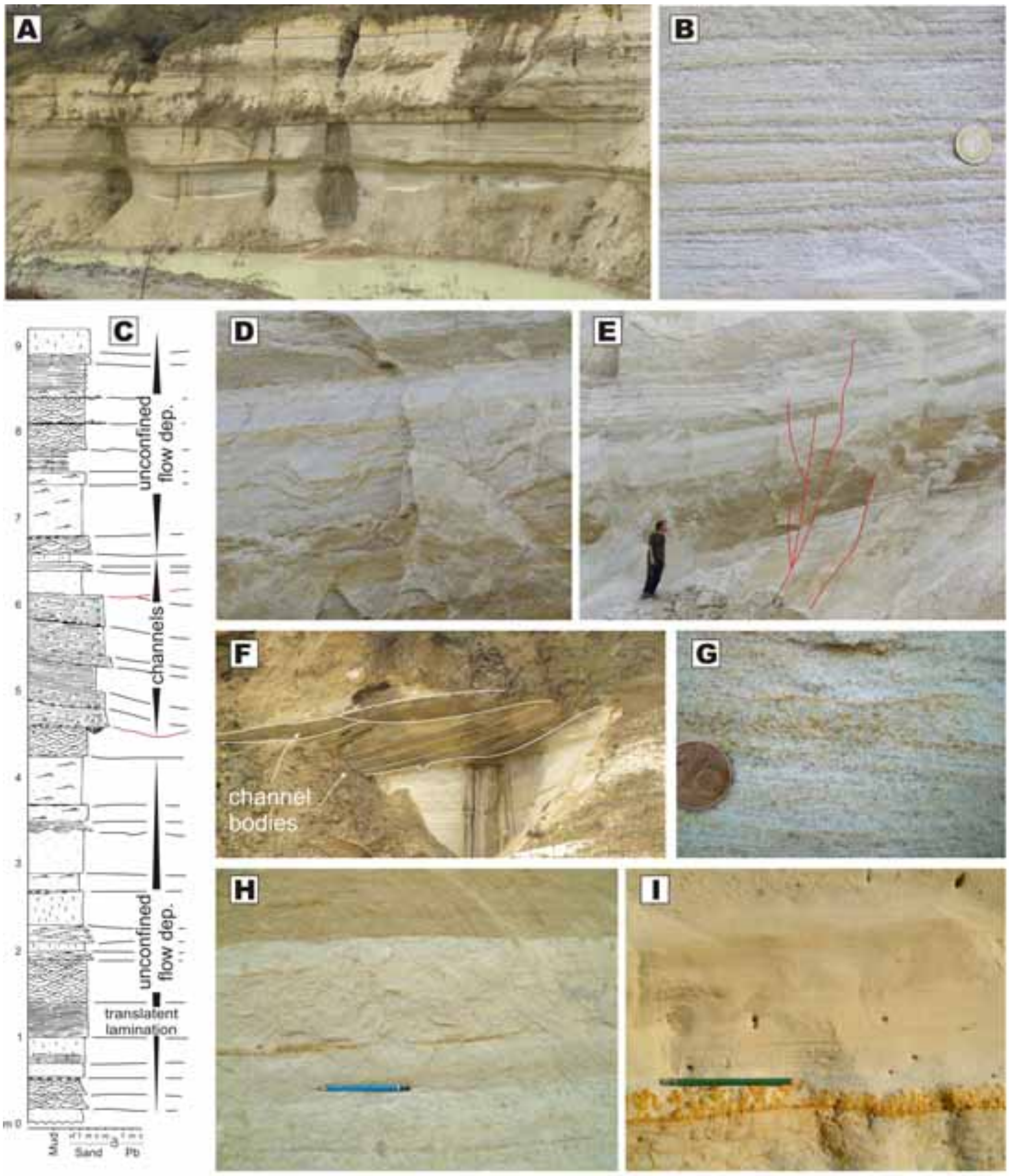

Fig. 2.16 – Unit VRC.b tabular sandy deposits in the S. Giovanni Valdarno area. A) Alternation between moderately sorted (brownish) and well sorted (whitish) sandy beds. B) Plane-parallel strata showing internal inverse grading. C) Sedimentological log. D) Load deformations (probably footprints) within VRC.b deposits. D) Syn-sedimentary faults affecting unit VRC.b deposits. E) Channel bodies showing lateral accretion surfaces. G) Isolated eolian ripple forms with coarser grains concentrated in the crest zone. H) Thin mud drapes showing dissiccation cracks. I) Iron incrustations capping sandy bed and showing a complex, dendritic geometry.

The abundance of sheet-like deposits with respect to channel-fill deposits, together with the high W/D ratio of channels suggests the deposition in a terminal fan setting, characterized by the presence of ephemeral channelized streams during the main flood events. The widespread occurrence of wind-worked deposits testifies periods of dry conditions during which eolian processes affected the previously accumulated alluvial sediments. Ciclic variability in humidity conditions and ground-water oscillations has been registered by iron oxides incrustations (Ghinassi et al., 2004).

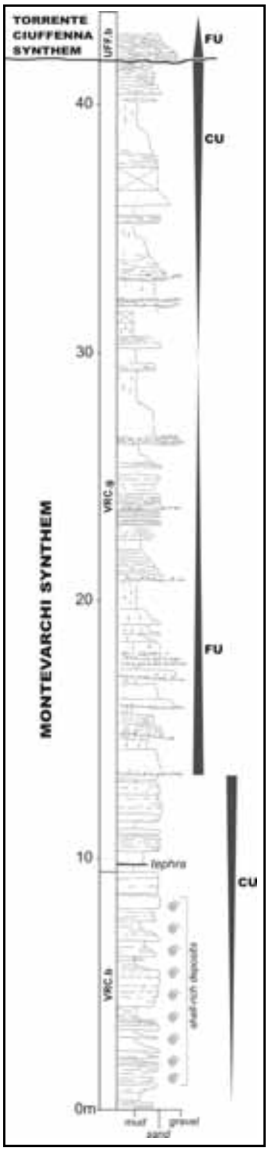

Fig. 2.17 - Sedimentological log across the VRC synthem in the S. Cipriano area.

Unit VRC.b mainly occupies the depression comprised between the Caposelvi fan (VRC,a) and the S. Cipriano topographic paleo-high, where gravelly alluvial fan deposits coeval with the Caposelvi system are not present. Minor outcrops of these deposits are located in the Figline Valdarno area.

2.3.2.3 Unit VRC.c

Unit VRC.c (Sabbie e Limi di Montecarlo in Ghinassi et al., 2005) is 15 m thick and, in plain view, forms a continuous belt slightly oblique (ENE-WSW) to the modern basin axis between S. Giovanni Valdarno and Figline Valdarno. It mainly consists of tabular sandy deposits rich in freshwater shells (Ghinassi et al., 2005). In the S. Cipriano area, the VRC.c sandy facies interfingers with and covers shell-rich muddy deposits defining a clear CU trend (**Fig. 2.17**). The occurrence of a taxon belonging to a primary marine family (*Mugilids*), in the fish assemblage recovered from these deposits, testifies the presence of a basin emissary (Ghinassi et al., 2005). In the Montecarlo and S. Cipriano areas (**Fig. 2.15** and **2.17**), unit VRC.c grades upward into muddy deposits of unit VRC.g.

Description

This unit consists of dominant sandy beds with subordinate muddy intervals, and is characterized by a high content in freshwater shells (**Fig. 2.18D**). Sandy beds, up to

20 cm thick, are commonly massive, normally graded and erosively based. In places, they show a poorly defined plane-parallel stratification in their upper part, vertical root traces and oxidized top surfaces. These beds contain dispersed gastropod shells, which can form discontinuous strings or be concentrated in basal scours (**Fig. 2.18D**). In the upper part of the unit, the several bioclastic beds are present (**Fig. 2.18E** and **G**). These beds, up to 20 cm thick, are massive, erosively based and don't contain any bivalve shell in life position. Muddy deposits are massive, intensely bioturbated and contain plant debris and detritic shells, although rare bivalve shells in life position have been find (**Fig. 2.18F**). The VRC.c unit is characterized by a cyclic alternation between sandy deposit rich in shell debris and fines sediments containing a minor amount of shells. In the S. Cipriano area, the lower part of the unit is dominated by muddy lithologies, which are locally characterized by a thin horizontal lamination (**Fig. 2.18B**) and by the presence of layers rich in Caracee algae (**Fig. 2.18A**).

Interpretation

Unit VRC.c represents distal alluvial fan deposits dominated by sheet-like beds. Massive, normally graded and erosively based sands are interpreted as highly concentrated, expanding, unconfined turbulent flow deposits (Benvenuti and Martini, 2001), locally entraining fresh-water shells hosted in the main channels (Ghinassi et al., 2005). Root traces and oxidation features testify subaerial exposure (Miall, 1996). Bioclastic beds, made of broken or inarticulated bivalve shells, formed by the expansion of unconfined turbulent flows (Ghinassi et al, 2005). These beds are interbedded with bioturbated muddy deposits, suggesting the accumulation of bioclastic-charged flows into small ponds (Ghinassi et al., 2005). Thinly laminated muddy deposits characterizing the base of the succession in the S. Cipriano area are interpreted as lacustrine deposits accumulated by fallout of fines, as attested by the presence of algae-rich layers.

Paleocurrent directions indicate thatunit VRC.c sandy flows were fed from the Chianti ridge (Ghinassi and Magi, 2004) and mainly reworked the underlying VRC.b deposits.

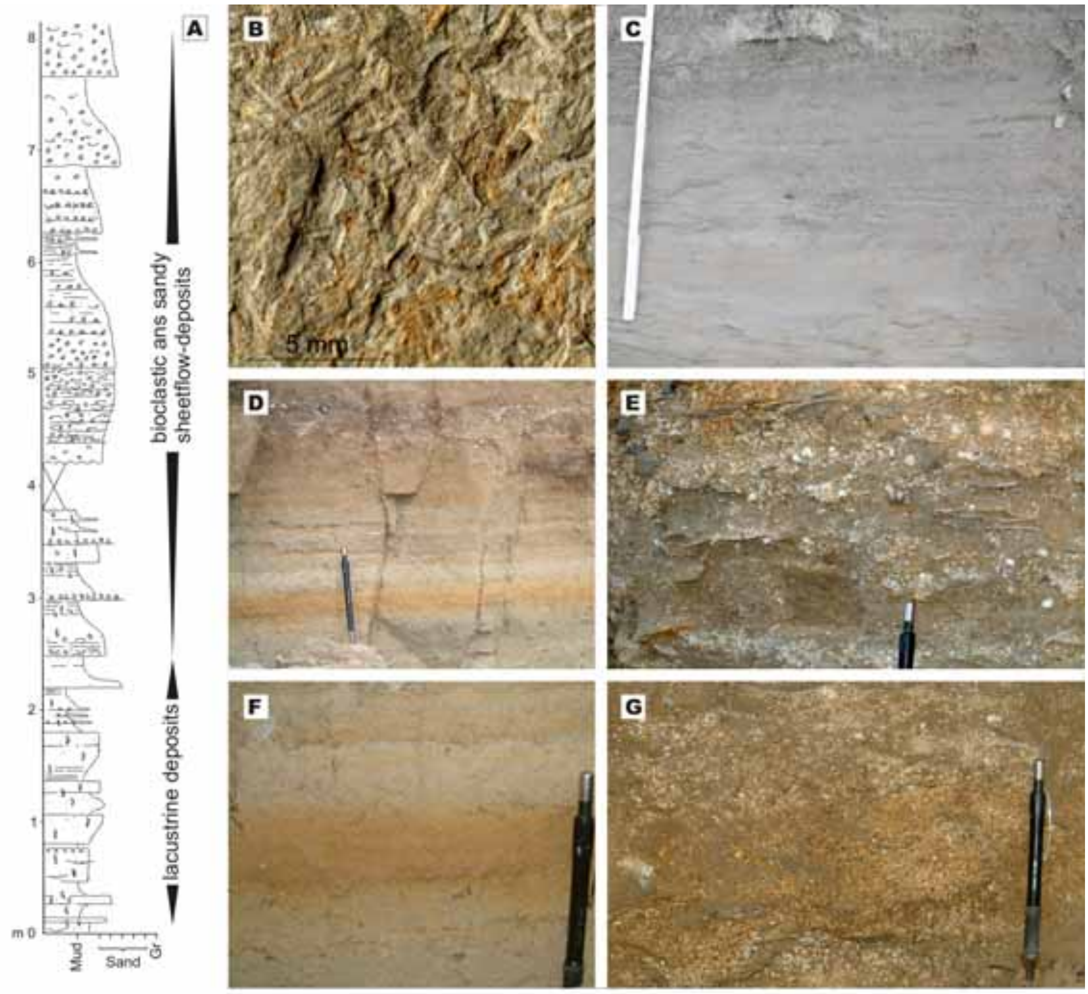

Fig. 2.18 – Unit VRC.c deposits. A) Sedimentological log from the S. Cipriano area. B) *Caracee* algae fragments on the top surface of a muddy layer. C) Thinly laminated muddy deposits characterizing the lowermost part of the succession in the S. Cipriano area. D) Sandy and muddy tabular beds interbedding with soured layers filled by shell fragments. E) Bioclastic beds (detail). F) Massive muddy deposits. G) Bioclastic beds.

2.3.2.4 Unit VRC.d-f

Units VRC.d-f (Limi di Terranuova, Argille del T. Ascione and Limi e Sabbie del T. Oreno, *Auctt.*) occupies the central part of the basin (**Fig. 2.19**). The maximum measured thickness of unit VRC.d is about 30 m (**Fig. 2.19**), but it is supposed to be higher close to the NE margin, where the base of the unit is not visible. Unit VRC.e and VRC.f show a maximum thickness of 20 m and 15 m respectively.

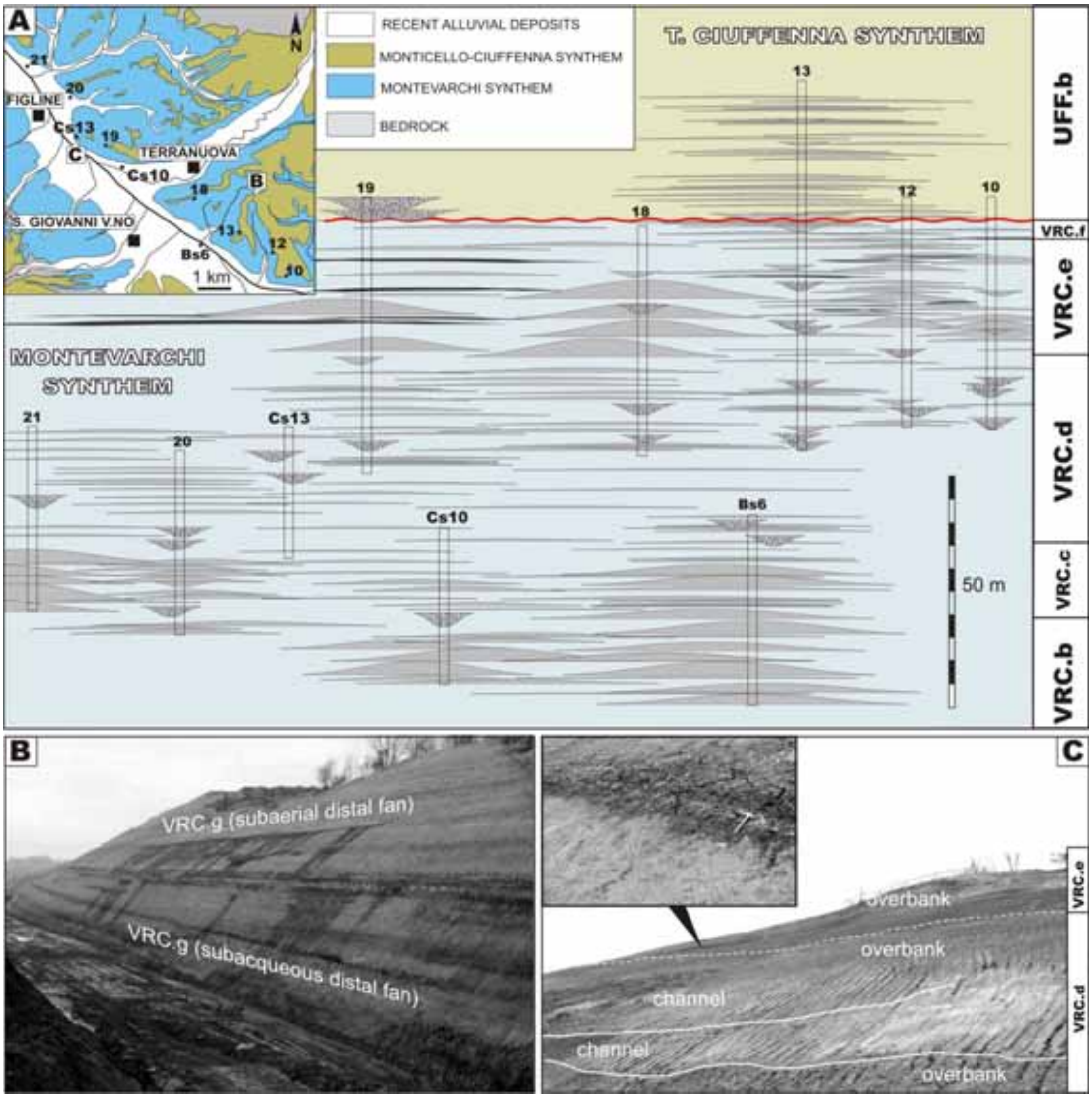

Fig. 2.19 - (A) Borehole data from the hilly area flanking the NE side if the Arno river (see inset map for location of wells). Note that units VRC.b and c have been recognised below the modern alluvium of the Arno River. (B) Fan-delta deposits in the Galleria Tasso section (see inset map for location). (C) VRC.d mud with isolated sandy channels covered by VRC.e mud bearing lignite layers.

Description

VRC.d-f units consist of muddy deposits containing discontinuous sandy intervals. Muddy deposits are characterized by poorly distinguishable bedding. They consist of massive mud with abundant pedogenic carbonate concretions and root remains (**Fig. 2.21D**). Isolated muddy layers, up to 1 m thick, lack pedogenic evidences and are rich in organic matter and plant debris (**Fig. 2.20**). The most common sandy deposits are represented by lensoid lithosomes with erosional, concave base and flat top (i.e. channel forms). These lithosomes, up to 4 m thick and 25-30 m wide, show a clear fining upward trend (from fine pebbles to mud) and consist of large scale inclined beds defining wedge-shaped sets (**Fig. 2.21C-E**). Beds dip about 15°-20° toward the basal surface and consist of plane-parallel, trough-cross, and ripple-cross stratified sand (**Fig 2.21B**) giving rise to a compound stratification (*sensu* Harms, 1975). Palaeotransport direction from cross strata and from the basal gravels was transverse to the beds dipping. Trough-cross stratification is more common in the lower part of the lensoid units, whereas plane-parallel stratification and ripple-cross lamination occur mainly in the upper part. In several places, these cross-bedded units are plugged by muddy deposits (**Fig. 2.21E**), which lack pedogenic evidences and contain plant debris. Subordinate sandy deposits are represented by tabular, sub-horizontal beds up to 1 m thick (**Fig. 2.21F**). These beds are made of coarse to fine sand, which can be massive, plane-parallel or ripple-cross stratified. Beds are commonly normal graded and erosively based, and, in places, are affected by pedogenetic processes in their uppermost part. The ratio between sandy and muddy deposits is similar in unit VRC.d and f, whereas mud is clearly dominant in unit VRC.e, where organic-rich muddy deposits are very common.

Interpretation

Units VRC.d-f represent alluvial deposits accumulated by the basin axial drainage system characterized by relatively high sinuous channels (Bridge, 2006). Pedogenized, rooted fines are interpreted to represent floodplain muds derived by sediment fall-out during periodical episodes of flooding (Bridge, 2003). These fines alternate with tabular sandy beds deposited by expanding, unconfined, turbulent flows, such as crevasse splays (Ethridge et al., 1981; Allen et al., 1983), and with organic-matter rich layers produced by plant debris accumulation in floodplain ponds and lakes (Basilici, 1997), as attested by the lack of pedogenic features. Sandy lensoid units represent channel-fill deposits (Bridge, 2003). The large scale, wedge-shaped clinoforms contained within these bodies are interpreted as meander point bars (Jackson, 1976; Nanson, 1980; Brierley, 1991), as suggested by the spatial architecture of facies and by the paleocurrent orientation with respect to the beds dip direction. Muddy deposits on top of channel-fill sequences accumulated by sediment fall-out after episodes of avulsion and channel abandonment (Bluck, 1980).

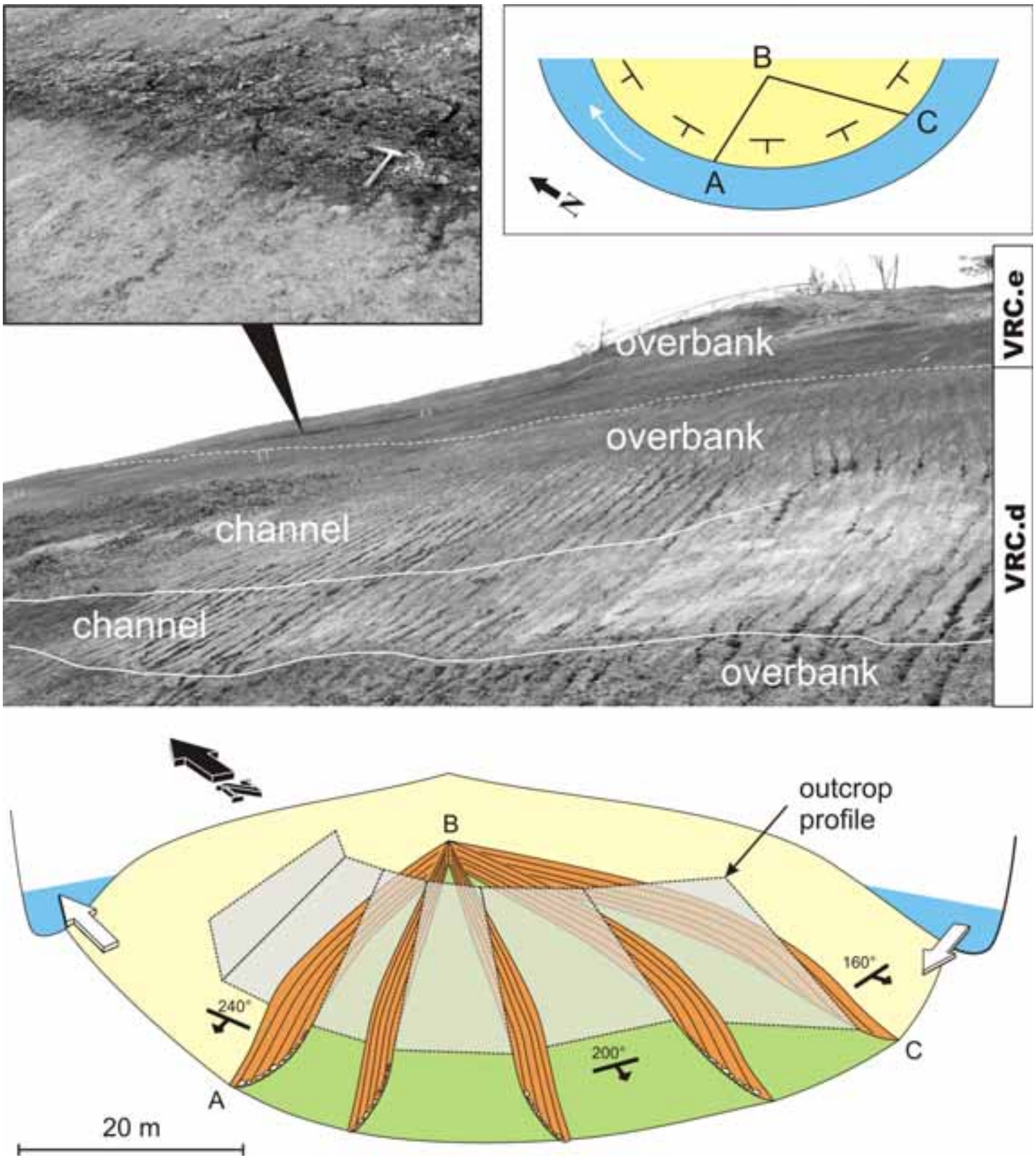

Fig. 2.20 – Units VRC.d-e fluvial deposits close to Terranuova Bracciolini and geometrical reconstruction of a lateral accretion bar (point-bar). Bar reconstructionhas been obtained by the measurement of five e logs qually spaced along the outcrop.

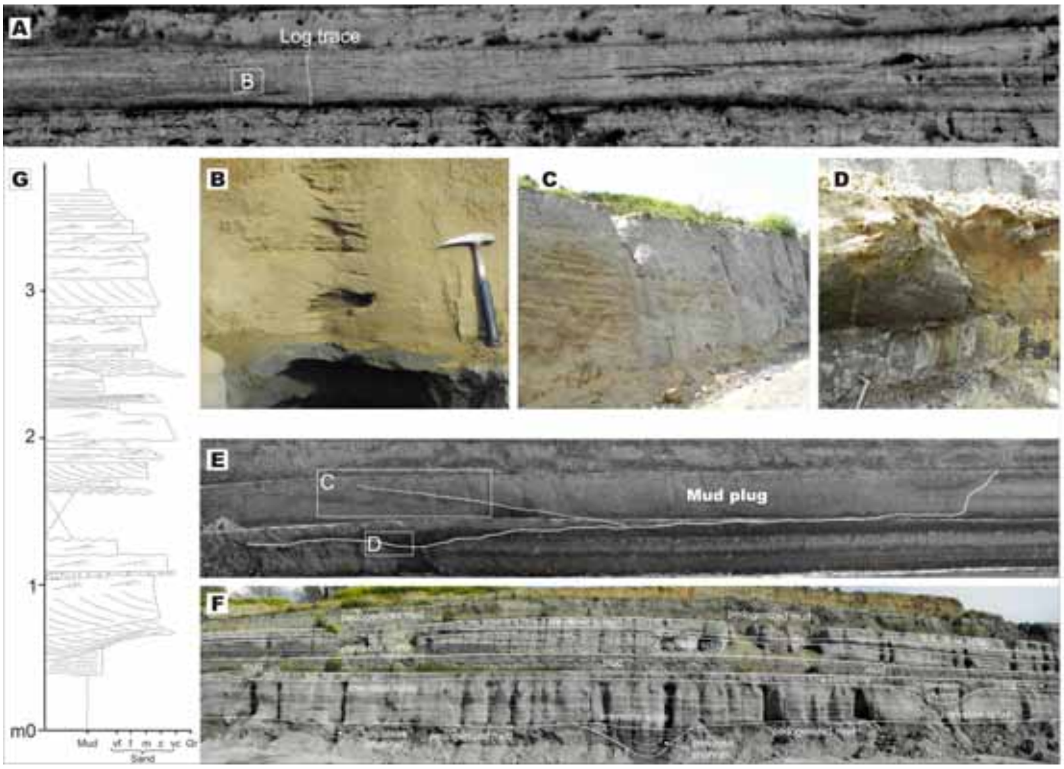

Fig. 2.21 – Unit VRC.f fluvial deposits in the Matassino quarry. A) Photomosaic showing a sandy channel body hosted within floodplain muds. B)Trough-cross stratified sands in the basal part of the channel. C) Large scale, wedge-shaped cross bedded unit interpreted as a point-bar. D) Channel base cutting pedogenized floodplain muds. E) Photomosaic showing a wedge-shaped cross-bedded unit plugged by meddy deposits. F) Photomosaic showing alternating tabular sandy and muddy beds interpreted as overbank deposits.

Although several Authors interpreted these sediments as lacustrine-palustrine deposits (e.g. Sestini, 1934; 1936; Merla and Abbate, 1967; Azzaroli and Lazzeri; 1977; Abbate et al., 1983; Magi and Sagri, 1992; Albianelli et al., 1995), stratigraphic and sedimentological evidences indicate a fluvial depositional environment. They consist of floodplain mud hosting isolated sandy lenses accumulated in relatively to high-sinuous channels. Units VRC.d and f show a relative dispersion of channelized bodies within floodplain mud, which is affected by a marked pedogenesis. Unit VRC.e is typified by a higher dispersion of channelized bodies within the floodplain mud, which is characterized by accumulation of laterally continuous, organic-rich layers emplaced in floodplain lakes. The VRC.d-f succession records condition of relatively high accommodation (Martinsen et al., 1999; see Chapter 4), which is maximum during deposition of unit VRC.e, as attested by higher dispersion of channelized bodies and development of lacustrine facies in the floodplain areas. The orientation of channelized bodies, along with paleocurrent data, suggests the axial fluvial system drained toward N-NW.

2.3.2.5 Unit VRC.g

Along the basin margins, the axial deposits of unit VRC.D-f interfinger with the marginal deposits of unit VRC.g (Ciottolami della Penna, Ciottolami e Sabbie di Casa Querce and Sabbie di Borro Cave, *Auctt.*). Along the Chianti margin, unit VRC.g unconformably overlays unit VRC.b, is up to 30 m thick and consists of sandy gravels showing a FU-CU trend (**Fig. 2.15** and **2.17**; see Chapter 4). Close to the Pratomagno margin (**Fig. 2.22**), the base of the VRC.g unit is not visible and only 50 m of deposits are exposed. The lower part of this unit mainly consists of sandy deposits, which pass laterally into unit VRC.e. Along the NE margin the succession shows a clear CU trend capped by a minor FU interval (**Fig. 2.23**; see Chapter 4).

Description

This unit consists of vertically stacked gravelly and sandy intervals, giving rise to different depositional trends (see Chapter 4).

The gravelly deposits consist of multistorey lensoid units of moderately to well rounded clast-supported pebble to boulder size gravels with rare sandy intercalations (**Fig. 2.24A**). Lensoid bodies are up to 2 m thick and 25-30 m wide and show an erosional basal surface floored by imbricated a(t)b(i) clasts (**Fig. 2.24D**). Within these units, plane-parallel stratified, clast-supported, gravelly beds (10-20 cm thick) are stacked vertically to form coarsening upward packages (**Fig. 2.24H**), typically up to 1 m thick. Paleoflows is parallel to the sediment bodies axis. In other cases, plane-parallel stratified, clast-supported, gravelly beds are gently inclined toward the axis of the lensoid body (**Fig. 2.24C**).

In these cases, palaeotransport is transverse to gently oblique to the main dip direction. Normal graded, cross-stratified, clast-supported gravels with strata dipping about 25°-30° parallel to the main transport direction are rare. Close to the basin margin, these lensoid bodies can contain massive, poorly sorted pebble to boulder gravel tabular beds up to 40 cm thick, bearing a variable amount of interstitial sandy matrix (**Fig. 2.24I**). These beds are disorganized to crudely normally graded with a common a(i)a(p) clasts imbrication, and seldom inversely graded, with an a(p) or a(p)a(i) fabric of elongate clasts.

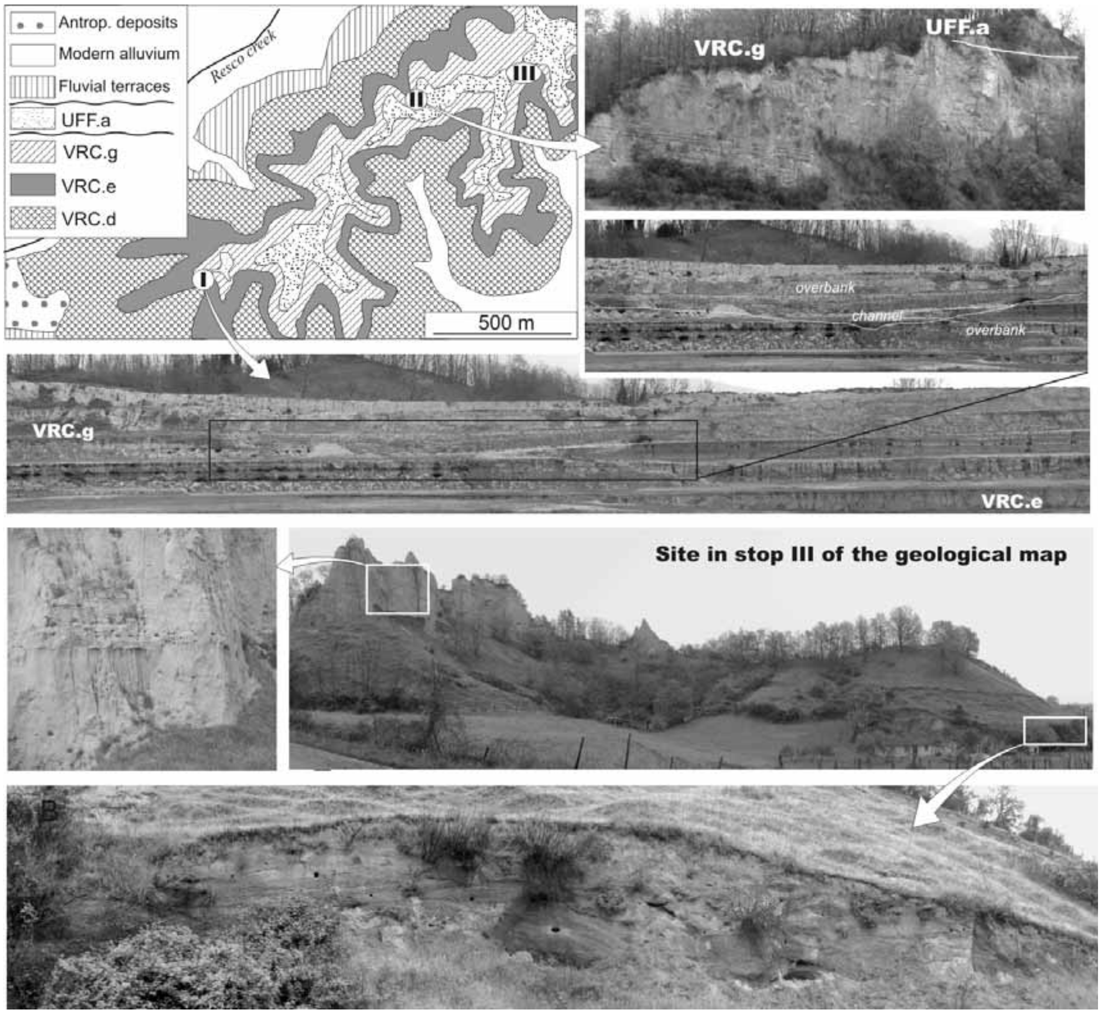

Fig. 2.22 - Interfingering between alluvial-fan (VRC.g) and fluvial (VRC.e-f) deposits in the Resco Creek area. Sites I and II show coeval fluvial and distal alluvial fan deposits respectively. In site III, sandy facies of unit VRC.g cover deposits of unit VRC.e as a consequence of alluvial-fans progradation over the axial alluvial plain.

Sandy intervals range from gravelly to muddy sand and grade to gravelly deposit both vertically and laterally (i.e. upcurrent). The gravelly/sandy deposits consist of vertically stacked tabular sandy beds truncated by sandy or, less frequently, gravelly lensoid bodies with erosive concave base and flat top (**Fig. 2.24E**). Tabular sandy beds are medium-to-coarse grained with dispersed pebbles. Bedding is commonly faintly observable due to extensive bioturbation, root traces and pedogenetic processes. The sandy lensoid units, up to 1.5 m thick and 10-15 m wide, are often floored by pebble-size gravels and show a fining upward trend. Overlying deposits consists of 5-15 cm thick inclined beds (5°-10°) of coarse- to medium-grained sand. Beds can be plane-parallel stratified or ripple-cross laminated, and indicate a palaeotransport mainly oblique to the beds dipping. The gravelly lensoid units are similar to those occurring in the gravelly interval, but show a higher W/D ratio. Massive deposits are rare, and most of the beds show a diffuse plane-parallel stratification. These beds, up to 10 cm thick, are commonly tabular and vertically stacked into form coarsening upward packages, typically up to 50 cm thick. In places, gravelly beds are gently inclined (10°-15°)

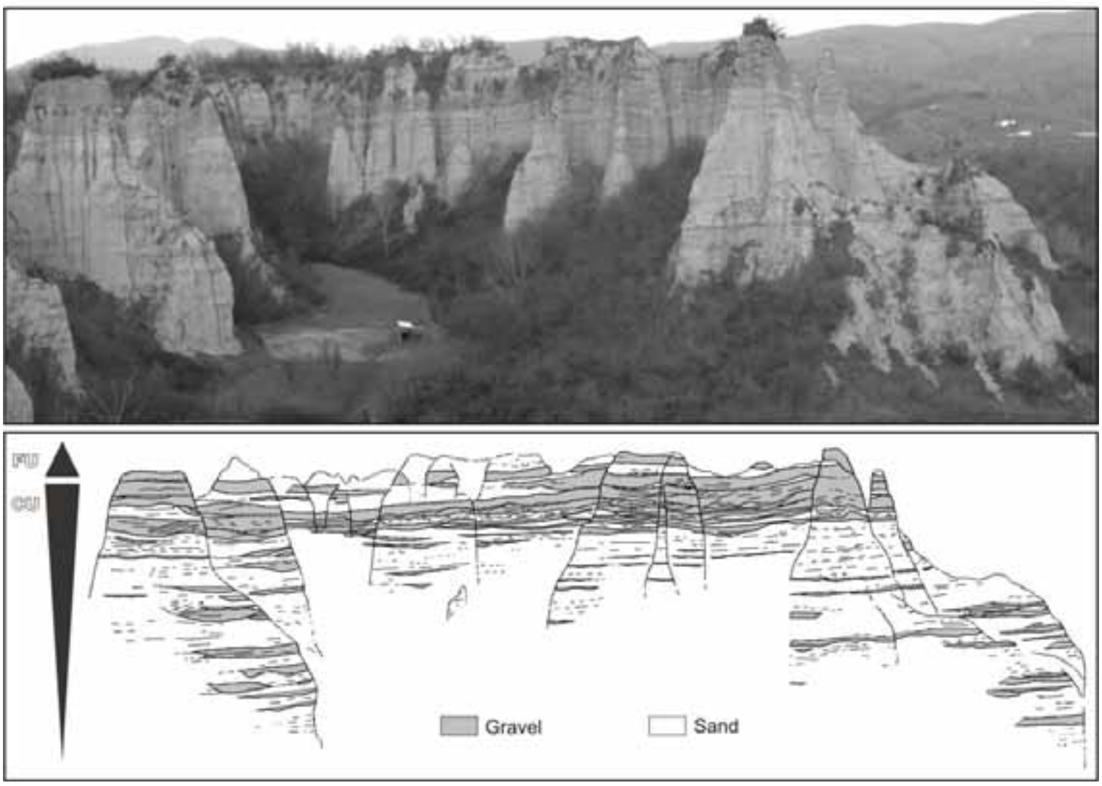

Fig. 2.23 - Alluvial-fan deposits of unit VRC.g in the Castelfranco di Sopra area. Note the CU-FU trend resulting by progradation and following backstep of the alluvial-fan system.

toward the axis of the lensoid body. The muddy/sandy deposits mainly consists of tabular, sub-horizontal deposits with rare lensoid sandy bodies. Tabular sandy beds are fine-to-coarse grained. Bedding can be locally masked by bioturbations or pedogenetic processes (**Fig. 2.24F**), but it is well defined where laterally persistent muddy layers occur. These layers lack of pedogenic evidences and are rich in organic matter and plant debris (**Fig. 2.24G**). Rare sandy lensoid bodies are 20-50 cm thick and 10-15 m wide. They show an erosional, concave base and flat top, and are commonly floored by fine pebbles. The inclined sandy beds (5°-10°) overlying the basal gravelly pavement are commonly rippled or plane-parallel stratified.

Interpretation

Unit VRC.g sediments are interpreted as alluvial fan deposits. Gravelly deposits accumulated in a proximal fan setting. In this framework, lensoid conglomerate bodies represent channel-fill deposits. Gravels with an a(t)b(i) imbrication flooring the erosional basal surface of channels are interpreted as channel-lag deposits (Miall., 1985). Channel-fill deposits typically consist of a variety of sedimentary bodies. These range from longitudinal bars (Boothroyd & Ashley, 1972), represented by the CU packages of horizontally stratified, clast-supported gravel, to lateral accretion bars (Lewin, 1976; Bridge, 1993), represented by the gently inclined cross-bedded units dipping towards the channel axis, to subordinate transverse bars, which consist of steeply inclined, clast-supported gravel beds dipping downstream. Massive, mainly disorganized, matrix-rich, ungraded-to-inversely graded conglomerates deposited by debris flows (Nemec and Steel, 1984) and slightly stratified, normally graded, erosively based conglomerates deposited by hyperconcentrated flows (Smith, 1986; Benvenuti and Martini, 2001) are hosted within the channel bodies in the most proximal areas, close to the basin margin.

Sandy intervals accumulated in intermediate/distal alluvial fan setting. These mainly consist of sheet-like overbank deposits, accumulated in intrachannel setting and represented by pedogenized, tabular sandy beds, produced by expanding sheetflows during flood events. These deposits are truncated by sandy and gravelly lensoid units, interpreted as channel deposits. In sandy channels the lateral migration of bank-attached bars over a channel lag, represented by the gravelly pavement, gave rise to gently inclined cross-bedded units, as attested by beds attitude and paleotransport direction (Bridge, 2003). In gravelly channels migration of longitudinal bars gave rise to horizontally bedded, coarsening-upward packages of graves (Boothroyd and Ashley, 1975), while subordinate cross-sets are interpreted as produced by the lateral migration of bank-attached bars (Lewin, 1976; Bridge, 1993).

Muddy/sandy intervals accumulated in areas where the distal reaches of the alluvial fan systems interacted with small lakes developed at the axial floodplain margins (Billi et al., 1991). Muddy layers within muddy/sandy deposits accumulated by sediment fallout in a subaqueous setting during periods of low sediment supply (Colella, 1988), as attested by the lack of pedogenic features and by the abundance of organic matter (Basilici, 1997). These muds are interbedded with tabular sandy beds produced by unconfined flows expanding both in a subaerial or subaqueous environment: the former typically show pedogenic and oxidation features, the latter are not affected by these processes but show intense burrowing. Within sandy lesoid bodies, interpreted as channels, the gravelly pavement represents the channel lag (Miall, 1985), while the gently inclined cross-sets formed by the lateral migration of sandy bars (Bridge, 2003).

Along the Chianti margin muddy/sandy deposits representing the finer sediments of the FU-CU trend interfinger with the axial VRC.e unit, and, 1.5-2 km far from the margin, show an interaction between the Chianti-sourced fans and shallow pools developed along the margins of the axial floodplain (**Fig. 2.15**). The same interaction is recorded in the lowermost part of the exposed succession along the NE margin (**Fig. 2.24G**). These muddy/sandy deposits represent the shallow-water fan deltas described by Billi et al. (1991), but they constitute the only evidence for the accumulation of fan-delta deposits within the basin succession.

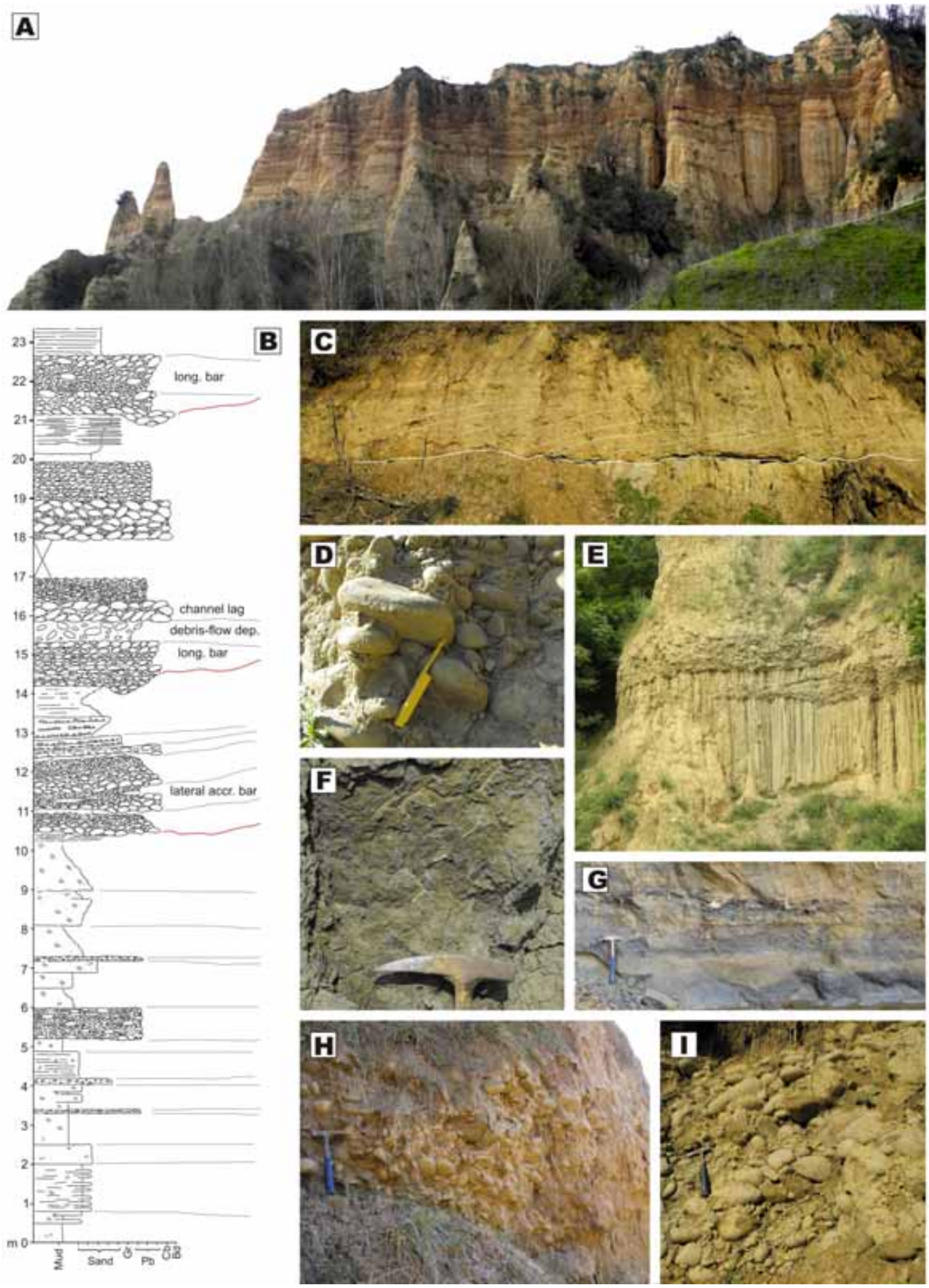

Fig. 2.24 – Unit VRC.g alluvial fan deposits. A) Photomosaic showing the exposed succession in the Castelfranco di Sopra area. B) Sedientological log measured close to La Penna village. C) Lateral accretion bar within a gravelly channel. D) Cluster of a(t)b(i) imbricated gravels. E) Lens-shaped channel bodies hosted within tabular sandy deposits. F) CU packages of horizontally bedded gravel accumulated by the downstream migration of longitudinal bars. I) Disorganized debris-flow deposits showing inverse grading and poor sorting.

2.3.3 Torrente Ciuffenna Synthem (UFF)

The Torrente Ciuffenna Synthem is up to 80 m thick and is exposed at the basin scale with a sub-horizontal attitude. It consists of axial deposits of unit UFF.a (**Fig. 2.25D**) interfingering with margin-fed deposits of unit UFF.b (**Fig. 2.25B**). Both axial and marginal units are covered by unit UFF.c deposits. The Torrente Ciuffenna Synthem deposits spread over the bedrock ridge separating the Valdarno from the adjacent Palazzolo Basin close to Incisa Valdarno.

Although the palinological record from the Torrente Ciuffenna Synthem is fragmentary, due to lithological and taphonomic conditions, these deposits seem to have been accumulated during alternating climatic phases, ranging from temperate to cool-temperate, with different humidity values (Bertini, 1994; Albianelli et al., 1995; Sagri et al., in press). The Brunhes paleomagnetic event has been detected in the middle part of this Synthem (Napoleone et al., 2003) and dates the succession to the upper part of Middle Pleistocene.

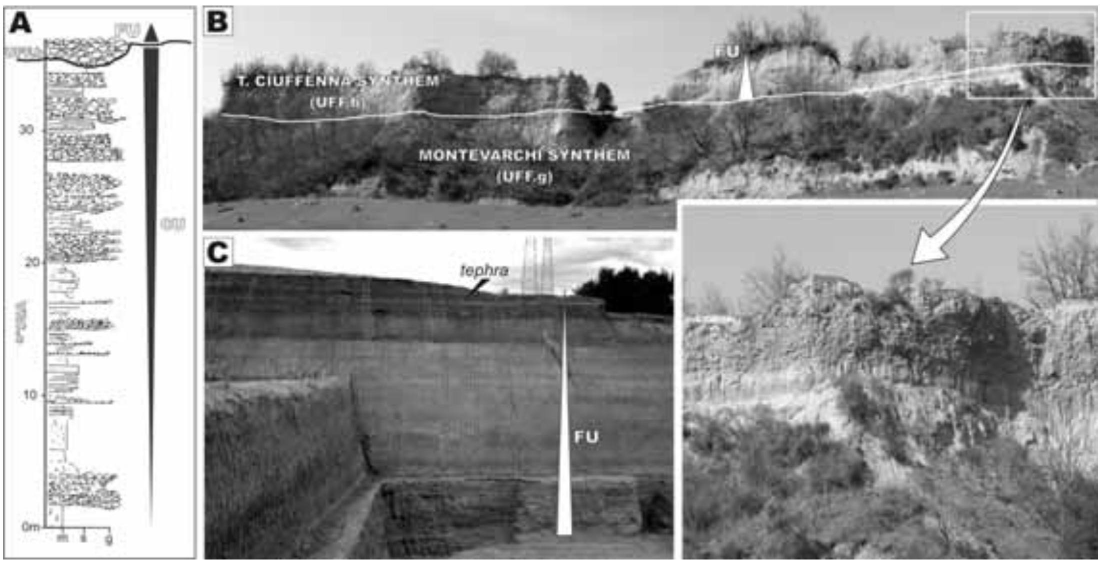

Fig. 2.25 - Alluvial deposits of the Torrente Ciuffenna Synthem. (A) FU alluvial-fan deposits of unit UFF.b unconformably overlaying the CU deposits of unit VRC.g in the Montemarciano area. (B) Panoramic view of the outcrop where the log shown in A was measured. Note the abrupt surface at the base of Monticello Synthem. (C) Fining upward fluvial succession of unit UFF.a in the Acquaborra area. Note the whitish tephra layer in the upper part of the succession.

2.3.3.1 Unit UFF.a

In the Monticello area, unit UFF.a (including Ciottolami di Laterina, Sabbie di Levane and Limi di Latereto, *Auctt.*), ranging between 30 and 50 m in thickness, is made of gravels passing upward into sandy deposits. These deposits, which show a transport direction toward W-NW, pass downstream into a sandy succession cropping out in the S. Giovanni Valdarno area.

Description

In the Monticello area, Unit UFF.a is about 30 m thick and consists of three stacked (Billi et al., 1987) subunits separated by sharp, gently erosional surfaces. The first two subunits are mainly made of gravels and show similar sedimentary features, whereas the third subunit is exclusively sandy (**Fig. 2.26C**). The first and the second subunits consist of multilaterally arranged gravelly bodies showing a flat top and a planar to concave-upward base (i.e. channel forms). In sections that are nearly perpendicular to the overall paleotransport direction, gravelly bodies are up to 8 m thick and several tens of meters wide, and consist of superimposed sets of large scale-inclined beds. In sections perpendicular to the transport direction, wedge-shaped (more common) and convex-upward (less common) sets can be distinguished. In convex-upward sets beds dip (5°-8°) in opposite directions into defining mounded units up to 2 m thick and 15 m wide, whereas in wedge-shaped bed sets, beds dip (5°-10°) constantly toward the same direction forming units up to 3 m thick and a few tens of meter wide. Convex-upward bed sets, commonly floored by well imbricated a(t)b(i) pebbles, are mainly made of plane-parallel stratified pebble beds. Wedge-shaped bed sets show a gentle fining upward trend, given by a gently increase in sand content. Also these beds mainly consist of plane-parallel stratified pebbles. Convex-upward and wedge-shaped bed sets are commonly associated within the same body. The third subunit is made of multilaterally arranged sandy bodies showing a flat top and a planar to concave-upward base (i.e. channel forms). In sections perpendicular to the main transport direction, gently (5°-10°) dipping sandy beds define wedge-shaped sets up to 3 m thick and several tens of meters wide. These sets show a fining upward trend, from gravelly coarse sand to very fine sand. Beds are mainly trough-cross stratified in the lower part of the set, and plane-parallel stratified to ripple-cross laminated in the upper part.

Several sets of large scale inclined beds, dipping toward different directions can occur within the same sandy body.

In the S.Giovanni Valdarno area, located downcurrent with respect to the Monticello outcrops, the partition of unit UFF.a into three subunits is still possible. The lower subunit is made of gravelly sand, whereas the second and third subunits are silty/sandy. The lower subunit consists of multilaterally arranged gravelly bodies showing a flat top and a planar to concave-upward base. Despite difference in grain size, the internal geometries of these sandy bodies are similar to those of the previously described gravelly deposits (e.g. presence of wedge-shaped and convex-upward sets). The second and the third subunits are made of multilaterally arranged bodies showing a well-defined fining upward trend, from gravelly sand to silt (**Fig. 2.26B**). These bodies are up to 7 m thick and show a flat base and top at the outcrop scale, although a proper description of their geometries would requires wider outcrops. In sections that are nearly perpendicular to the overall palaeotransport (i.e. NW) these bodies are entirely made of large scale inclined (10°-15°) sets constantly dippind toward the same direction and forming units at least 100 m wide. The lower part of these sets is made of trough-cross stratified gravelly sand with minor internal truncations. The upper part is dominated by rippled to plane-parallel laminated fine sand passing upward into pedogenized silty sand. Palaeotransport from the basal stratified gravelly sand was almost transverse to the beds dip direction.

Interpretation

Unit UFF.a represents fluvial deposits accumulated by the axial drainage system. The internal subdivision of the unit in three subunits reflects a change in channels patterns, sinuosity and fluvial architecture, both in temporal (i.e. stratigraphical) and spatial (i.e. downcurrent) terms.

Referring to the upstream portion of the studied system, the wedge-shaped gravelly units recognized as the most common features in the Monticello area are interpreted as lateral accretion bars (Lewin, 1976; Bridge, 1993; Billi et al., 1991), because of the bed dipping perpendicular to the main transport direction and the FU trend of beds, whereas the convex-upward gravelly units represent mid-channel,

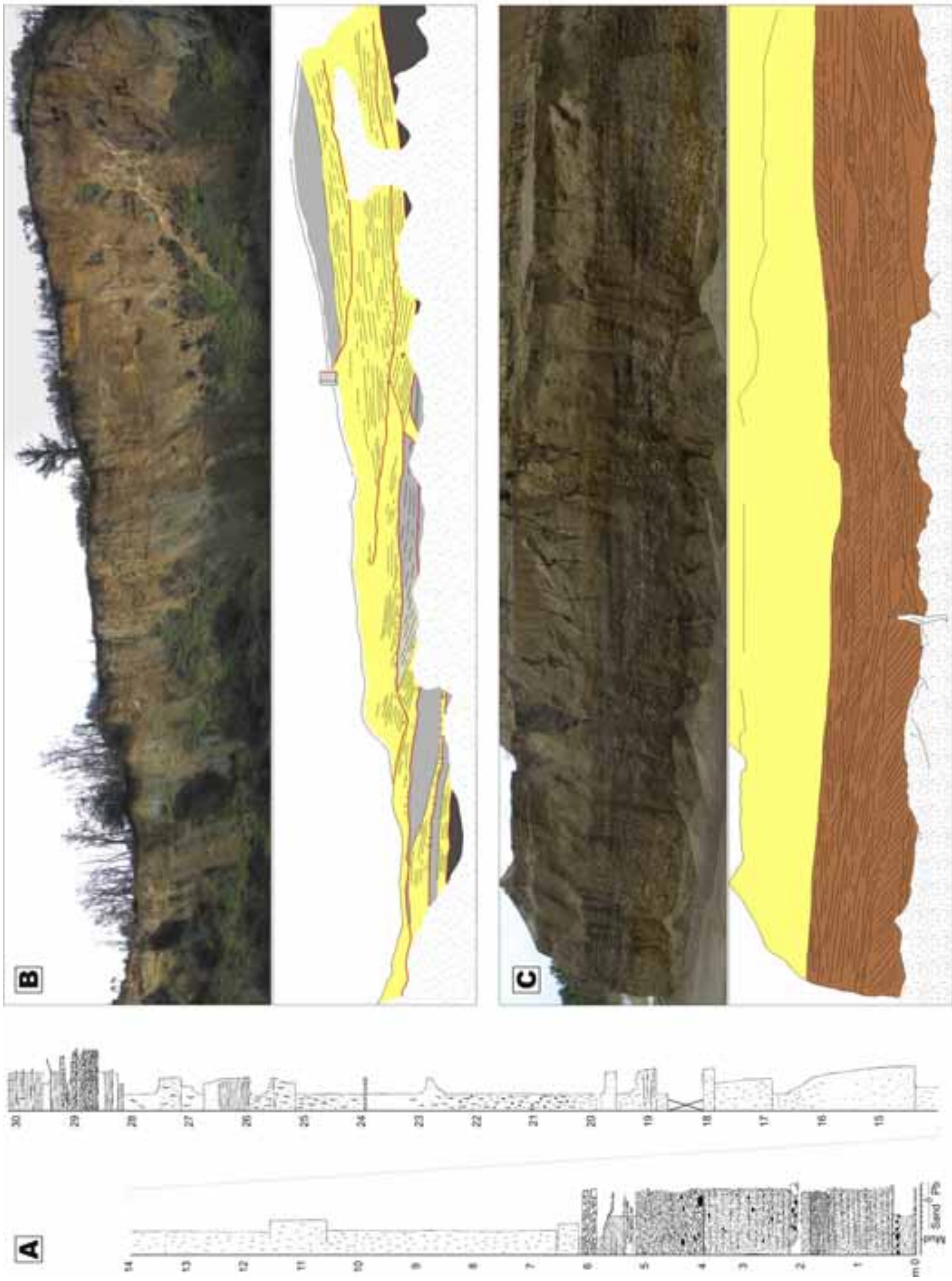

Fig. 2.26 – Unit UFF.a fluvial deposits. A) Sedimentological log across unit UFF.a succession in the Monticello area. B) Photomosaic and linedrawing showing relatively high-sinuosity fluvial deposits in the S. Giovanni Valdarno area. C) Photomosaic and linedrawing showing low-sinuosity fluvial deposits in the Laterina area (Vitereta quarry).

longitudinal bars (Boothroyd & Ashley, 1975; Miall, 1977) with no evidence of avalanching processes, as suggested by the gentle inclination of beds. The first ones built up by progressive accumulation of sediment from the upstream part of the bar to the downstream part, and from the lowermost part to the uppermost, giving rise to FU inclined beds of gravels. The second ones built up by the downstream migration of the bar head, made of coarse material, over the bar tail, where finer grains accumulate in the hydraulic shadow produced by the head.

Close to San Giovanni Valdarno the whole deposits become sandier. Within the lowermost subunit channel forms are characterized by the occurrence of both lateral accretion bars (wedge-shaped bodies) and mid-channel bars (convex-upward bodies); on the other hand, the uppermost portion of the UFF.a succession here is characterized by the presence of large scale, FU cross-bedded sets whose dipping direction is at high angle with respect to the main paleotransport direction, interpreted as meander point bars (Jackson, 1976; Nanson, 1980; Brierley, 1991).

According to that, close to Monticello the relative abundance of lateral accretion bars with respect to mid-channel bars increases passing from the first two subunits to the third one, where lateral bars become highly predominant, recording a significant increase in channels sinuosity. The same stratigraphic transition is evident also in the San Giovanni Valdarno area (i.e. downstream), where the two basal subunits are characterized by the presence of both sandy mid-channel bars and lateral accretion bars, while the uppermost unit is uniquely made of large-scale point bars.

2.3.3.2 Unit UFF.b

Unit UFF.a deposits interfinger with and cover the UFF.b deposits (including Ciottolami di Loro, Sabbie del Tasso, *Auctt.*), which are sourced from the margins. These show a clear FU trend, and reach a maximum thickness of 35 and 60 m along the Chianti and Pratomagno margin respectively (see Chapter 4 for discussion).

Description

Unit UFF.b consists of a basal gravelly interval passing upward into gravelly/sandy deposits. The basal gravelly interval (up to 40 m thick along the

Pratomagno margin) is made of multistorey lensoid gravelly units. Individual lenses (up to 3 m thick and 20 m wide) have a flat top and an erosional, concave-upward basal surface, typically floored by imbricated a(t)b(i) clasts. Gravels are moderately rounded and clast-supported, and range in size from pebble to boulder. The most common gravelly deposits forming these lenses are organized into form coarsening upward packages of vertically stacked, plane-parallel-stratified, clast- supported beds. These packages are up to 1 m thick and show a downstream decrease in grain size. Normal graded, cross-stratified, clast-supported gravels with 25°-30° inclined cross strata are less common, and are visible in section oblique to the lens axis. In rare cases, plane-parallel stratified, clast-supported, gravelly beds are gently inclined toward the axis of the lens. In these cases, palaeotransport was transverse to gently oblique to the main dip direction. Disorganized to crudely normally graded, and seldom inversely graded, gravelly beds (up to 1 m thick) with a a(i)a(p) clasts imbrications can be locally present within the lensoid units.

The gravelly/sandy interval (up to 20 m m thick along the Pratomagno margin) consists of vertically stacked tabular sandy beds truncated by sandy or gravelly lensoid bodies with erosive concave base and flat top. Tabular sandy deposits are medium-to-coarse grained with dispersed pebbles, both in clusters or strings. Bedding is faintly observable due to extensive pedogenetic processes. The sandy lensoid units, up to 2 m thick and few meters wide, show a fining upward trend and are characterized by a basal gravelly pavement. Overlying deposits consists of gently inclined (5°-10°) or sub-horizontal beds of coarse- to medium-grained, plane-parallel stratified sand. Inclined beds dip almost transverse to the main palaeotransport direction. The gravelly lensoid units are similar to those of the basal portion. Massive deposits are absent, and most of the beds show a diffuse plane-parallel stratification. These beds, up to 20 cm thick, are tabular and vertically stacked into form coarsening upward packages, typically up to 50 cm thick.

Interpretation

Unit UFF.b sediments are interpreted as alluvial fan deposits. The basal gravelly interval accumulated in a proximal fan setting. In this framework, lensoid conglomerate bodies represent channel-fill deposits. Gravels with an a(t)b(i) imbrication flooring the erosional basal surface of channels are interpreted as channel-lag deposits (Miall., 1985). Channel-fill deposits are typically made of a variety of sedimentary bodies. These range from longitudinal bars (Boothroyd and Ashley, 1975), represented by the CU packages of horizontally stratified, clast-supported gravel, to subordinate transverse or diagonal bars bars, which consist of steeply inclined, clast-supported gravel beds dipping downstream. Lateral accretion bars (Lewin, 1976; Bridge, 1993), represented by the gently inclined cross-bedded units dipping towards the channel axis, are rare. Disorganized, matrix-rich, ungraded-to-inversely graded conglomerates deposited by debris flows (Nemec and Steel, 1984) and massive, normally graded conglomerates deposited by hyperconcentrated flows (Smith, 1986; Benvenuti and Martini, 2001) are hosted within the channel bodies in the most proximal areas, close to the basin margin.

The gravelly/sandy deposits, mainly occurring in the middle part of the succession, represent intermediate alluvial fan deposits. Pedogenized tabular sandy beds are interpreted as accumulated by expanding, unconfined sheetflows, rapidly dumping their sediment load in a intrachannel setting during flood events. These tabular deposits are truncated by both sandy and gravelly channel deposits. In sandy channels, migration of longitudinal bars gave rise to horizontally bedded packages, while cross-bedded units formed by the oblique migration of bank-attached bars, as attested by the general dip of beds (Bridge, 2003). Gravelly channels are mainly filled by longitudinal bars, represented by the coarsening-upward packages of horizontally bedded gravels (Boothroyd and Ashley, 1975).

The occurrence of gravelly/sandy deposits, representing intermediate alluvial fan deposits, over gravelly sediments, representing proximal fan deposits, gives rise to the clear FU trend shown by unit UFF.b succession. This trend is interpreted as backstepping of the alluvial fan system (see Chapter 4).

2.3.3.3 UFF.c

The uppermost unit of the T.Ciuffenna Synthem (including Limi di Latereto, Limi di Pian di Tegna *Auctt.*) drapes the succession at a basin scale and has a maximum thickness of 20 m in the western reaches of the basin (**Fig. 2.26A**). Unit UFF.c outcrops are distributed between 250 and 280 m above the sea level, forming a relict surface representing the depositional top for the Plio-Pleistocene succession (lithostructural top surface; Bartolini, 1992).

Description

This unit is typically made of vertically stacked tabular muddy layers and interbedded sands. Muddy deposits show poorly distinguishable bedding. They mainly consist of massive silty mud showing intense pedogenetic features. Root traces are very common and carbonate, iron and manganese concretions are present. Isolated muddy layers, up to 1 m thick, rich in organic matter and plant debris and lacking of pedogenic evidences can occur within the succession. Rests of fresh-water mollusks may be present within these layers. Subordinate sandy beds, up to 1 m thick and fine- to coarse-grained, can show plane-parallel stratification or ripple-cross lamination, although sedimentary structures are commonly obliterated by pedogenesis. Beds are normally graded and laterally persistent.

Interpretation

Unit UFF.c deposits accumulated in an alluvial setting. Tabular sandy beds represent the products of expanding, unconfined flows, such as spillover flows (Ethridge et al., 1981; Allen et al., 1983), while muddy deposits are interpreted as accumulated by fallout of fines during the last phases of flood events (Bridge, 2003). The widespread presence and nature of pedogenetic features indicates long periods of low sediment supply, intense biogenic activity and soil formation. Organic-matter rich mud accumulated in floodplain ponds or small lakes (Basilici, 1997), as also attested by the local presence of fresh-water bivalves. These data, together with the lack of channel forms, indicate that the main streams were almost fixed and probably entrenched. This is probably related to a lowering of the base level for both the Paleo-Arno River and its tributaries (see Chapter 4).

3.1 CONCLUSIONS

The described paleoenvironmental reconstruction points to a depositional evolution of the basin that can be summarized as follows:

1. Castelnuovo Synthem: Once the basin was generated, as a consequence of tectonic damming of a NE flowing drainage, an FU alluvial succession (unit CSB.a) accumulated on the SW margin. These deposits represent the backfilling of three valleys cut within the rocky substrate. The retrogradational succession emplaced during a period of base-level rise, as attested by the transition from a fluvial setting to a shallow-water deltaic environment. Lignite deposition (unit CSB.b) took place due to accumulation of abundant plant debris within a coastal palustrine environment during a period of low sediment supply. Progressive base level rise led to the development of lacustrine conditions, characterized by the rhythmic accumulation of delta-fed turbidites coming from the SW margin. Several mouth-bar type deltas prograded in the basin from the SW margin, as indicated by the CU trend registered in unit CSB.c and pointed to the complete filling of the lacustrine basin.

2. Montevarchi Synthem: After a tectonic phase that produced a basin broadening, two major alluvial-fan systems (unit VRC.a) developed on the SW margin, both showing a retrogradational trend from proximal to distal deposits. This retrogradational phase culminated with the accumulation of fluvio-eolian deposits (unit VRC.b) in the depressed area between the two deactivated fans. These deposits emplaced in a terminal-fan/sandsheet setting during a climatic deterioration. With the re-establishment of more humid conditions, alluvial fan systems (VRC.c) developed along the Chianti margin and prograded towards the center of the basin. Such a progradation was accompanied by a cannibalization of VRC.b deposit (i.e. formation of a minor unconformity surface) due to a tectonic uplift of the SE margin. During this period an embryonic axial drainage system developed, according with the finding of Mugilids remains. After that, two coalescing margin-fed alluvial-fan systems (VRC.g) developed on both sides of a large alluvial plain (VRC.d-f) drained by a major high-sinuosity stream flowing to NW. Transition from VRC.d to VRC.e fluvial deposits indicates a progressive increase in channel-bodies dispersion, accompanied with a retrogradation of alluvial-fan systems along the Chianti margin, suggesting the

accumulation during high subsidence rate conditions. During the subsidence acme floodbasin lakes and ponds developed (unit VRC.e) giving rise to the local accumulation of peat and to the development of shallow-water fan deltas. A new progradation of the marginal systems over the floodplain is registered by the uppermost part of unit VRC.g and by VRC.d (see Chapter 4 for further discussion).

3. T. Ciuffenna Synthem: The entrance of the Paleo-Arno River into the basin, due to the headward erosion of one of the basin tributaries, triggered a further erosional phase. After that a marginal alluvial-fan succession and an axial fluvial succession accumulated. Alluvial-fan deposits (UFF.b) show a clear FU trend, documenting systems retrogradation, while axial fluvial deposits (UFF.a) show an evident change in sinuosity and fluvial architecture. The latter show a progressive passage from gravelly braided deposits to sandy braided fluvial deposits in the Monticello area (i.e. upstream part) and from sandy braided to sandy meandering fluvial deposits in the S. Giovanni Valdarno area. A successive base-level fall, due to erosion of the Incisa Valdarno threshold, caused embanking of the streams draining the basin. This resulted in a progressive sediment starvation of the floodplain and the non-channelized parts of the fans. In this phase a thin succession of overbank deposits (UFF.c) accumulated at basin scale. As incision proceeded, pedogenic processes affected these deposits.

Chapter 3

SEDIMENTOLOGY AND STRATIGRAPHY OF UNIT CSB.c

RIVER-DOMINATED, LACUSTRINE MOUTH-BAR TYPE DELTAS

3.1 INTRODUCTION

Mouth-bar type deltas are deltas (*sensu* Dunne and Hempton, 1984) constituted by isolated shoals of sediment accumulation (i.e. bars) located at the mouth of distributary channels. This kind of deltas develops an uneven, indented coastline and typically forms if the outlets are not closely spaced and/or if they have quite stable positions (Postma, 1990). Although mouth-bar deltas develop in conditions of gentle subaqueous slopes (Nemec, 1990a; Postma, 1990), they may develop or not a cross-set (foreset), depending on water depths and basin floor slope immediately basinward of the outlet (Dunne and Hempton, 1984; Postma, 1990). Prograding mouth-bar successions are characterized by coarsening-upward trends, developed as sediments are progressively transported and deposited basinward filling the accommodation at the river mouth. Sediment accumulation seaward of the mouth produces a progressive shoaling and an increase in friction-induced deceleration of the effluent, causing an adverse effect on the flow (Wright, 1977). This will result in a bifurcation of the flow itself to either sides of the mouth-bar (Wright, 1977; Wellner et al., 2005), with development of coalescent lobes with a compensational stacking pattern (Ilgar and Nemec, 2005). As stated by Wright (1977) sediment transport and deposition at river mouths is ruled by three main effluent forces: 1) outflow inertia, 2) turbulent bed friction and 3) outflow buoyancy. When inertial forces dominate, the effluent behaves as a fully turbulent flow called “jet flow” (*sensu* Bates, 1953; Wright, 1977). A jet flow is, therefore, an inertia-driven flow, discharging into a body of standing similar fluid through a well defined and stable orifice, and expanding and decelerating through turbulent fluid entrainment (Bates, 1953; Hoyal et al., 2003; Wellner et al, 2005). Recent studies suggest that sediment accumulations produced by jets (i.e. jet deposits) can be considered as the fundamental building blocks of several sedimentary bodies, including deltas (Hojal et al., 2003; Wellner et al., 2005) and crevasse splay systems

(Wellner et al., 2005). Despite this detailed knowledge on the dynamics active at river mouth, the interpretation of ancient mouth-bar deposits in terms of mechanisms of sediment transport and flood-related changes in sediment and water discharge is still matter of discussion (Mutti et al., 1996; Tinterri, 2007).

Mouth-bar type deltas, besides being an archive of the sedimentary processes acting at the river month, can also record the main variations in the ratio between the amount of sediment supplied by the fluvial feeders and changes in marine or lacustrine base level (Schomacker et al., 2010). Interaction between these factors is commonly expressed by development of transgressive-regressive (Fischer and Roberts, 1991; Dam and Surlyk, 1992; Ilgar and Nemec, 2005; Schomacker et al., 2010) cycles giving rise to stacked fining or coarsening-upward sedimentary packages separated, or not, by erosive surfaces (e.g. sequence vs. parasequences development; Van Wagoner et al.,1990). Lacustrine systems differ from marine realms since they are not affected by eustasy and because they contain a definite water volume, which allows rapid and significant coastline shifts (Beuning et al., 1997; Johnson et al., 1996; Talbot and Lærdal, 2000) where climate and/or tectonics affect the basin (Ilgar and Nemec, 2005). In particular, the role that tectonics play in controlling fluctuations in lacustrine setting is to be underlined (Carrol and Bohacs, 1999; Keighley et al., 2003) since it can be significantly different from marine realm. In a lacustrine setting, for example, different subsidence rates can cause rapid water mass shifts associated with asymmetric coastline migrations (Ilgar and Nemec, 2005).

Preservation of both sedimentary facies formed at river mouths and depositional architectures derived from lacustrine oscillations is strongly mined by the relative shallowness of the basins where mouth-bar type deltas develop. In open lacustrine settings, these deposits are easily reworked by wave processes, as they often locate above the wave base. On the contrary, a small and protected lacustrine environment is therefore the best setting to preserve the main sedimentary features of mouth-bar type delta deposits.

The present chapter deals with Unit CSB.c lacustrine deltaic deposits (S. Donato Sand in Albianelli et al., 1995; see Chapter 2) formed in a protected Late Pliocene lake that was hosted in the Upper Valdarno Basin. The identification of these deposits as generated by a mouth-bar type delta system is based on their lithofacies characteristics and geometries. In particular, the scarce wave reworking, which characterized these deposits, allows to describe their primary sedimentary features and geometries, and to discuss them in terms of waxing and waning phases of flood events. Finally, the role of climate and tectonics in controlling development of the internal architecture of the deltaic succession will be discussed.

3.2 METHODS

The present study is a sedimentological investigation carried out on the facies analysis principles (Nemec, 1996) and based on the descriptive sedimentological terminology of Harms et al. (1975, 1982) and Collinson et al. (2006). Sedimentary facies are here considered to provide basic information on depositional processes, and, therefore, represent the basic building blocks of a sedimentary succession. Facies associations are assemblages of genetically and spatially related facies, representing particular sedimentary environments or subenvironments.

Three main outcrops (**Fig. 3.1**) have been selected in order to show the main sedimentary features of the study deposits. Twelve sedimentary facies have been distinguished (**Table 1**; **Fig. 3.2** and **3.3**) and grouped into five facies associations (A to E), which will be discussed further in the text. The main geometries and stratal architectures have been highlighted through linedrawing of the most significant outcrops. Finally, the stratigraphic meaning of coarsening- and fining-upward packages forming the prograding deltaic complex will be described and discussed through a 25 m sedimentlogical log from the middle part of the S. Donato Sand.

Facies	Thickness (cm)	Description	Interpretation
M1	2-80	Massive to laminated mud and silt. Beds are locally capped by plant debris and commonly bioturbated; they may contain coal iterlayers.	Sediment fallout in standing water bodies.
M2	30-200	Composite units of mud or silt split by sharp based graded sandy interlayers into beds 2-10 cm thick. The mudy portion is commonly capped by plant debris.	Episodes of deposition from mud-rich turbulent currents.
SF	10-30	Cross stratified sand, medium to coarse grained, filling small (~30 cm wide) erosional depressions with concave base and flat top. Beds can contain sparse pebbles.	Scour-fill deposits formed in turbolent conditions. Sedimentation occurs by progressive avalanching of grains over the inclined strata.
S1	4-120	Ripple-cross laminated sand, very fine to medium grained, commonly silty. Beds are ungraded or normally graded with flat, non-erosional or erosional, shrap or irregular, base. Locally bioturbated.	Migration of 2D and 3D unidirectional ripples by quasi-steady currents.
S2	8-50	Plane-parallel stratified sand, very fine to medium grained, commonly silty. Beds can be normally graded or ungraded, they may have non-erosional or erosional base, flat or irregular, locally scoured and filled with sigmoidal cross stratification. They locally contain carbonaceous debris within the strata.	Tractional deposition of upper-flow laminae by quasi-steady currents.
S3	8-18	Plane-parallel stratified to ripple-cross laminated sand, very fine to very coarse grained. Units can be normally graded or ungraded with flat locally erosional base. Locally bioturbated.	Deposition from surge-type, low-density turbulent currents passing from upper-flow to lower-flow regime. Normal grading, where present, is due to the waning nature of the flow.
S4	15-40	Sandy beds with inverse grading, normal-to-inverse grading or irregular grain-size trend, ranging in grain size from very fine to coarse sand. Beds can be fully plane-parallel stratified, fully ripple-cross laminated or can show one or more transitions between the two. Some beds show internal truncation and reactivation surfaces. They may have transitional, non-erosional or erosional base and locally they show an erosional upper boundary.	Tractional deposition from sustained, low-density turbulent currents, fed by pulsating flows.
S5	25-70	Planar-cross or trough-cross stratified sand, medium to very coarse grained. Sets can show flat non-erosional or irregular erosional base. Planar inclined strata are tangential, commonly steep (>20°), but they can be low-angled (~10°). Sets range from 15 to 25 cm in thickness.	Sedimentetion associated with the migration of 2D and 3D dunes. These bedforms reflect a lower flow regime and unidirectional tractional currents.
S6	5-20	Massive or massive to plane-parallel stratified, fine to coarse sand. Beds may contain sparse granules and pebbles and mud clasts. Beds are normally graded with sharp, commonly erosional base.	Deposition from high-density turbulent currents during waning flow conditions. The massive interval reflects rapid sediment dumping, while the laminated portion is due to tractional deposition from the depleted, low-density derived flow.
S7	5-20	Massive sand, fine to coarse grained. Beds can be ungraded or can show a coarse-tail inverse grading and can contain scattered granules and pebbles. They show flat, non-erosional base.	Non-tractional deposition from sandy debris flows, due to frictional freezing of grains.
W1	10-50	Well sorted fine to medium sand with trough-cross laminations.The laminae define cuspidate symmetrical forms up to 2–3 cm high. Beds show sharp and locally erosional base.	Symmetrical ripples (wave ripples) formed by wave reworking in coastal setting.
W2	5-200	Massive or crudely plane-parallel stratified sand, fine to very coarse grained and well sorted. Beds, tipically 5-20 cm thick, can occur individually or in composite units made of several amalgamated layers, stacked upon each other. In both cases the basal surface is erosional, sharp or irregular, locally bearing a pebble lag. Composite units normally show a coarsening-to-fining upward trend, while individual beds are normally graded. Bioturbation is common to the base. Beds show high lateral percistence.	These sediments formed by wave reworking in low energy conditions. Crude horizontal stratification may represent tractional deposition of lower-flow laminae.

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Table 1 – Sedimentary facies description and interpretation.

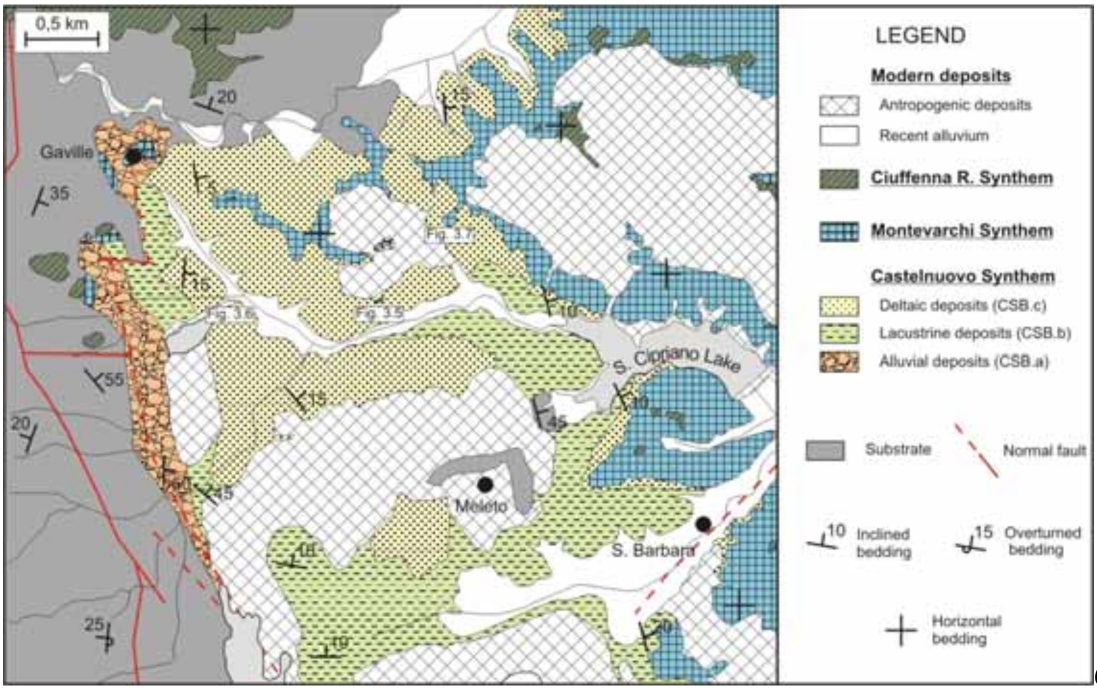

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Fig. 3.1 – Geological sketch map of the study area.

3.3 THE STUDIED SUCCESSION

3.3.1 Facies and facies associations

Facies Association A

These deposits constitute fining upward lensoidal units with concave erosional base and flat top (**Fig. 3.3D-E**), which have been subdivided in two different types.

Type 1 units are up to 2 m thick and 12-15 m wide. These lens-shaped units are often floored by a 3-10 cm thick layer of very coarse sand with scattered fine pebbles and moderately rounded pebble-size mud clasts. This basal layer is commonly covered by a single set of large-scale inclined beds (10°-20°) consisting of coarse- to medium-grained sand split by thin mud drapes pinching out in the dip direction (**Fig. 3.3E**). Cross-sets are sigmoidal and 1-2 m thick. Sandy beds, up to 25 cm thick, are plane-parallel (facies S2), and planar- or trough-cross stratified (facies S5). Paleocurrent directions, inferred from cross-stratified sands and basal scours, are oblique to the dip of beds. Cross-bedded units commonly bear evidence of subaerial exposure (e.g. root traces, mottling and oxidation) in their uppermost part. In Type 1 units Facies association A can overlay associations C and D and is commonly capped by association E.

Type 2 units are up to 70 cm thick and few meters wide. These lensoidal units are mainly formed by vertically stacked, horizontal beds of coarse to very coarse sand (**Fig. 3.2E**). Sandy beds, 15-25 cm thick, are planar-cross stratified (facies S5). Paleocurrent directions, inferred from cross-strata, are parallel to the unit flanks. In Type 2 units Facies association A overlays association C and is commonly capped by association E (**Fig. 3.3D**).

These lensoidal units represent deposits of fluvial channels. In Type 1 channels migration of sandy bars gave rise to sets of large-scale inclined beds. Beds attitude and paleoflow oblique to the beds dipping suggests migration of bank-attached bars, which migrated oblique to the main flow (Bridge, 2003). Sand was transported on bar surface mainly as dunes or upper plane laminae. The deeper part of the channels was affected by sand bypass and deposition of mud clasts eroded from the channel banks (Collinson, 1986). Mottling and root traces on top of cross-sets represent subaerial exposure of sediments in the abandonment stage of channels. In Type 2 channels the migration of sandy bars gave rise to the vertical stacking of horizontal beds. Beds geometry and paleotransport direction parallel to channel banks indicates downstream migration of mid-channel bars formed by progressive superposition of sandy 2D dunes (Nemec, 1992; Bridge, 2003).

Facies Association B

These deposits form clinostratified sandy units up to 3 m thick (see **Fig. 2.11E**, Chapter 2). In sections parallel to bed dipping, each unit is made of a set of regularly stacked, sigmoidal beds dipping up to 20°. The dominant deposits are represented by normally graded, 5-20 cm thick, massive or massive to plane-parallel stratified sandy beds of facies S6 (**Fig. 3.2F**), deposited by high-density turbidity currents. Subordinate sandy debris flow of facies S7 (**Fig. 3.3A**) and low-density turbidity current sand of facies S4 are present (**Fig. 3.2D**). Sandy beds are locally split by thin (3-6 cm) bioturbated muddy interlayers locally rich in plant debris (facies M1; **Fig. 3.2A**). In sections transverse to bed dipping, cross-bedded units form mounded bodies up to 2 m high and 15-20 m wide. On the whole, bed attitude of these clinostratified units suggests they form high-relief, fan-shaped bodies spanning around 180°. Facies association B conformably overlays and interfingers laterally with to association C (**Fig. 3.4**) and is erosively capped by association E (**Fig. 3.4**).

The fan-shaped geometry of these deposits suggests that sediment was accumulated on a lobe fed from a stable entry point (Bates, 1953; Hoyal et al., 2003; Wellner et al, 2005) in a subaqueous setting, according with the lack of evidences for subaerial exposure. Although beds dipping reaches the repose angle of sand, and rare debris-flow beds are present, the dominant process delivering sediment on the lobe front is represented by high-density flows (Lowe, 1982), which were not derived from sandy debris-flows transformation (Nemec, 1990b; Plink-Björklund and Steel. 2004) given the limited extent of the lobe front. In a river-fed lobe, high-density turbidity currents would develop during the flood peak, when deposit accumulated during the waxing phase can be entirely removed (Mulder et al., 2003) and a significant volume of sediment is dropped down in the proximal areas because of flow expansion and deceleration (Wright, 1977). The low-density turbidity current deposits, attributed to pulsating, long-lived, river-fed flows (Nemec, 1990b; Mulder and Alexander, 2001; Mulder et al., 2003), record the occurrence of floods with a minor magnitude. Accordingly, mud drapes were deposited during phases of low sediment discharge (Colella et al., 1987).

Facies Association C

In sections parallel to the main transport direction (i.e. NE), these deposits form 1-1.5 m, gentle-dipping (~5°) to horizontally bedded, coarsening-upward packages, which, in transverse sections, are gently mounded (**Fig. 3.4**). On the whole, these mounded units form low-relief, fan-shaped bodies, which are compensationally stacked (Ilgar and Nemec, 2005) and form 2-3 m thick, laterally continuous horizons. The mounded units are mainly formed by 15-40 cm thick sandy beds stemmed out from both sustained- (facies S4) and surge-type (facies S3) low-density turbidity currents (**Fig. 3.2B** and **D**). Some of these beds are entirely made of plane-parallel stratified (facies S2) or ripple-cross laminated (facies S1) sand. Rare massive beds (~5 cm thick) emplaced by high-density turbidity currents of facies S6 are present, whereas muddy intervals are more common and thicker than in facies association B. Bioturbation is frequent and locally masks the primary sedimentary structures. Paleocurrents, inferred from cross-laminated sand, span around more than 90° and are conformable with the mounded architecture of these deposits. Locally, the topographic lows located between adjacent lobes host lensoid, erosive-based sand bodies, up to 50 cm thick and 2 m wide. These bodies are made of massive to plane-parallel stratified tabular beds up to 10 cm thick. These beds are commonly erosive-based, and rich in mud clasts in their lower part. Facies association C conformably overlays association D and passes upward and interfingers laterally with to association B (**Fig. 3.4**).

The lobate geometry of facies association C deposits suggests the presence of localized sediment entry points (Bates, 1953; Wright, 1977; Hoyal et al., 2003), which were recurrently affected by avulsion, according with the compensational stacking pattern (Ilgar and Nemec, 2005). Abundance of well-stratified sand indicates dominance of a tractional deposition, which occurred from sustained and surge-type, river-generated flows (Mulder and Alexander, 2001; Mulder et al., 2003; Plink-Björklund and Steel. 2004; Petter and Steel 2005; Zavala et al.,2006). The occurrence of pulsating and quasi-steady flows indicated floods characterized by irregular and almost stable discharge respectively (Zavala et al., 2006), whereas the rare high-density turbidity currents could have been triggered by high-magnitude floods (Mutti et al., 1996) or sediment entrainment from bank collapses (Mulder et al., 2003). The sandy deposits located between adjacent lobes were deposited by turbidity currents, which were funnelled in interlobe areas (Huppert and Simpson, 1980; Nemec, 1990b), where entrainment of unconsolidated sediment occurred (e.g. mudclasts). The abundance and thickness of muddy intervals, along with the increase in bioturbation, indicate long periods of low sediment discharge and biogenic activity.

Facies Association D

These deposits consist of sheet-like, horizontal beds of mud with subordinate sand (**Fig. 3.6**), which form coarsening-upward packages up to 1 m thick. These packages are vertically stacked into form 3-4 m thick horizons. Mud is dominant and occurs as massive or thin plane-parallel laminated beds (facies M1) or as muddy graded beds, commonly capped by plant debris and leaves layers (**Fig. 3.2C**) and floored by a 2-3 mm thick layer of very fine sand (M2). Subordinate sandy beds are represented by deposits from low-density turbidity current, mainly of sustained type (facies S4) with associated deposits of quasi-steady flows (facies S1and S2) and subordinate surge-type flows. Where muddy deposits are dominant, the sandy layers are commonly 1-3 cm thick, ripple-cross laminated and preserve the ripple forms. Locally these sheet-like, heterolitic beds are cut by lens-shaped units, with erosional concave base and flat top, 30- 50 cm deep and 1.5-2 m wide. These lenses are commonly floored by pebble-size mudclasts and filled with massive to ripple cross- and plane parallelel-stratified medium sand. Facies association D conformably overlays association E and passes upward to association C.

Facies association D testify deposition in a distal, low-energy lacustrine environment. Mud accumulation was the dominant process and occurred as suspension fallout (facies M1) from hypopicnal plumes (Nemec, 1995) or deposition from muddy turbidity currents (facies M2). The presence of numerous layers containing plant debris highlights the importance of this second depositional mechanism in mud accumulation. Lateral persistence of the sandy beds testifies the presence of unconfined flows, which were represented by river-generated, low density turbidity currents (Lowe, 1982; Nemec, 1990). The erosive-based lensoid units are thought to be the basinward expression of the interlobe scours of facies association C.

Facies association E

These deposits form sheet-like, horizontally bedded sandy units (0.2 to 3 m thick) with relevant lateral persistence. They show a fining-upward trend and an erosional base, commonly floored by a discontinuous pavement of fine pebbles (**Fig. 3.3C**). Beds are 5 to 20 cm thick and consist of whitish, quartz-rich sand deprived of its silty matrix. The sand texture ranges from moderately to well sorted. Most of the beds are characterized by a diffuse plane-parallel stratification (facies W1) and subordinate beds show low-relief (2-4 mm), symmetric ripple forms (facies W2: **Fig. 3.3B**), commonly highlighted by millimetric mud coat. The beds characterized by the better textural sorting appear as massive, although faint of a primary lamination can be locally distinguished. Rare sharp-based, normal graded beds (5-10 cm) made of massive, poorly sorted sand (facies S6) are present, mainly in areas where facies association E reached the major thicknesses. Bioturbation is very common and is mainly concentrated in the lower part of the units. Facies association E can overlay all the other associations and pass gradually upward into muddy deposits of association D.

The sedimentary characteristics of these deposits indicate deposition by the winnowing action of lacustrine waves. The stratigraphic position of these deposits (see paragraph 3.3), along with their limited thickness and fining-upward trend, suggests they represent the condensation of nearshore sedimentation in transgressive conditions (Cattaneo and Steel, 2003). The basal, discontinuous gravelly pavement represents a transgressive lag developed during condensation of foreshore deposits (Hwang and Heller, 2002). In other cases, the basal lag apparently overlies a pavement related to a regressive surface of lacustrine erosion, referred to also as the "exhumation lag" (Brachert et al., 2003) or "armoured pavement" (Lòpez-Blanco et al., 2000) and considered to be the time equivalent of falling stage deposits (*sensu* Plint and Nummedal, 2000). The distinction between such a composite lag (bearing the combined record of the base-level fall and subsequent rise) and a simple transgressive lag is not always an easy task (Ghinassi, 2007), requiring an integrated analysis of facies associations and their stratigraphic architecture. Plane-parallel stratified sand developed in shallow water, where waves passage induces a marked stress at the bottom with development of strong landward directed orbital velocities (Clifton, 2006). Symmetric ripples formed in deeper water, where symmetrical orbital velocities develop on the lake bottom during wave passage (Clifton and Dingler, 1984; Clifton, 2006). Structureless, well-sorted sand likely developed under tractional condition, but detection of sedimentary structures is prevented by the absence of grain size changes. Isolated massive, normal graded beds of facies S6 were probably emplaced by flood events, which spread sediment in nearshore setting. These flood-generated flows increased the local sediment supply, allowing to facies association E to reach a metric thickness. The reduced grain size of wave-reworked sediments, along with the limited vertical development of these deposits, suggests that wave action scarcely influenced the nearshore sedimentation, which was dominated by riverine input. The scarce development of waves is also suggested by the limited extent of the lacustrine basin and by its orography (i.e. confined between the Chianti and Pratomagno ridges).

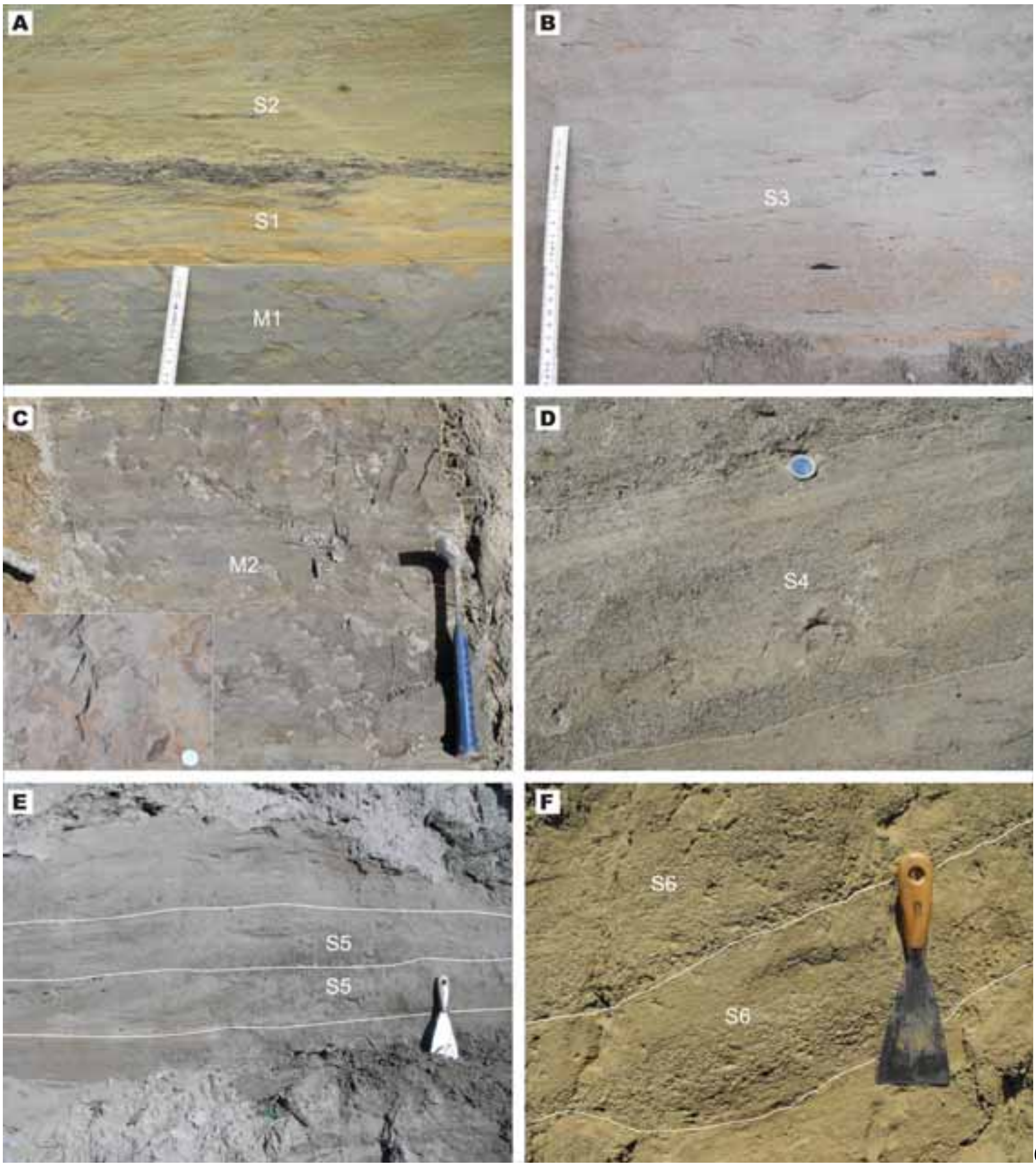

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Fig. 3.2 – Unit CSB.c deltaic deposits. A) Ripple-cross laminated and plane-parallel stratified sands overlaying massive muds. B) Plane-parallel to ripple-cross laminated sandy bed. C) Thin-bedded sandy-to-muddy graded beds capped by leaves layers. D) Plane-parallel laminated sandy bed showing repeating grain-size variations. E) Planar-cross stratified sandy beds in distributary channel of Type 2. F) Granules to coarse sand normally graded, massive, inclined beds.

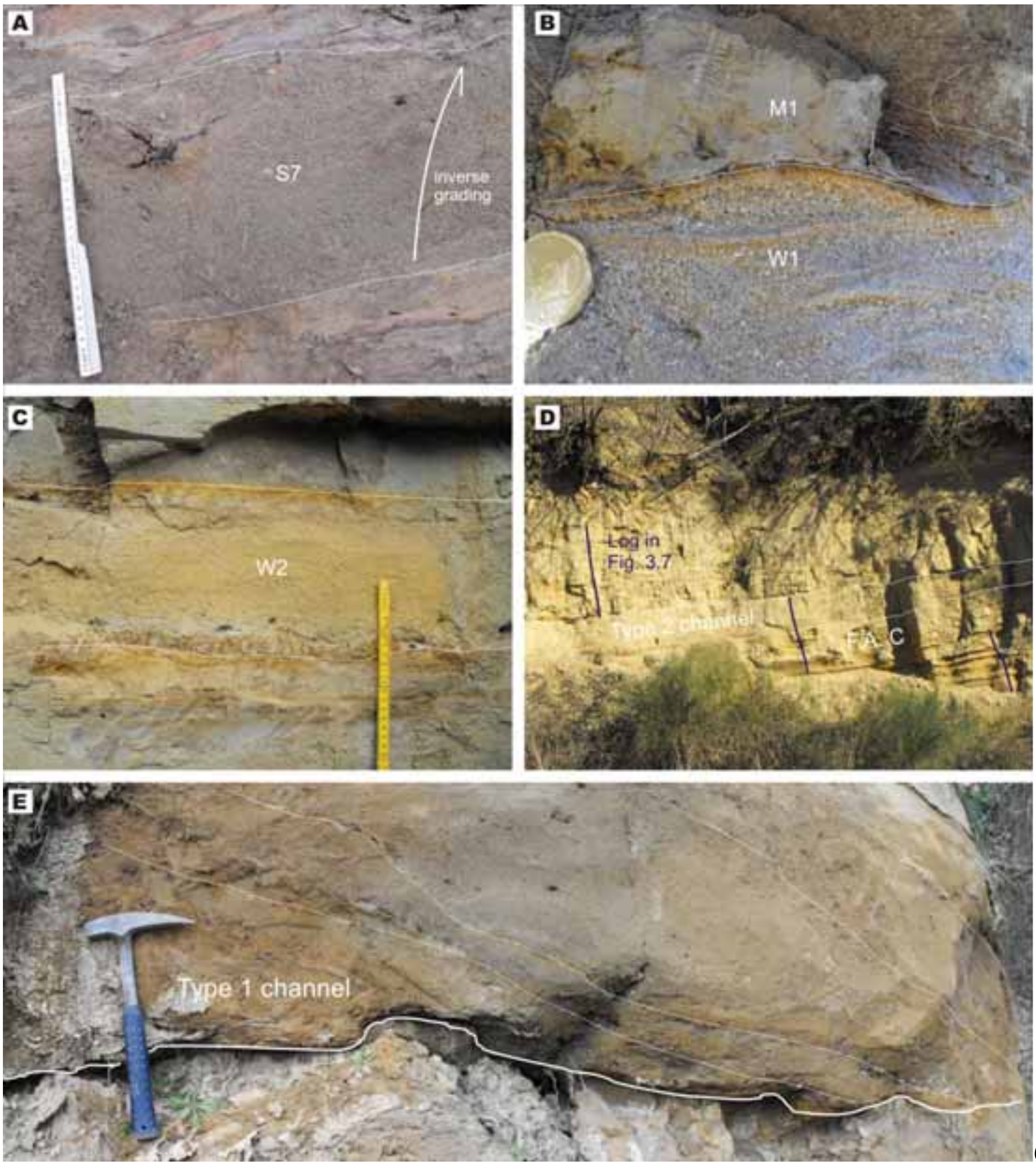

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Fig. 3.3 – Unit CSB.c deltaic deposits. A) Inversely graded sandy bed. B) Matrix-free medium sand showing symmetrical ripple-cross lamination, capped by massive mud. C) Matrix-poor coarse to medium sandy bed, showing intense bioturbation to the base, within muds. D) Type 2 channel truncating F.A. C deposits. Lateral percistence of the channel due to outcrop orientation. E) Type 1 channel, consisting of superimposed inclined beds of coarse sand, cutting massive mud.

3.3.2 Mouth-bar geometry

Vertical sections where bed attitude and spatial distribution of facies associations are visible allowed to define the internal geometry of mouth-bar units. In particular, normal regressive successions (*sensu* Plint and Nummedal, 2000) exposed in sections transverse to the main transport direction (**Fig. 3.4**) resulted to be particularly functional to this aim.

A normal regressive mouth-bar succession overlays the fining upward deposits of association E and is represented by a 6-8 m thick lithosome consisting of sandy mud grading upward to very coarse sand (**Fig. 3.4** and **3.5**). The lower portion of this lithosome is made of laterally persistent, tabular muddy deposits of association D (**Fig. 3.6**), which grade upward to sand of association C (**Fig. 3.5**, Log 2). The laterally offset, low-relief lobes of association C grade upward to deposits of association B (**Fig. 3.4** and **3.9**), which are, in turn, covered by the wave-winnowed sand of association E (**Fig 3.4** and **3.5**, Log 3). Such a vertical stacking is visible in section both parallel and transverse to the main transport direction. In particular, transverse sections highlight that low-relief lobes of association C underlie, but also interfinger laterally with the mounded, clinostratified sand of association B (**Fig. 3.4** and **3.9**). Within a regressive unit, about one third is commonly represented by horizontal beds of association E, and the remnant two third are equally shared between association B and C.

According to the vertical stacking of facies association, the more distal portion of a mouth-bar unit is represented by the tabular, mud-dominated deposits of association D, which passes landward to the sandy, low-relief lobes of association C. Transverse sections highlight that the low-relief lobes of association C develop downcurrent, but also laterally, to the main high-relief lobes of association B. As suggested by their sedimentary features, the more distal deposits were accumulated by unconfined flows, whereas a defined sediment entry point is required for development of both high- and low-relief lobes (Bates, 1953; Wright, 1977; Hoyal et al., 2003). The size and the landward location of the high-relief lobes of association B indicates that those lobes formed at the outlet of the main distributary channels (Wright, 1977; Hoyal et al., 2003) as due to expansion of inertia flows, as suggested by development of steeply-inclined fronts (Wright, 1977). In terms of geometry and stratal architecture, such lobes resemble the lunate bar of Bates (1953) and the jet deposit described by Hoyal et al. (2003) and Wellner et al. (2005). The reduced grain size and location suggest that lobes of association C were formed by secondary distributary channels, developed during the low-flow discharge of the distributary system. The low-relief of

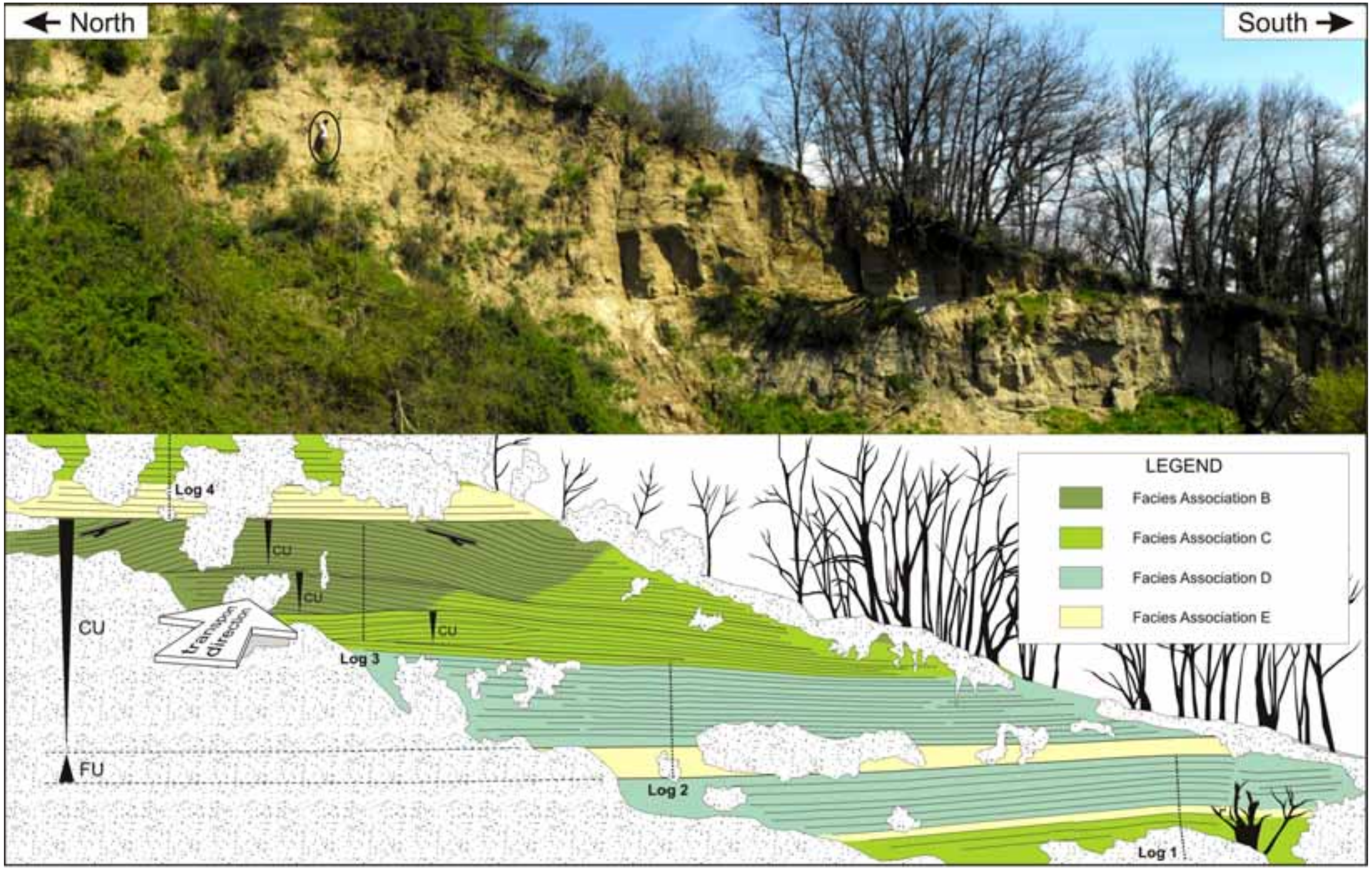

Fig. 3.4 – Section transverse to the main transport direction, showing mouth-bar geometry and vertical stacking pattern of facies associations.

these lobes indicates they were formed by friction-dominated flows (Wright, 1977). The occurrence of these lobes on the sides of the high-relief, axial jet lobe suggests they were fed by minor channel bifurcating in front of the main lobe. Some of these small lobes can also be fed by the minor flows funnelled in the interlobe areas.

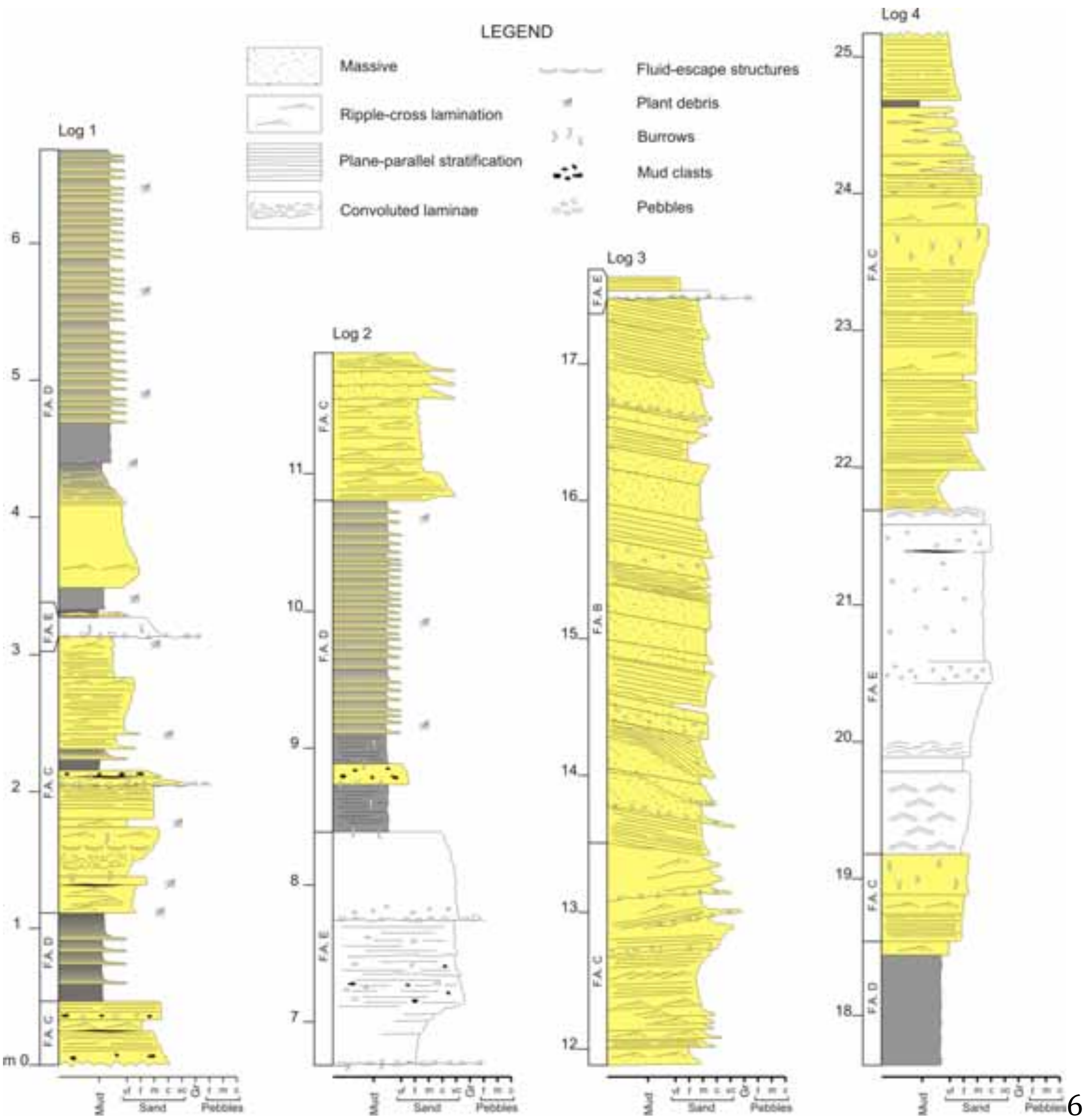

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Fig. 3.5 – Sedimentological logs measured on section shown in Fig. 3.4.

3.3.3 Deltaic record of high-frequency lacustrine oscillations

The S. Donato sand succession stemmed out from the progradational vertical stacking of moth-bar units (Albianelli et al., 1995; see Chapter 3). The upper part of this

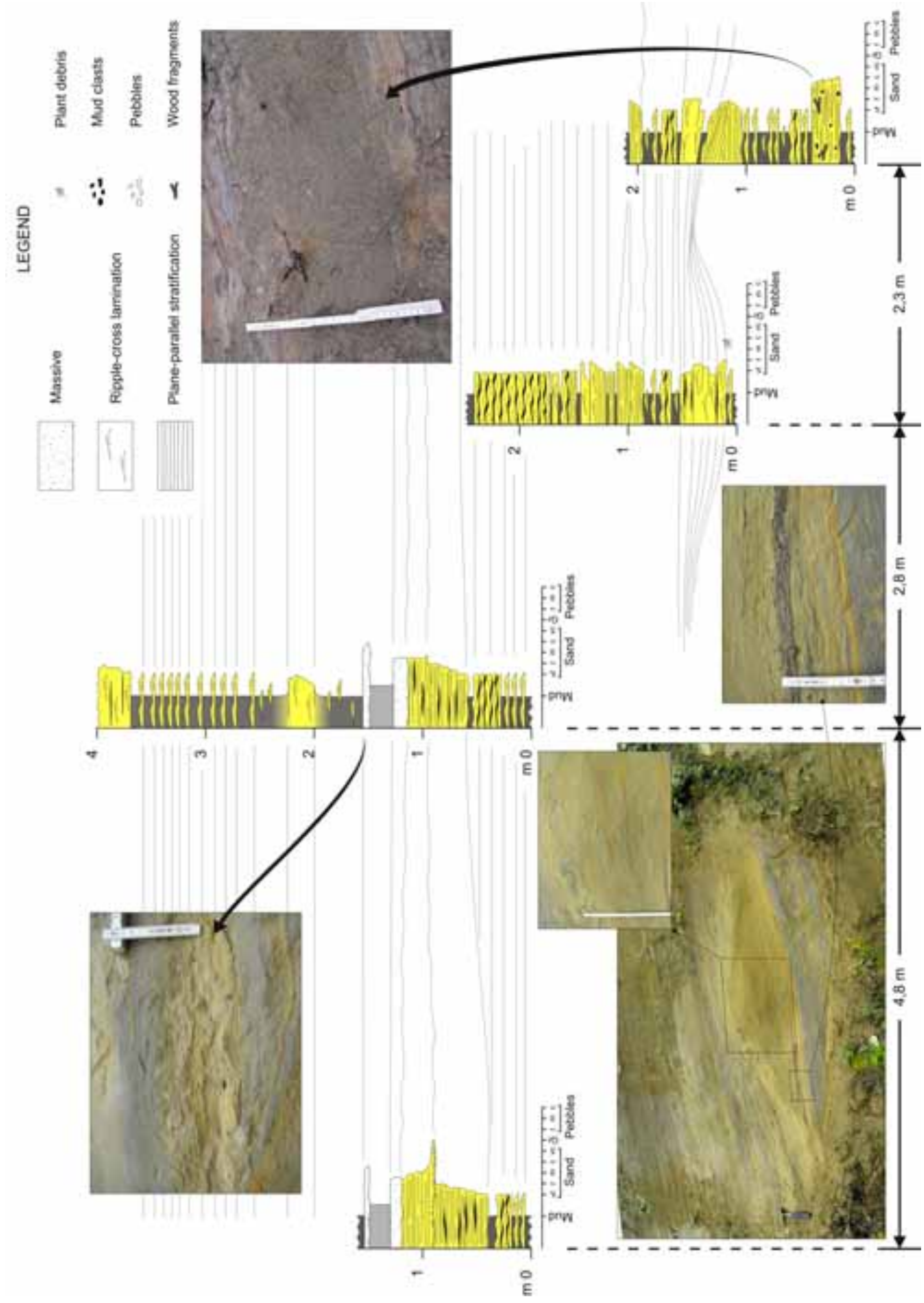

Fig. 3.6 – Sedimentological logs measured through distal deltaic deposits.

succession (**Fig. 3.7**) is mainly represented by proximal mouth-bar sand, and appears to be particularly prone to record minor, high-frequency lacustrine oscillations. In this framework, the fining upward, wave-winnowed sand of association E are thought to have been accumulated in transgressive conditions during high-frequency lacustrine rises. Accordingly, the coarsening-upward packages made of stacked facies associations D, C and B (**Fig. 3.4**) are interpreted as formed during highstand normal regressions. Where the transgressive lag at the base of wave-winnowed sand sharply overlay deposits of association C or D (**Fig. 3.7**) a surface of forced regression (*sensu* Plint and Nummedal, 2000) is inferred. A similar meaning is attribute to the surface at the base of channelized fluvial sand cut onto deposits of association C or D (**Fig. 3.7**).

The palinological record of the S. Donato Sand indicates stable humid climatic conditions (Albianelli et al., 1995) and no significant difference has been detected between samples collected in transgressive and regressive deposits (see Chapter 5).

3.4 DISCUSSION

3.4.1 Mouth bar model

Wrights (1977) recognises three different types of effluent flows on the basis of outflow dominating forces: inertia-dominated fully turbulent jets, bed-friction dominated plane turbulent jets and buoyancy-dominated effluents. Inertia-dominated jets are characterized by a low lateral dispersion (Bates, 1953; Wright, 1977; Hoyal et al., 2003; Wellner et al., 2005), and by the accumulation of the coarsest material within a restricted region at the end and along the lateral margins of the flow establishment zone (Wright, 1977; Wellner, 2005). The depositional expression of this phenomenon is a narrow lunate bar, originally described by Bates (1953), that shows a gently landward-dipping back and a relatively steep front (Wright, 1977). Bed-friction dominated river-mouth deposits develop where basin depth just seaward of the outlet is similar or shallower than the outlet depth itself. In such conditions bed shear stress is high and turbulent bed friction becomes dominant, causing an increasing in effluent spreading angle and flow deceleration (Wright, 1977). In depositional terms, this process results in a rapid accumulation of the coarsest sediments very closely to the river mouth, with the formation of a shoal which causes channel bifurcation (Wright, 1977). Such a shoal is

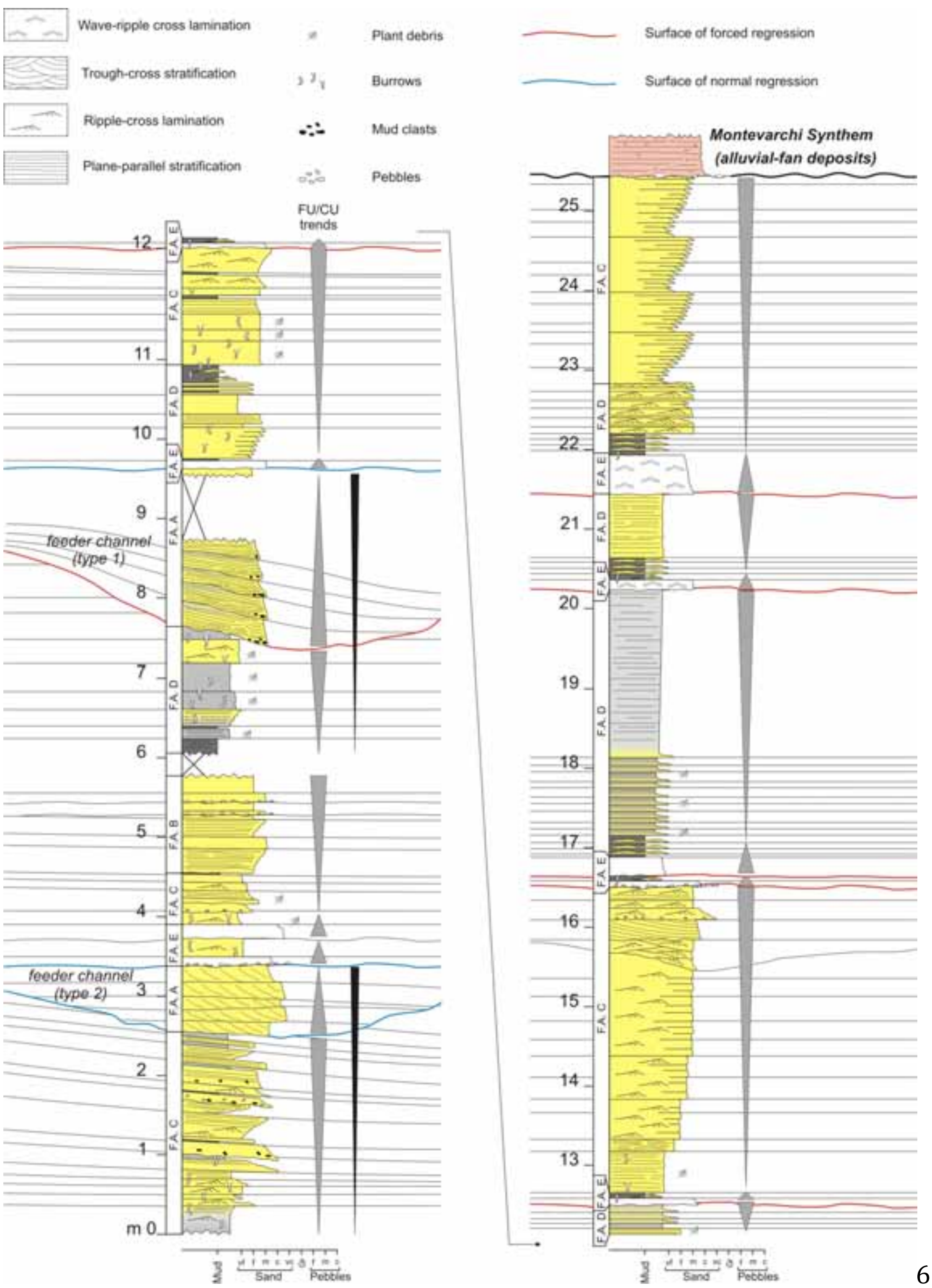

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Fig. 3.7 – Stratigraphic section measured in the upper part of unit CSB.c. Deltaic deposits records repeated transgressive/regressive cycles.

characterized by a relatively steep landward-dipping back and a gentle front (Wright, 1977). In buoyancy-dominated effluents the density contrast between the effluent and the receiving water body allows formation of plumes which can cover remarkable distances from the river mouth (Nemec, 1995).

The sedimentary expressions of inertia- and friction-dominated effluents have been recognised in the mouth-bar units forming the S. Donato deltaic succession. The high-relief lobe developed at the outlet of the main effluent was generated by inertia-dominated flows, whereas coalescent low-relief lobes were formed by friction-dominated effluents. The presence of adjacent lobes generated by different effluent dynamics can be explained in terms of changes in river-flood discharge and their effects on sedimentary processes acting at channel outlet (**Fig. 3.8**). Alternation between flood waxing and waning periods, along with the succession of floods with different magnitude, have remarkable effects on the sedimentary products of hyperpycnal flows (Kneller, 1995; Mulder and Alexander, 2001; Mulder et al., 2003). At the river mouths, the same mechanisms controlled changes between inertia- and friction-dominated effluents. During periods of high discharge, the steeply sloping lobes of association B formed as jet deposits (i.e. from an inertia-dominated effluent) at the outlet of the main distributary channels. During periods of low discharge, minor channels bifurcated around the jet lobe feeding friction-dominated effluents which give rise to low-relief lobes of association C. During the waxing flood time (**Fig. 3.8**) flow velocity is low and water at the channel mouth is shallow. The jet bar formed at the channel outlet by the previous floods causes bifurcation of the distributary channel that flows around the bar, feeding shallow-water lobes in a frictional-dominated setting. Sediment is transported in tractional conditions, and the waxing phase can be recorded in the lower part of beds by a coarsening upward trend. At this time, sedimentation on the axial jet bar is not active. As the flood increases its discharge reaching the peak, flow velocity also increases and water level at the river mouth rises (**Fig. 3.8**). In such conditions the effluent is dominated by inertia forces and a jet flow develop at the outlet of the main channel reactivating deposition on the jet bar. The upstream portion of the bar is affected by sediment bypass (Wright, 1977), whereas the downstream side (i.e. bar front) is markedly progradational. The flow restriction occurring at the bar crest cause a velocity increase which allows the flow to keep its sedimentary load in a fully turbulent suspension. Downcurrent of the crest zone, the fluid exchange between the effluent and the basin waters causes expansion, mixing and deceleration of the effluent, which drops the coarser particles on the bar front. After the peak, the early phase of flood waning leads to settling of finer particles, which accumulate in the upper part of normal graded beds on the bar front. The presence of normal- and inverse- to normal-graded beds suggests that the jet bar front was activated during or just before the flood peak respectively. Although the coarser particles have been dropped of jet bar front, the concentration of suspended sediment is still enough to allow plunging of the effluent (Mulder and Syvitski, 1995), which generates a hyperpycnal flow (Bates, 1953; Mulder and Syvitski, 1995; Mulder et al., 2003) spreading on the distal part of the bar. Basing on the changes in water and sediment discharge occurring during the flood (Mulder et al., 2003) those hyperpycnal flows will generated surge-type or sustained-turbidity currents, which could be quasi-steady or pulsating. At this time, the adjacent low-relief lobes receive a limited amount of sediment or can even be affected by bypass/erosion. As the flood wanes, the flow decelerates and water level at the channel mouth decreases causing bifurcation of the effluent around the jet bar. At this stage the adjacent low-relief lobes will be reactivated and fed by frictional-dominated effluents like during the early waxing stage of the flood.

3.4.2 High-frequency lacustrine oscillations

In the upper part of the S. Donato succession, the presence of transgressive and regressive deposits, along with surfaces of forced regression, highlights the occurrence of repeated lacustrine rises and falls. Such a stacking pattern resembles that formed in overfilled or balance-filled lakes (Bohacs et al., 2000), where accommodation space derives from the balance between basin subsidence and sediment and water supply (i.e. climate; Carrol and Bohacs, 1995). Lake-level falls associated with marked channel incision (e.g. feeder channels cutting distal mouth bar deposits; **Fig. 3.7**) indicates that channel discharge (i.e. erosive power) didn’t decrease during S. Donato lake contractions, suggesting a non-climatic control on lacustrine oscillations (Bohacs et al., 2000). The lack of any significant difference in palinological content between samples collected in transgressive and regressive deposits support this hypothesis. Tectonic control on lacustrine sedimentation is typical of underfilled lakes, where the contribute of sediment and water supply is almost negligible (Carrol and Bohacs, 1995; Bohacs et al., 2000), although tectonic-driven oscillations have been documented also for non-underfilled lakes (Keighley et al., 2003; Ilgar and Nemec, 2005).

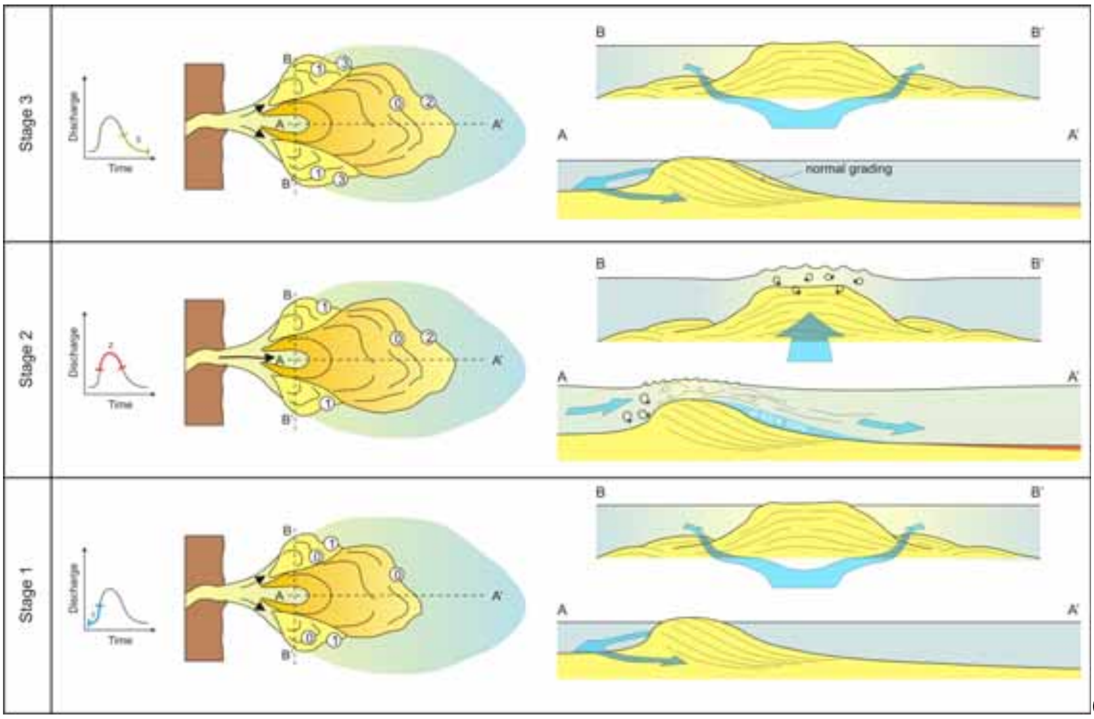

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Fig. 3.8 – Three-stage sketch showing the proposed mouth-bar model development.

The contrasting tectonic scenario (half-graben vs. thrust-top basin) defined by different Authors for the S. Donato basin allows to speculate on possible models for lacustrine oscillations stemmed out in different tectonic settings under constant climatic conditions (**Fig. 3.10**).

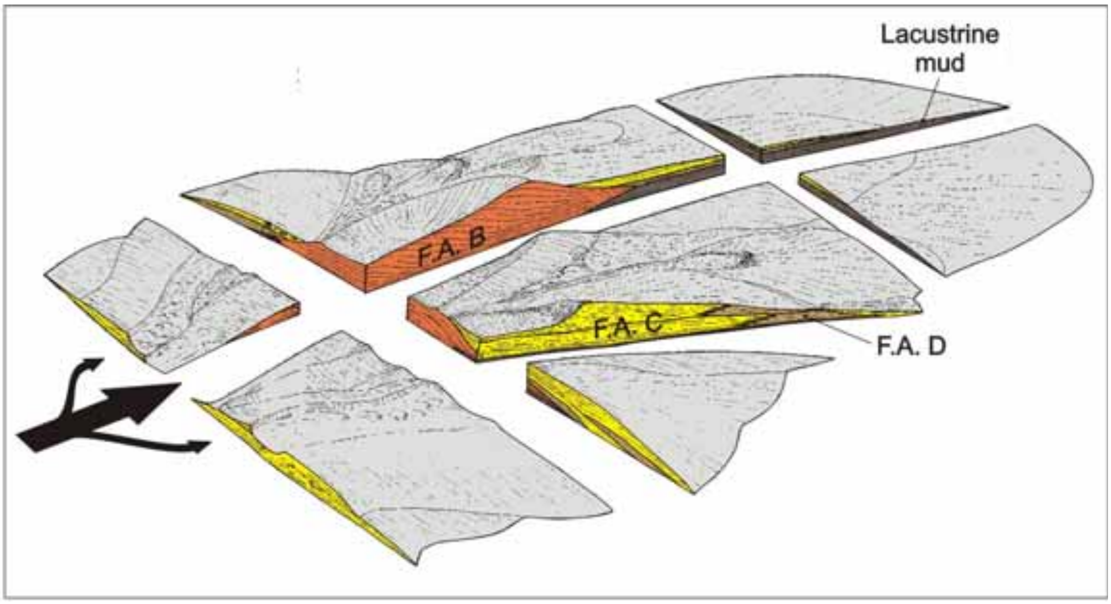

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Fig. 3.9 – 3D model for the studied mouth-bars.

In the half- graben model (**Fig. 3.10A**), the S. Donato deltas prograde on the hangingwall block and the master normal fault is located on the opposite margin (Martini and Sagri, 1993; Albianelli et al., 1995; Martini et al., 2001). Fault activity caused repeated episodes of basin-floor subsidence, which moved the water mass toward the faulted margin and caused a basinward coastline shift (i.e. forced regression) on the opposite side. Successively, the constant water discharge and limited evapotranspiration allowed the lake to reach its previous level allowing accumulation of transgressive and highstand deposits. In the half-graben model, tectonic-driven lacustrine oscillations are prone to produce deltaic successions characterized by stacked sequences (*sensu* Van Wagoner et al., 1990).

In the thrust-top model (**Fig. 3.10B**), the S. Donato lake occupies the depression between two tectonic nappes (Boccaletti and Sani, 1998; Bonini, 1999). Thrust reactivation caused repeated episodes of basin shortening, which reduced the accommodation available for the water mass causing flooding of the margins. The constant water discharge and limited evapotranspiration aided such process, preventing lacustrine falls. In the thrust-top model, even if coastline dynamics are highly dependent on fault geometry, tectonic-driven lacustrine oscillations are more prone to produce deltaic successions characterized by stacked parasequences (*sensu* Van Wagoner et al., 1990). In this framework, the presence of surfaces of forced regression in the study deltaic interval would suggest that the oscillations of the S. Donato lake would have been driven by extensional tectonics (i.e. activation of the Trappola fault).

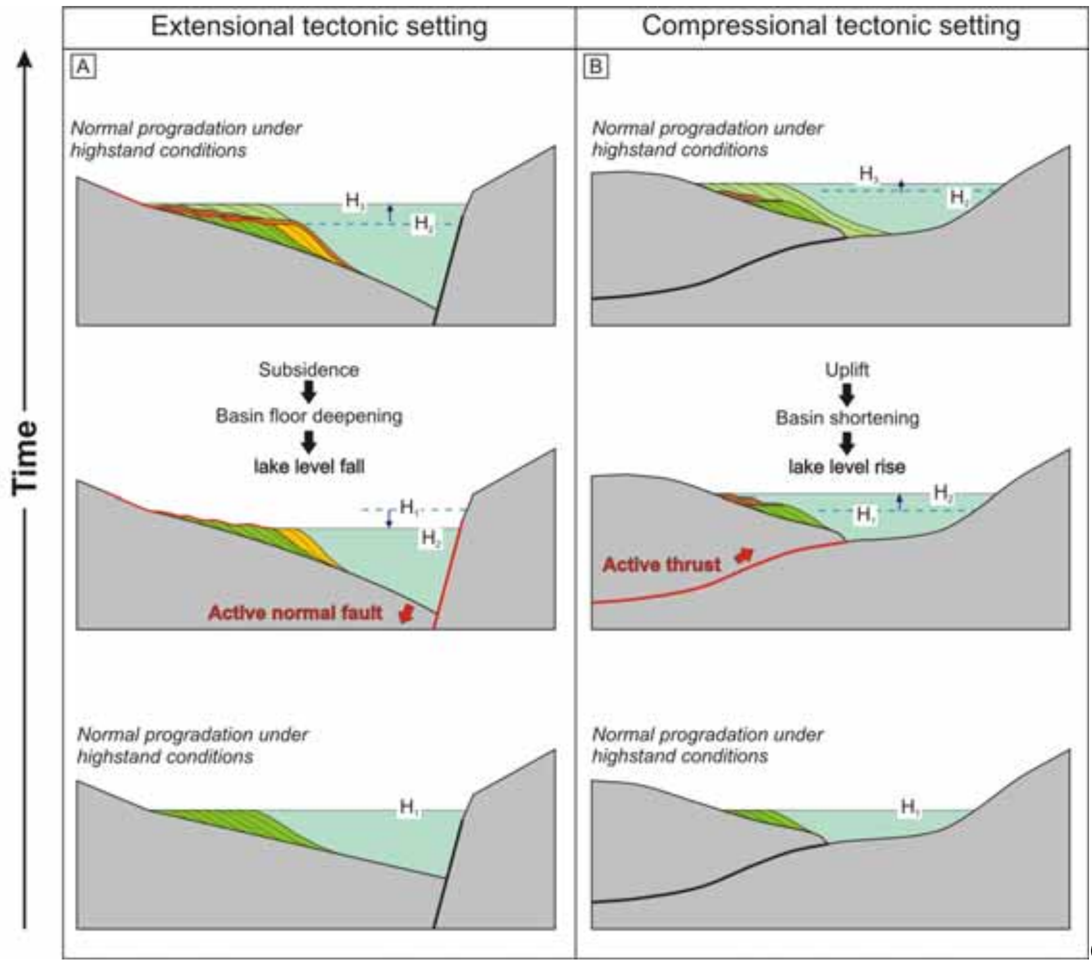

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Fig. 3.10 – Models showing the effects of tectonic control on lacustrine sedimentation. A) Extensional tectonic setting. B) Compressional tectonic setting.

3.5 CONCLUSIONS

The present paper has documented the sedimentary processes and stratigraphic architecture of mouth-bar type delta deposits developed during Late Pliocene in the Upper Valdarno Basin (Northern Apennines, Italy). The study deposits consists of mouth-bar units, which were stacked as a response to transgressive-regressive cycles induced by lacustrine oscillations.

Single mouth-bar units consist of a distal muddy portion passing landward into adjacent lobate units generated by inertia- and frictional-dominated effluents. The presence of adjacent lobes generated by different effluent dynamics can be explained in terms of changes in river-flood discharge and their effects on sedimentary processes acting at channel outlet. During episodes of high discharge (e.g. flood peak) jet-flow deposits (i.e. from an inertia-dominated effluent) develop at the outlet of the main distributary channels. During periods of low discharge, minor channels bifurcated around the jet lobe feeding friction-dominated effluents which give rise to low-relief lobes. Sediment is commonly transported under tractional conditions, and changes in flood discharge can be recorded by deposits accumulated both on inertia- and frictional-dominated bars.

Stratigraphic and palinological evidences highlight the role of tectonics in controlling development of lacustrine oscillations. The contrasting tectonic scenario (half-graben *vs*. thrust-top basin) defined by different Authors for the S. Donato basin allow to speculate on possible models for lacustrine oscillations stemmed out in different tectonic settings under constant climatic conditions. In an extensional setting, tectonic-driven lacustrine oscillations are prone to produce deltaic successions characterized by stacked sequences, whereas stacking of parasequences appear to be more prone to develop in a compressive setting.

Chapter 4

ALLUVIAL FAN AND AXIAL-FLUVIAL SEDIMENTATION IN THE PLIO-PLEISTOCENE UPPER VALDARNO BASIN

4.1 INTRODUCTION

Alluvial-fan sedimentary successions with cyclothemic architecture have been reported from different geological settings (Heward, 1978; Gloppen and Steel, 1981; Blair, 1987; DeCelles et al., 1991; Ravnas and Steel, 1998; Mack and Leeder, 1999; Benvenuti, 2003) where sediment supply and changes in accommodation space are driven by the interplay between eustasy, climate and tectonism (Catouneanu, 2002). In alluvial basins, which are not affected by shoreline variations (Shanley and McCabe, 1994), development of cyclothemic successions is strictly influenced by the tectonic control on the basin margin relief and by the climatic control on the hinterland denudation and the water discharge of the alluvial systems (Blum and Price, 1998; Gibling *et al*., 2005). Where development of alluvial-fan cyclothems is strictly controlled by tectonics, formation of coarsening- or fining-upward successions as a response to tectonic activity (Steel et al., 1977; Blair and Bilodeau, 1988; Paola et al., 1992; Benvenuti, 2003) is still matter of discussion. Furthermore, cyclothems development and alternation between aggradational and erosional phases in alluvial-fan systems have been rarely discussed in terms of the interaction between alluvial fans and fluvial axial systems (Leeder and Gawthorpe, 1987; Alexander et al., 1994; Mack and Leeder, 1999).

In this chapter Plio-Pleistocene alluvial-fan and fluvial-axial deposits of the Montevarchi and Torrente Ciuffenna Synthems are described. Alluvial-fan deposits were sourced from fault-bounded escarpment and are organized into CU (coarsening) and FU (fining) upward units. Fluvial-axial deposits drain almost parallel to this escarpment and show a different depositional style in proximal and distal areas. Alluvial-fan and axial deposits are not genetically related to variations in the level of a standing water (sea or lake) body (Martini and Sagri, 1993) and formed during two different depositional phases separated by a major unconformity surface (Martini and Sagri, 1993; Albianelli et al., 1995; Martini et al., 2001). The role of local tectonics in the development of alluvial-fan depositional motifs will be analysed. Moreover, alternation between aggradational and erosional phases in alluvial-fan systems will be discussed in terms of the interaction with fluvial axial systems

4.2 METHODS

This study is based on the facies analysis principles (Nemec, 1996) and aims to define sedimentary features, stratal architecture and depositional trend of coeval alluvial-fan and axial-fluvial deposits. Alluvial-fan deposits have been investigated in natural exposures, which covers a 20 km^2 area (**Fig. 4.1** and **4.2**) located at the toe of the escarpment generated by the Trappola normal fault (Abbate et al., 1991; Martini and Sagri, 1993). Fluvial deposits have been studied in several quarries located the central part of the basin (**Fig. 4.1**). The main sedimentary features of both alluvial-fan and fluvial deposits have been characterized through a detailed bed-by-bed logging. The used descriptive sedimentological terminology follows Harms et al. (1975, 1982) and Collinson et al. (2006). Stratal architecture has been highlighted through linedrawing of the most significant outcrops in sections both parallel and transverse to the main transport directions. Channel bars in fluvial and alluvial-fan deposits have been reconstructed trough integration of bed attitude and palaeocurrent data inferred from channel-lag deposits. Coarsening- and fining-upward depositional trends in alluvial-fan successions stem out from integrating linedrawings and sedimentological logs. The spatial distribution of these CU and FU lithosomes has been defined through a 1:10.000 scale field mapping.

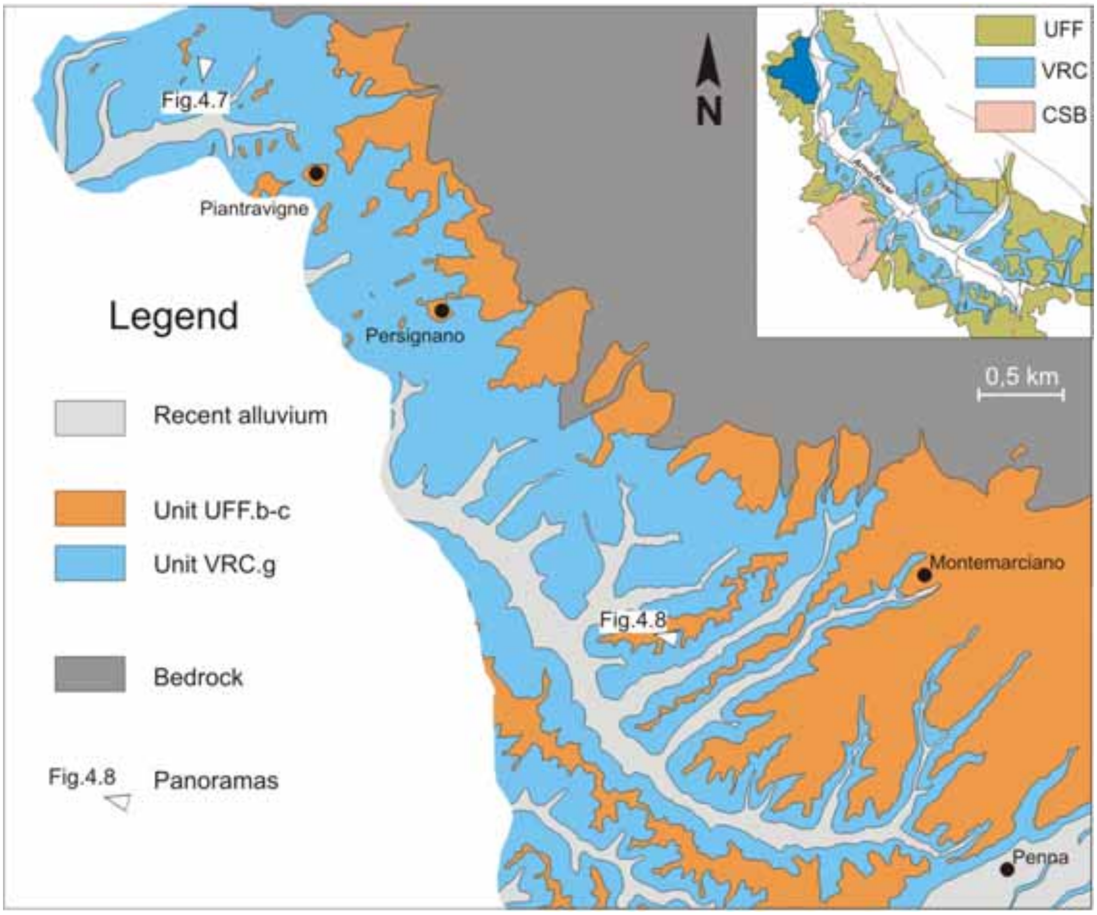

Fig. 4.1 – Geological sketch map for the study area.

4.3 THE STUDIED DEPOSITS

The study succession, up to 80 m thick, includes the middle-upper part of the Montevarchi Synthem and the overlying Torrente Ciuffenna Synthem (**Fig. 4.1** and **4.7**) (see Chapter 2 for details).

The Montevarchi Synthem (**Fig. 4.8**) consists of distal alluvial-fan sand and silt (unit VRC.g, 10 m thick) interfingering with axial sediments, which are represented by organic-rich mud accumulated in shallow floodplain lakes and representing a basin scale key-horizon (unit VRC.e, Argille del T. Ascione *Auctt.*). Interfingering of distal fans with these lakes gave rise to the shoal water fan-deltas described by Billi et al. (1991.) Channelized sandy bodies, up to 1.5 m thick and 10-15 m wide, are dispersed within the organic-rich muds. Distal alluvial-fan succession grades upward into proximal, gravel-dominated facies, giving rise to a well-defined CU trend (**Fig. 4.3**), which is associated with a diminishing of inter-channel deposits and increase of gravelly channels amalgamation (**Fig. 4.8**). Toward SW (i.e. downcurrent) the proximal alluvial-fan facies interfinger with axial fluvial deposits consisting of pedogenized floodplain mud with isolated channel-like sand bodies. These axial deposits don't bear any evidence of deposition in floodplain lakes. The CU package formed by stacked distal and proximal alluvial fan-deposits forms a laterally continuous horizon (**Fig. 4.2**) at the toe of the Pratomagno ridge. In the northern part of the study area, this CU package is covered by 10 m thick FU distal alluvial-fan deposits, which are capped by the erosional surface delimiting the top of the Montevarchi Synthem. In the remnant parts of the study area this FU lithosome is missing, and the erosional surface directly overlies the top of the CU horizon.

The alluvial-fan deposits of the Torrente Ciuffenna Synthem (unit UFF.b), with a maximum thickness of 60 m, are formed by the vertical stacking of distal on proximal facies (**Fig. 4.10**). This FU succession is well developed in the study area (**Fig. 4.2**), and interfingers with axial fluvial deposits formed by the palaeo-Arno river (unit UFF.a) (**Fig. 4.7**).

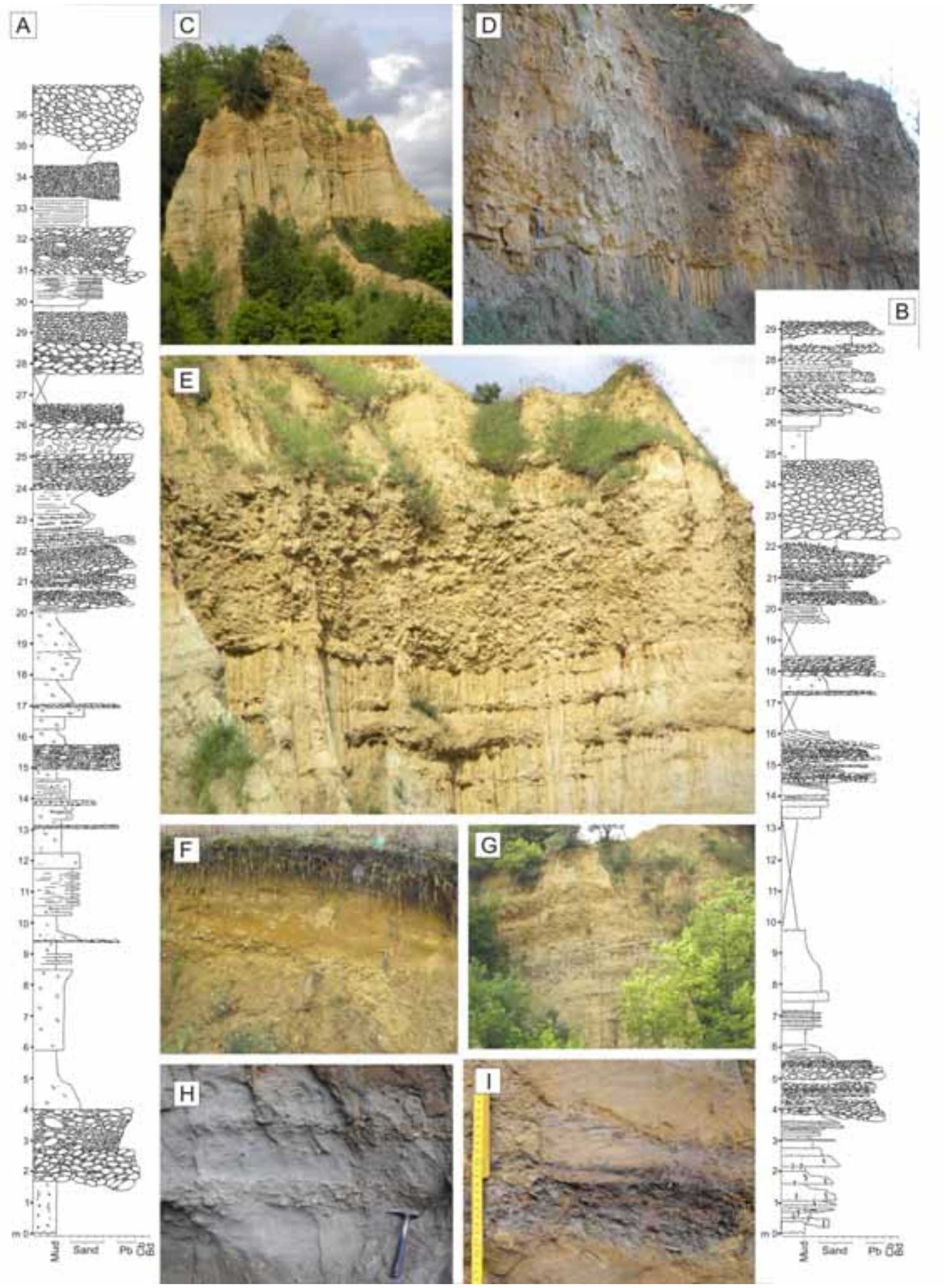

Fig. 4.2 – Alluvial fan deposits of unit VRC.g in the Montemarciano-Persignano area. A-B) Sedimentological logs across the exposed succession. C) Upper part of VRC.g succession showing a clear CU trend. D) Gravelly channel showing cross-bedded gravelly units accumulated on a lateral accretion bar. E) Detail of C showing a cross-bedded gravelly channelized body cutting tabular sandy beds. F) Sandy cross-bedded channel. G) Alternating sandy and gravelly deposits in the intermediate part of the succession. H) Thin gravelly layers alternating with sandy beds. I) Sandy and muddy, orgainc-rich beds occurring in the lowermost portion of VRC.g succession.

Fig. 4.3 – Photomosaic showing the Montevarchi Synthem axial-fluvial deposits (unit VRC.g) in the Matassino quarry.

4.4 DISCUSSION

4.4.1 CU-FU trends in the VRC Synthem alluvial fans

The persistence of difficult issues in understanding dynamics of alluvial fan developed in tectonically active settings stems out from using independently the geomorphological and stratigraphic approach. The geomorphological approach is based on the study of modern systems and provides information concerning geometries of alluvial fans and their relationship with geomorphic processes acting in the catchment areas (Bull, 1962; 1964; Viseras et al, 2003). The sedimentological and stratigraphic approach focuses on fossil successions and gives information on temporal variability of the systems in terms of changes in accommodation space and sediment supply (Steel et al., 1977; Heward et al., 1978; Paola et al., 1992). More recently an integrated geomorphological and sedimentological approach has been used by several Authors to analyze development of CU and FU depositional cycles in alluvial fan and fan-delta setting (Blair and Bilodeau, 1988; Posamentier and Allen, 1999; Benvenuti, 2003).

Although signals of the global glacial/interglacial cycling are documented in the upper Montevarchi Synthem (Bertini et al., 2010), the lack of changes in palinological content associated with the study CU and FU units (Albianelli et al., 1995) allows to rule out climate as the main forcing on sedimentation, which appears to has been mainly controlled by the Trappola fault.

The alluvial-fan sand and silt forming the lower part of the succession formed when the subsidence rate (i.e. Trappola fault activity) balanced the amount of sediment provided by the adjacent relief promoting aggradation (Paola et al., 1992) and preventing any move of the alluvial-fans front. Emersion of groundwater table, which promoted development of floodplain lakes (Miola et al., 2006) in axial areas (unit VRC.e), is coherent with an increase in subsidence rate (McCarthy, 1993). At this stage, the coarser sediments are stored in the proximal alluvial fan areas (Paola et al, 1992; Benvenuti, 2003) although a clear retreat at of the systems (Blair and Bilodeau, 1988) is not promoted. The overlaying CU interval developed when the subsidence rate, due to the Trappola fault activity, started to decrease. At this time, accommodation was not enough to receive sediments produced from the dismantling of the uplifted margin (i.e. re-equilibration of morphological profile) and the alluvial fans shifted toward the basin axis (Paola et al., 1992; Viseras et al., 2003), where absence of floodplains lakes agrees with decrease in basin subsidence (unit VRC.f). Finally, the FU unit capping the study succession developed as consequence of alluvial fans retreating occurred during conditions of tectonic quiescence. After producing CU deposits, the ongoing re-equilibration of morphological profile caused an upstream migration of erosion (Posamentier and Allen, 1999) with consequent starvation of distal area and alluvial fans retreat.

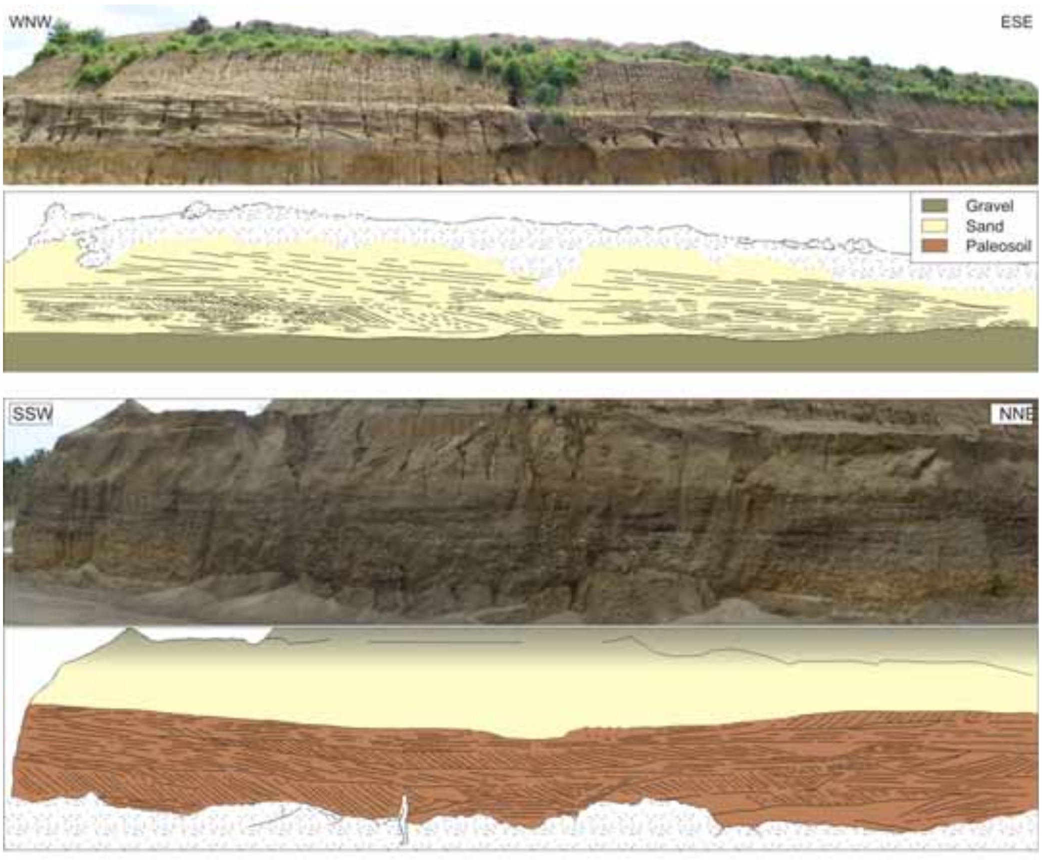

Fig. 4.4 –Photomosaics showing axial-fluvial deposits of the Torrente Ciuffenna Synthem (unit UFF.a) in the Vitereta quarry, close to Laterina. In the lower picture: gravelly low-sinuosity fluvial deposits forming the lowe part of the succession. In the upper picture: sandy low-sinuosity fluvial deposits forming the upper portion of the succession.

4.4.2 Origin of the unconformity between the VRC and UFF Synthems and FU trend in the UFF Synthem

The unconformity surface capping the Montevarchi Synthem is easily identifiable at the basin scale and commonly ascribed to a further tectonic phase (i.e. re-activation of the Trappola fault), which caused the entrance of the Arno River into the basin (Azzaroli and Lazzeri, 1977; Abbate, 1983; Sagri and Magi 1992; Albianelli et al., 1995). Although a tectonic event between the Montevarchi and Torrente Ciuffenna Synthem deposition is documented across several Tuscan basins (Boccaletti et al., 1995), its role in formation of the unconformity surface would have been less important, according with the undisturbed deposits of the Montevarchi Synthem. Moreover, basin subsidence associated with reactivation of the Trappola fault eventually prevented erosion of the axial areas (Paola et al., 1992). The main forcing on the unconformity formation would be discussed in terms of changes in water and sediment supply (Lane, 1955; Schumm, 1993) caused by the entrance of the Arno River in the basin. Such a marked change in basin hydrology is highlighted by the increase in size of the channels forming the axial deposits of the Montevarchi and Monticello Synthem (Fig. 4.4 and 4.6).

The Arno River, which flowed to SE through the Arezzo Basin (Bartolini and Pranzini, 1981), was captured by one of the tributaries entering the Valdarno Basin from E-NE (Bartolini and Pranzini, 1981). The progressive headwall migration of such a stream incised the rocky ridge separating Valdarno from the Arezzo Basin and allowed the Arno River to flow into the basin, as attested by the presence of biocalcarenitic clasts, belonging to bedrock units cropping out in the Casentino area, within the UFF.a fluvial deposits (Sestini, 1936). As for most of the captures, the Arno River capture can be considered as geologically instantaneous, although it is thought to be occurred through a transitory phase. During this phase the stream's headwall meet the Arno River, which flowed both into to the Valdarno Basin and through its previous course, where most of its bedload was trapped in the thalweg zones. As a result, a large volume of water flushed into the Valdarno basin increasing the hydraulic discharge of the axial drainage, which started to erode the central basin-fill deposits in order to acquire its bedload (Lane, 1955). The Arno River axial incision caused a base-level lowering at the basin scale, with consequent entrenching of its transverse tributaries. The major tributaries (e.g. Ciuffenna Stream) eroded the whole FU interval capping the Montevarchi Synthem alluvial fans (e.g. southern part of the study area; **Fig. 4.2**), whereas such an interval was preserved in areas drained by minor streams (e.g. northern part of the study area; **Fig. 4.2**). The large amount of water drained into the basin, along with the lack of cementation in the Montevarchi Synthem deposits, allowed erosion of a large volume of sediment in a short time. The end of this transitory phase was marked by the definitive intersection between the Arno River and the stream's headwall with the definitive sidetracking of the Arno water and bedload into its new course. The entering of sediment-laden water into the Valdarno Basin brought erosion to an end and promoted aggradation of the Torrente Ciuffenna Synthem deposits.

Until the embanking of the Arno River persisted, erosion in the distal reaches of the fans was boostered, but when the axial base level lowering ceased, a marked upstream migration of the knickpoints occurred in order to re-equilibrate the streams profile (Posamentier and Allen, 1999). The sediment produced during such a re-equilibration was accumulated above the unconformity surface, but a progressive starvation affected the distal areas as consequence of knickpoint upstream migration. The progressive re-equilibrium of streams profile induced starvation in the alluvial fans, with consequent development of the FU succession of the Torrente Ciuffenna Synthem.

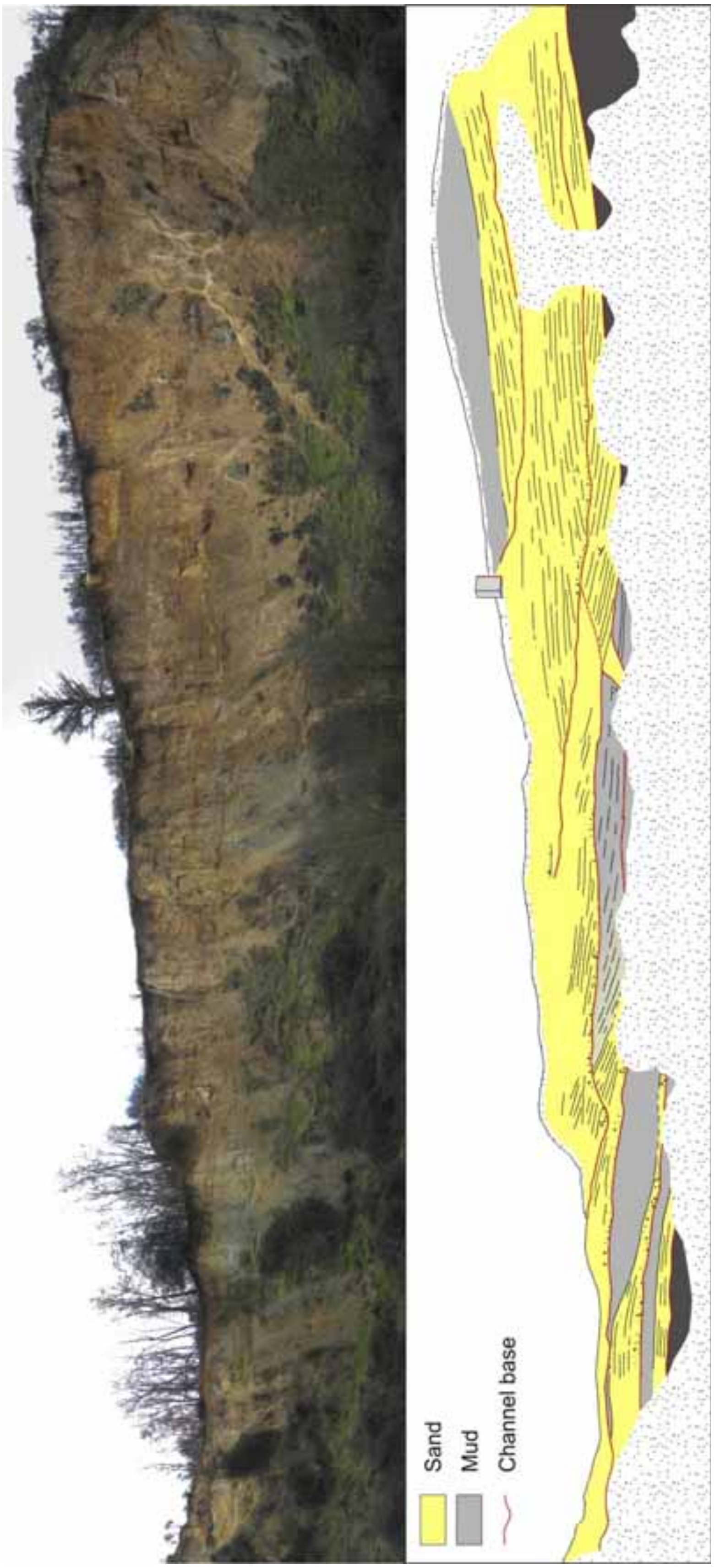

Fig. 4.5 – Photomosaic showing sandy axial-fluvial deposits of the Torrente Ciuffenna Synthem in the San Givanni Valdarno area.

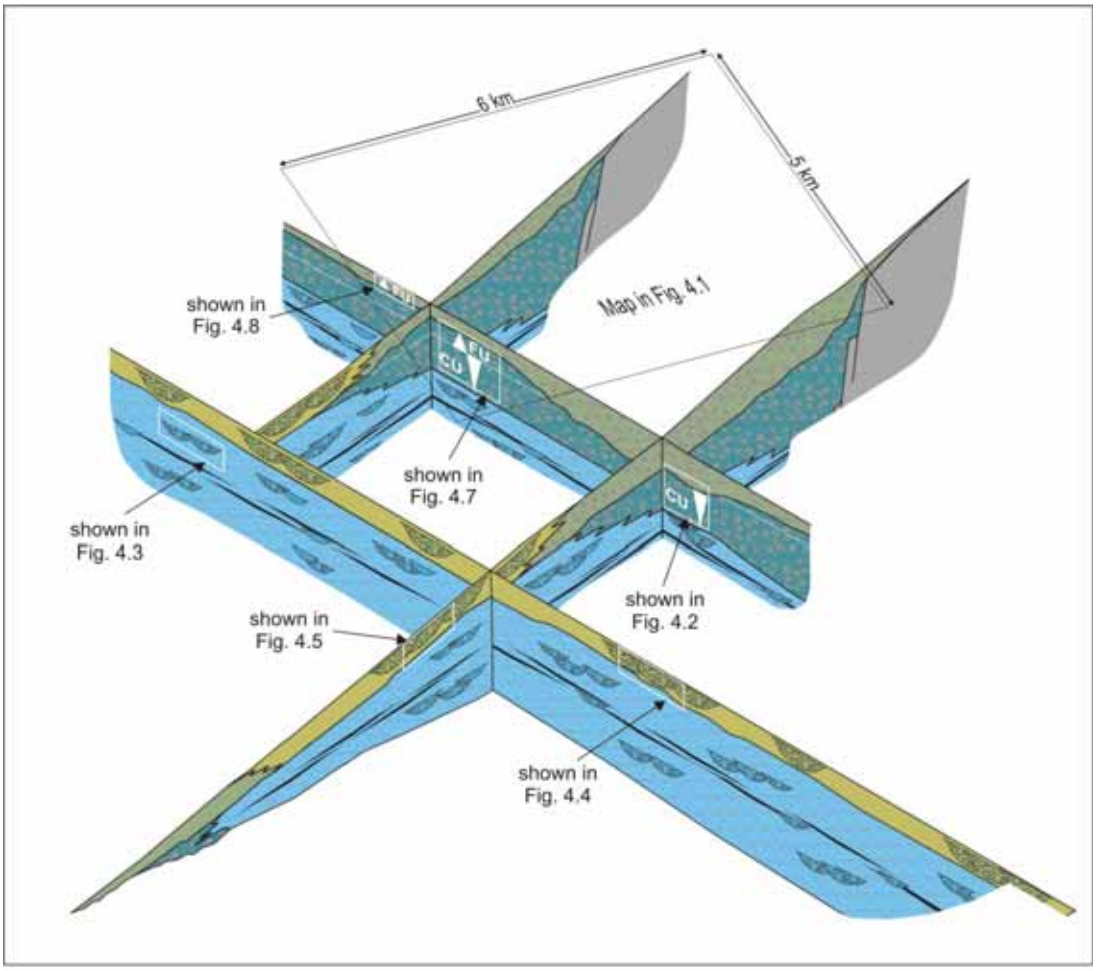

Fig. 4.6 – 3D sketch for the studied succession, showing the geometrical relations between the axial-fluvial and alluvial fan systems.

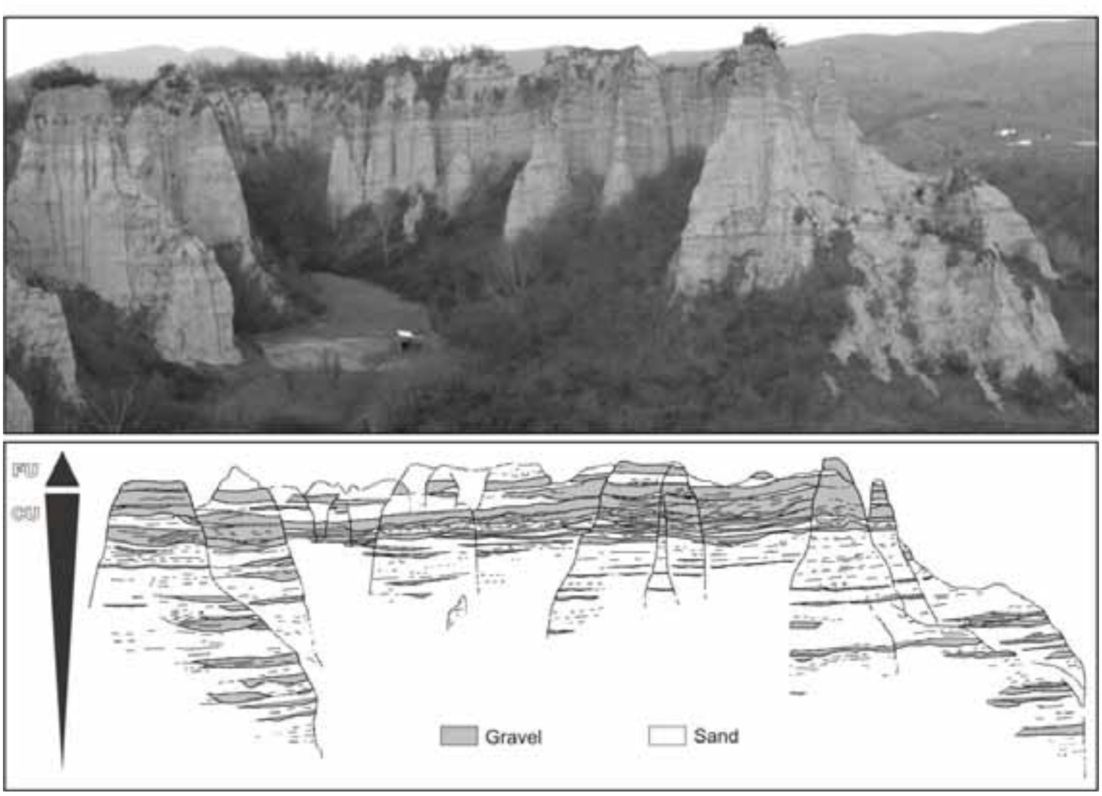

Fig. 4.7 - Alluvial-fan deposits of unit VRC.g in the Castelfranco di Sopra area. Note the CU-FU trend resulting by progradation and following backstep of the alluvial-fan system.

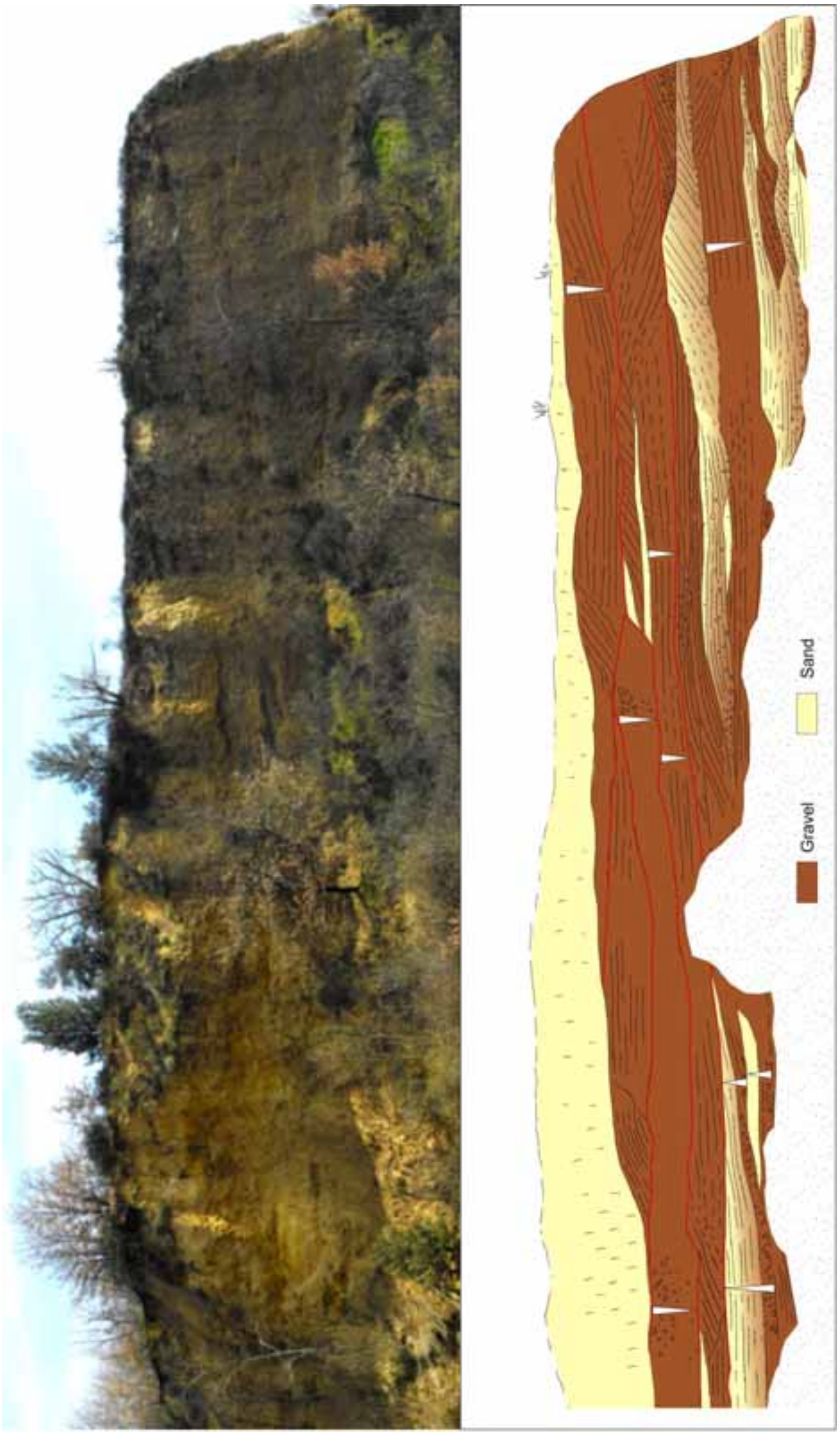

Fig. 4.8 – Photomosaic showing the FU trend characterizing the alluvial fan deposits of the Torrente Ciuffenna Synthem north of Montemarciano.

4.5 CONCLUSIONS

Progradational (i.e. CU) and retreogradational (i.e. FU) stacking patterns recorded in the alluvial-fan succession of the Plio-Pleistocene Valdarno basin (Northern Apennines, Italy) have been discussed in terms of interaction between fault-related accommodation space and amount of sediment produced by re-equilibration of river profile. Fine-grained aggrading alluvial fan facies formed during tectonic activity, when high subsidence rate prevented basinward shifts of fans. At this stage, the coarser sediments are stored in the proximal alluvial fan areas. When subsidence ceased, accommodation was not enough to store the sediments produced from dismantling of the uplifted margin, and the alluvial fans shifted toward the basin axis. After this progradational phase, the ongoing re-equilibration of morphological profile caused an upstream migration of erosion with starvation of distal area and development of a FU succession.

The basin-scale unconformity, which splits the study alluvial-fan succession in two portions, was generated by a hydrological disequilibrium affecting the axial drainage as consequence of the entering of the Arno River into the basin. The consequent increase in axial water caused embanking of the axial system and consequent propagation of erosion along the transverse tributaries. Erosion propagated from the distal to the proximal reaches of the fans and was associated with formation of an upstream-migrating knickpoint in the drainage system.

When the axial base-level lowering ceased, a re-equilibration the streams profile occurred through an upstream knickpoints migration. The sediment produced during such a re-equilibration was accumulated above the unconformity with consequent development of a FU succession.

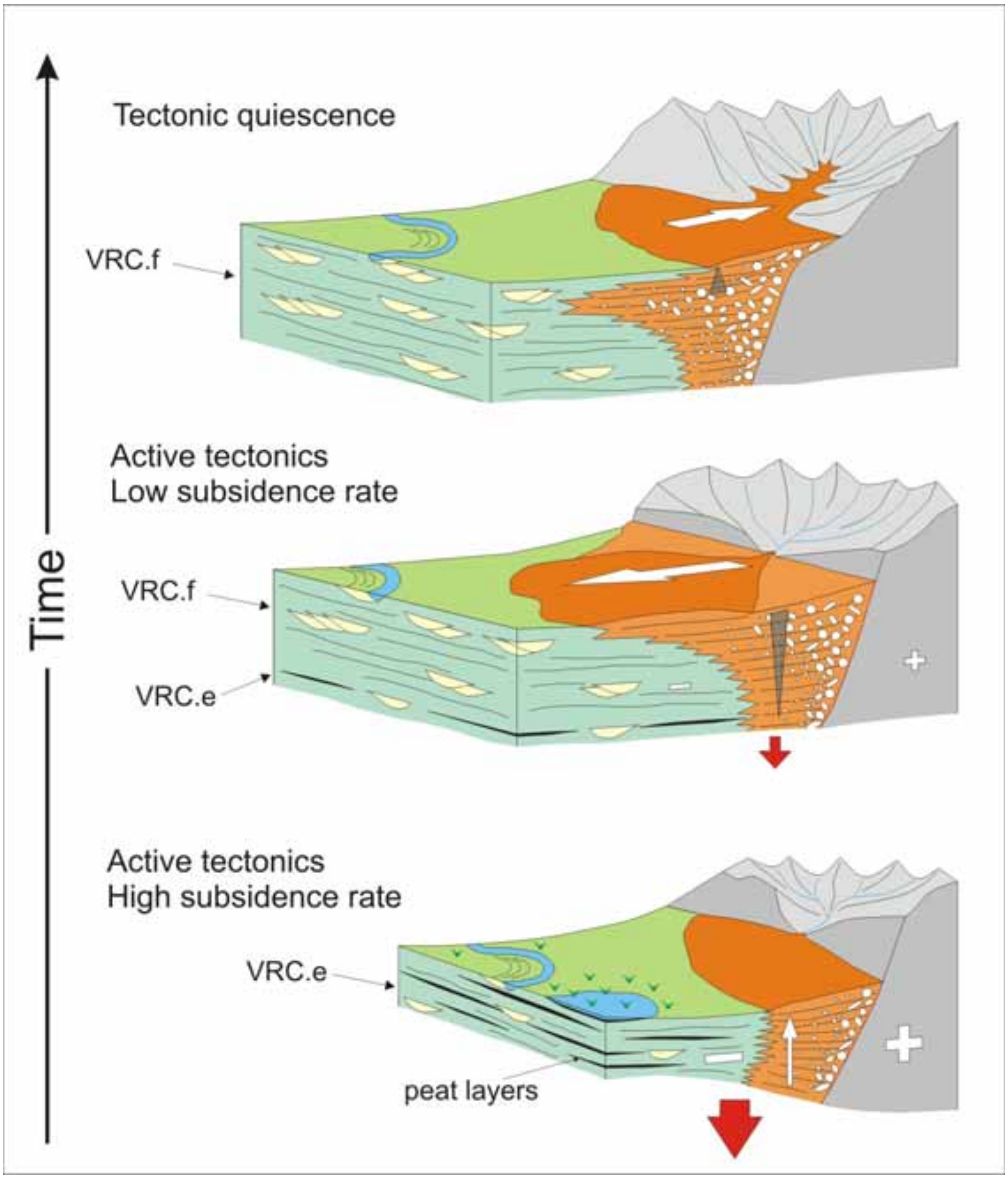

Fig. 4.9 – 3D sketch showing the development of CU-FU trends in the Montevarchi Synthem alluvial-fan deposits (unit VRC.g) and their interaction with the axial-fluvial system (units VRC.e-f).

Chapter 6

PALYNOLOGICAL DATA

6.1 INTRODUCTION

During the past years several studies were carried out at the boundary between the Castelnuovo and Montevarchi Synthems (Albianelli et al., 1995; Ghinassi et al, 2004; 2005; Ghinassi and Magi, 2004; Carta Geologica Regione Toscana 1:10.000). These studies aimed to define the main changes affecting the basin in terms of depositional systems, and to identify the main forcing factors on sedimentation. Three main depositional units were distinguished just above the unconformity cutting the deltaic deposits (unit CSB.c in Chapter 3 and "Sabbie di S. Donato" *Auct*.) at the top of the Castelnuovo Synthem. These units, labelled as VRC.a, b and c in Chapter 3, were formed by alluvial systems sourced from the Chianti ridge. In particular, units VRC.a and b (Ciottolami e Sabbie di Spedalino and Sabbie di Palazzetto *p.p.*, in Carta Geologica Regione Toscana 1:10.000) indicate emplacement of alluvial fans (VRC.a), which were progressively deactivated and affected by eolian reworking (VRC.b) as consequence of a global climatic deterioration (e.g. Albianelli et al., 1995; Ghinassi et al., 2004; Bertini, 2010). Unit VRC.c (Sabbie di Palazzetto p.p., in Carta Geologica Regione Toscana 1:10.000) records the temporaneous re-establishment of wetter climatic conditions (e.g. Ghinassi et al., 2005; Bertini, 2010 and references therein).

Since climatic control appears to be a significant forcing on sedimentation at the boundary between Castelnuovo and Montevarchi Synthems, a further detailing of the palynological record was required. Besides its palaeoclimatic meaning, the palynological data have been used as an additional correlative tool between stratigraphic units.

Palynologic analysis allows studying microfossils with an average diameter of 10-100 μm, such as pollen, spores, dinocysts and other algae. For paleoclimatic reconstructions the analysis focuses on pollen produced by Angiosperms and Gymnosperms. Pollen produced by these plants is commonly abundant and well preserved within sediments, giving the opportunity to speculate on the environment where the mother-plant lived, through the evaluation of its ecologic needs.

Pollen grains preservation through time is assured by a very strong outer wall, called sporoderm and formed by two layers: the inner one is called intine, the outer one is called exine. The latter is made of sporopollenin, one of the most resistant organic substances existing in nature. The exine is not affected by weathering due to the action of strong acids or alkalis or high temperatures, then pollen grains can be treated with chemical-physical processes, which allow separating them from the hosting sediment. Pollen can be recognized using the peculiar morphological features of the exine, and their classification follows the one used in botanic systematics. Microscope analysis of fossil findings commonly point to determine the genus for arboreal plants, whereas for herbaceous plants the identification is in general limited to the family. A correct reconstruction of the vegetal assemblages is also based on the evaluation of production and. In fact, although plants produce a big amount of pollen grains and spores, only a minor part of them is used for reproduction, whereas most of the grains are dispersed in the environment.

The different amount of pollen that a plant produces depends on its pollination process. A larger pollen production will be reflected by a larger representation of that type of pollen grains within the sediments and, as a consequence, in the pollen record. This fact is to be taken into consideration for a critical evaluation and interpretation of the data. Moreover, the granules dispersed within the sediments could have been produced in loco or transported by depositional processes or by animals. The most suitable settings for pollen fossilization are those characterized by limited oxygenation, because oxidation is one of the main causes for exine degradation. Thus muddy deposits and peaty sediments are generally favorable frames for palynomorphs preservation.

Summarizing, through the evaluation of all the factors influencing the nature of the final palynological association it is possible to reconstruct the floristic-vegetational history of a studied area, and so its climatic evolution.

6.2 SAMPLED SECTIONS

As a support for paleoenvironmental and stratigraphic analysis, three sections have been sampled for palynologic investigations. The selected stratigraphic interval is the one covering the passage between the Castelnuovo Synthem and the Montevarchi Synthem (Units CSB.c, VRC.a and VRC.b). The sampled sections are located close to the SW margin of the basin, in an area comprised between San Giovanni Valdarno and Montevarchi (**Fig. 5.1**). As a whole 23 samples have been collected.

6.2.1 San Donato Section (SD)

The section, 25 m thick, is located north of the San Cipriano artificial lake and represents the medium-upper part of unit CSB.c. In this section 8 samples have been drawn within the muddy interlayers of unit CSB.c deltaic deposits (see Chapter 4).

6.2.2 San Cipriano Section (SC)

This section, 25 m thick, is located close to the San Cipriano village, west of San Giovanni Valdarno. Here recent road-cuts have exposed the uppermost part of Unit CSB.c and its unconformable contact with Unit VRC.b. This boundary is marked by a major erosional surface, a clear lithological shift and by a subtle angular unconformity.

Samples belonging to this section have been taken from the muddy intervals interbedded within fluvial deposits on top of unit CSB.c (samples SC01-02) and from the thin muddy intercalations in fluvial sands of unit VRC.b (samples SC03-07) (see Chapter 2 and 3).

6.2.3 Ricasoli Section (RIC)

This section (20 m thick) is exposed on a small escarpment close to the Ricasoli village, west of Montevarchi. In this area distal alluvial fan deposits of Unit VRC.b crop out (see Chapter 3) and samples have been collected from muddy layers contained within overbank deposits or capping channel deposits.

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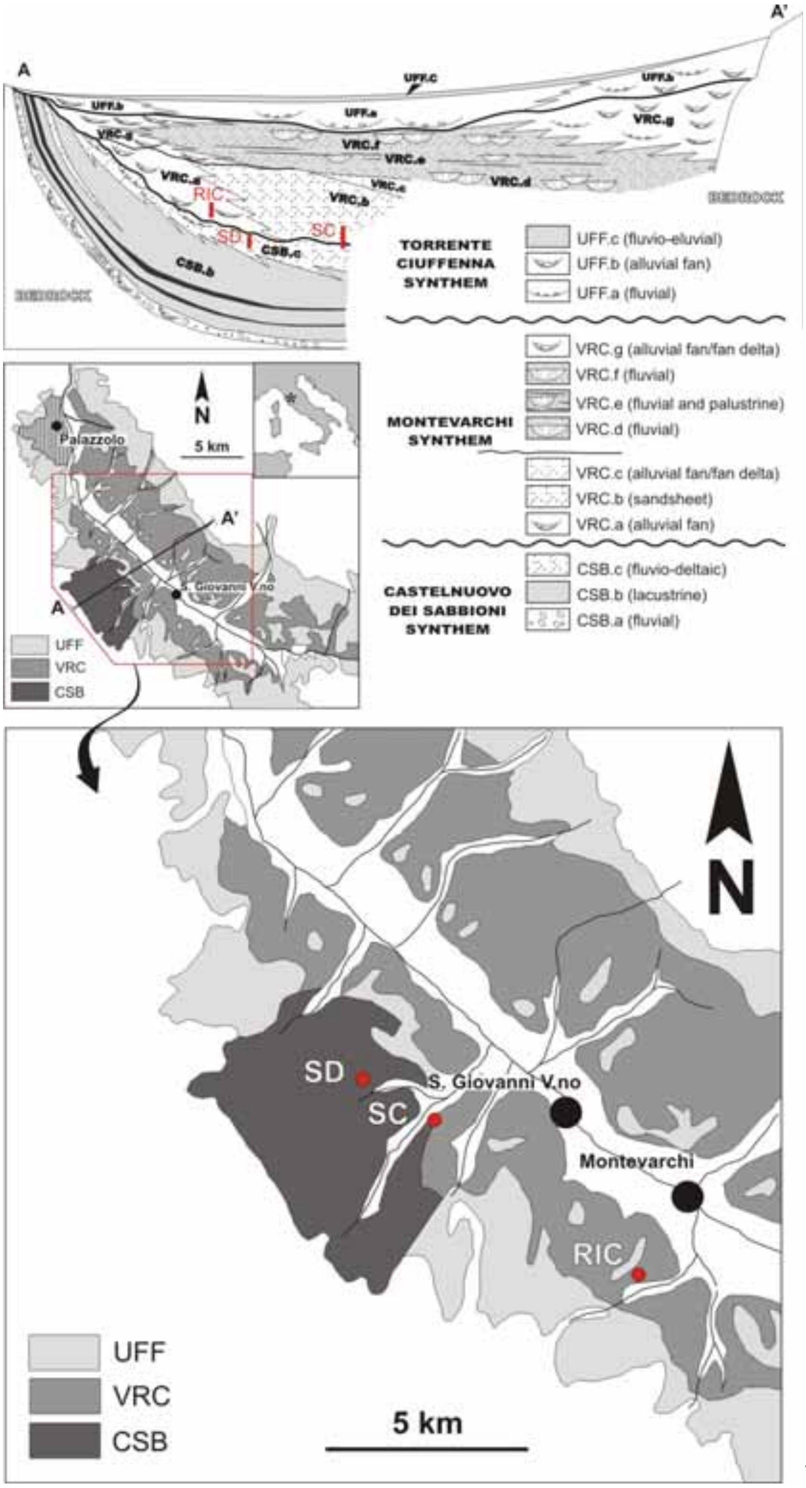

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6.3 PREPARATION OF THE COLLECTED SAMPLES

6.3.1 Chemical-physical treatment

The collected samples have been treated in the Laboratory of Palynology of the Earth Sciences Department, University of Florence, according to the following methodology.

6.3.1.1 Sample preparation

- The sample must be dry.
- The outer parts of the sample, which may be affected by pollution, must be removed with an uncontaminated knife or similar tool.
- The sample is triturated. The amount of sediment drawn for the treatment ranges between 5 and 30 g, depending on how many palynomorphs are expected to be found within the deposits.
- A tablet containing a fixed quantity of *Lycopodium* spores (18583 per tablet) and some drops of Hydrochloric acid (HCl) for its dissolution are added in the test-tubes used for the treatment. The *Lycopodium* spores will be used as a reference for the measurement of fossil palynomorphs concentration, following the *marker-grains* method (Matthews, 1969).

6.3.1.2 Attack with acids

- A 20% solution of Hydrochloric acid (HCl) is added in the test-tubes containing the sediment. The acid ambient allows carbonates dissolution and the reaction occurs commonly in 2-3 hours. When the reaction is completed the sample is centrifuged with a speed of 2500 rpm for 10 minutes, then it is decanted and washed with filtered water.
- A 38-40% solution of Hydrofluoric acid (HF) is then added to the sediment samples to dissolve the silicates. When the reaction is completed, generally after 24-48 hours, the test-tubes are balanced with HCl and centrifuged with a speed of 2500 rpm for 10 minutes, then decanted. After that every sample is washed two times with filtered water. To eliminate the eventually formed fluorosilicates

a treatment with HCl in warm conditions is needed. HCl is added to the test-tubes which are heated through immersion in hot water. The reaction is completed in 3 hours.

6.3.1.3 Sample neutralization

- Test-tubes are balanced with filtered water and centrifuged with a speed of 2500 rpm for 10 minutes, then decanted. This passage is repeated at least two times to neutralize the acid ambient developed during the previous phases.
- The next treatment consists in the addition of Sodium esametaphosphate ($(NaPO_3)_6$) with pH=7. This passage is carried out to clear the pollen grains and to solubilize, and then eliminate, the eventually formed metal cations (Fe^{2+} and Fe^{3+} in particular) involved in the structure of clays. Such a process allows a better dispersion of the particles. The reaction is left going for 15-20 minutes. Then the samples are balanced, centrifuged and washed until the decanted water appears clear.

6.3.1.4 Attack with alkalis

- A treatment with Potassium hydroxide (KOH) in heated conditions for 10-15 minutes is needed to eliminate humic and fulvic acids.
- The residual material for every sample is collected through a mechanical sieving using filters with 200 μm meshes, then it's washed, centrifuged, decanted and dried.

6.3.1.5 Separation with heavy metals

- A quantity of Zinc chloride ($ZnCl_2$), with density=2, comparable with the amount of residual sediment is added in every test-tube. This passage allows the separation of the denser parts, mineral or organic, from the remaining of the material. The treated sample is centrifuged at 1000 rpm for 5 minutes, then the overlying material is collected in a new test-tube. To complete this passage it is necessary to check the lack of palynomorphs within the eliminated heavy fraction; if not the passage must be repeated. To carry out this control microscope slides with the heavy residual must be mounted.

6.3.1.6 Ultrasound filtering

- The remaining sediment is filtered through a 10 μm mesh filter positioned within a ultrasound bath, to eliminate the finer particles and disaggregate the minerals still present. This treatment is particularly aggressive and pollen grains must always remain within the water during the proceeding.

6.3.1.7 Glycerol addition

- Samples are centrifuged at 2500 rpm for 10 minutes, residual water is decanted and sediment is left to dry for few hours.
- All the samples are added with glycerin and volumetric measurements are carried out using a Gilson pipette.

6.3.2 Microscope slides mounting

First of all coverslips are prepared. Using a pipette cone, a narrow trail of adhesive is traced along each of the coverslips longer borders and then left to dry. In the meantime 50 μl of residual material are drawn from the test-tube and disposed in the center of the microscope slide. Other two trails of adhesive are traced over the previous and the coverslip is positioned on the microscope slide. When the material is distributed all-over the available surface, the two open borders of the coverslip are sealed with a trail of adhesive.

The described technique points to leave some mobility to the pollen grains through the presence of a small thickness of adhesive between the microscope slide and the coverslip. This allows the analysis operator to move the grains, favoring a better observation of their morphological characteristics and an easier recognition.

6.4 MICROSCOPE OBSERVATIONS

Quantitative microscope analyses have been carried out by Dr. Adele Bertini of the Earth Sciences Department, University of Florence, using an optical microscope with an immersion 100x objective in the Laboratory of Palynology of the same department. Palynomorphs identification has been supported by the consultation of "Pollen et spores d'Europe et d'Afrique du nord" by Maurice Reille, of the "Review of Paleobothany and Palynology" collection, of the department comparing collection and other available photographic material.

Although the results are still preliminary, they provide useful information for stratigraphical discussion and can be summarized as follows.

In the **SD** section the palynological analyses are still in progress, nevertheless from the preliminary results pollen assemblages are very close to those already observed in the stratigraphic interval across the transition between unit CSB.b and CSB.c, which documents the dominance of warm forest associations typical of a humid, subtropical to warm-temperate climate; the dominance of such assemblages is also observed in some samples from the **RIC** section (e.g. RIC05); in this section, unfortunately, many samples are barren to virtually barren in pollen (e.g. RIC04, 07, 08). The most relevant vegetational change is clearly observed throughout the **SC** section where, starting from sample SC03, a progressive increase in herbaceous elements is recorded and *Artemisia,* a steppic element, reaches its major values in sample SC06.

6.5 DISCUSSION

The pollen assemblages found within samples from the San Donato section resemble those reported in literature for unit CSB.c (Albianelli et al., 1995; Napoleone et al., 2003). Moreover, the pollen associations of transgressive deposits are not dissimilar from those of the regressive ones, highlighting that probably lacustrine oscillation were not promoted by climatic changes (see Chapter 4).

Samples belonging to the Ricasoli section have been collected from the distal part of alluvial-fan deposits of unit VRC.a. Those facies have been previously interpreted as the upstream expression of fluvio-eolian deposits of unit VRC.b (Denise, 2005). Incompatible pollen associations for the two units in this section reveal that such a correlation is not motivated. Integration of palynological data with a detailed field mapping highlighted that unit VRC.b overlays the distal part of unit VRC.a (see Chapter 2). Moreover sedimentological evidences indicate a progressive deactivation of the alluvial fan system and the onset of eolian-reworking processes, in agreement with the high content in *Artemisia* recorded in the fluvio-eolian deposits of unit VRC.b.

The pollen assemblages resulting from samples collected in the uppermost part of unit CSB.c in the San Cipriano section are close to those reported for the San Donato section. Samples SC03-07, belonging to unit VRC.b, show a progressive increase in *Artemisia* content, indicating dryer conditions compared with the underlying samples. Nevetheless, the content in *Artemisia* for these deposits is lower than the one documented in the uppermost part of unit VRC.b in the S. Giovanni Valdarno area (Albianelli et al., 1995), suggesting that the S. Cipriano section represents the lower portion of VRC.b succession.

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6.6 CONCLUSIONS

The main results obtained by the integration of palynological analyses and stratigraphic/sedimentological data can be summarized as follows:

- Pollen associations of transgressive and regressive deposits from unit CSB.c deltaic sediments are not dissimilar, suggesting a tectonic origin for lacustrine oscillations (see Chapter 4).
- Pollen assemblages of unit VRC.b deposits are not compatible with those recorded by unit VRC.a and a stratigraphic correlation of the two units is not motivated. This confirms stratigraphic and sedimentological evidences, indicating that unit VRC.b overlays the distal reaches of unit VRC.a.
- New data from VRC.b unit in the S. Cipriano area, suggest that this part of the succession is older that the one exposed close to S. Giovanni Valdarno, basing on the relative abundance of *Artemisia*.

Chapter 6

BASIN EVOLUTION AND FINAL REMARKS

6.1 BASIN EVOLUTION

Basin evolution can be discussed in terms of changes in accommodation space availability (*sensu* Jervey, 1988) and considering that, since the basin was out of marine base-level control, tectonics and climate have been the main forcing on sedimentation.

6.1.1 Basin development and accumulation of CSB Synthem

Deposition in the Castelnuovo dei Sabbioni area is thought to have started during the Late Pliocene, as indicated by the occurrence of the Kaena paleomagnetic event at the top of the lignitiferous deposits of unit CSB.b (Albianelli et al., 1995). Concave-upward base of the elongated alluvial bodies of unit CSB.a suggests they represent the infill of valleys cut onto the rocky substrate and draining toward NE, according to paleocurrent data. A similar hypothesis was suggested also by Coltorti et al. (2007), which ascribed the whole CSB Synthem to a NE flowing fluvial drainage sourced from the Mid-Tuscan Ridge (Martini and Sagri, 1993), implying the absence of the Chianti Ridge during the Late Pliocene. Sedimentological evidences from the present study highlight that such a drainage was limited to the accumulation of CSB.a unit, whereas CSB.b and CSB.c units developed in a lacustrine and deltaic setting, respectively. Moreover, thermochronological data point out that the Chianti Ridge was uplifted since Late Miocene (Tangocci et al., 2010). Valley-floor aggradation documented by CSB.a deposits was promoted by a tectonic disturbance related to basin development, without necessarily implying establishment of a lacustrine environment in the more distal areas. A tectonic disturbance (e.g. epeirogenic movements *sensu* Holbrook and Schumm, 1999) affecting the longitudinal profile of several adjacent valleys indicates aggradation upstream and downstream of the uplifted area, respectively (Holbrook and Schumm, 1999). In the frame of the Valdarno Basin development, the uplift of the Pratomagno district fits with alluvial aggradation in westernmost located areas (**Fig. 7.1A).** The ongoing of this uplift allowed the uplift rate to prevail on the erosional capacity of rivers, leading to valley drowning and development of a lacustrine environment (**Fig. 7.1B**). Such a damming caused a fast transgression of CSB.a alluvial gravels, preventing formation of well-developed deltaic systems. Small shallow-water deltas recorded at the base of unit CSB.b remained nested within valley depressions, where swampy environments developed during lacustrine rises (Magi and Sagri, 1994; see Chapter 2). The large amount of woody material accumulated in these swamps gave rise to the main lignite layers. The occurrence of small shallow-water type deltas during the early phase of lake formation indicates a low gradient of the coastal areas (Postma, 1990), suggesting the absence of major faults bounding the SW margin of the basin. During this shallow lacustrine phase, the drainage system was not probably completely dammed according with the absence of a significant lake deepening (Holbrook and Schumm, 1999). Such a deepening occurred just after deposition of the main lignitiferous layers leading to a significant expansion of the lake (**Fig. 7.1C**) and accumulation of the thick muddy CSB.b unit. Once the lake reached its maximum size, the CSB.c deltas prograded from the Chianti margin (**Fig. 7.1D**). Again, development of shallow-water type deltas points to a low gradient of the coastal areas and absence of major faults bounding the SW margin of the basin. The occurrence of deltas prograding from NW indicates that watercourses adjacent to the basin were captured by the evolving basin drainage (**Fig. 7.1D**).

The size of the Castelnuovo lake is not certain, and, although the basal lignitiferous layers have been followed 2-3 km toward NE in the subsurface, the presence of the Castelnuovo Synthem below the Arno River is uncertain. The NW-SE extent of the Castelnuovo lake was traditionally limited between Gaville and Vacchereccia (Albianelli et al., 1955; Napoleone et al., 2003). On the contrary, borehole data from the S. Giovanni Valdarno and Montevarchi areas would suggest the lake was spread several kilometers southeastward.

6.1.2 From the CSB to the VRC Synthem

The unconformity surface marking the top of the Castelnuovo Synthem stemmed out from a tectonic pulse that is clearly documented by the angular feature of the unconformity. The structural setting of the CSB deposits indicates that such a tectonic event caused an uplift of the Castelnuovo area and a tilting of the lacustrine deposits. This change in basin configuration implied an eastward shift of the depocentral areas and erosion of the CSB deposits, which were probably re-deposited below the modern Arno River (**Fig. 7.1E**). According to the magnetostratigraphic record (Albianelli et al., 1995), the tectonic event leading to basin reorganization occurred between 3 and 2.5 Ma and can be correlated with similar surfaces documented in several basins of the Northern Apennines (Pascucci, 1997; Boccaletti and Sani, 1998; Bossio et alii, 1998; Martini et alii, 2001).

6.1.3 Alluvial sedimentation and unconformity formation in the lower VRC Synthem

The development of the unconformity capping the Castelnuovo Synthem forced a significant eastward shifting of the hingepoints (*sensu* Posamentier and Allen, 1999) belonging to the Chianti alluvial systems (Fig. 7.1E). Basinward hingepoints migration caused erosion along the Chianti margin with consequent broadening of the basin drainage. During the following re-equilibration of the morphological profile, the alluvial hingepoints moved upstream allowing aggradation of FU alluvial-fan successions of unit VRC.a in the Caposelvi and Figline Valdarno areas (**Fig. 7.1F**). These alluvial-fan deposits indicate two significant sediment entry points from SE and W, which probably developed as consequence of basin drainage widening (e.g. river capture) during the previous phase of margin uplift. The FU trend of VRC.a deposits points to a progressive alluvial fan deactivation, which culminated with accumulation of the eolian facies of VRC.b unit (Ghinassi et al., 2004) in the topographic low confined between the Caposelvi fan and the San Cipriano high (**Fig. 7.1G**). Development of these peculiar eolian facies occurred at about 2.5 Ma (Albianelli et al., 1995; Ghinassi et al., 2004) and stemmed out from a global climatic deterioration (Hornibrook, 1992; Raymo et al., 1992; Shakleton et al., 1995) that was further enhanced by local orography (Ghinassi et al., 2004). The syn-sedimentary tectonics occurred during VRC.b deposition culminated with a new deformative phase, which caused erosion along the Chianti margin and deposition of unit VRC.c in more distal areas. As a consequence of this tectonic pulse, an unconformity surface developed at the top of the more proximal VRC.b unit (**Fig.**

7.1H) and a topographic low in the S. Cipriano area (**Fig. 7.1H**), where lacustrine facies accumulated. During deposition of unit VRC.c, occurred under a progressive climatic readjustment following the fluvio-eolian phase (Ghinassi and Magi, 2004), the lacustrine basin probably had a fluvial emissary (**Fig. 7.1H**), according to the fish faunas (Ghinassi et al., 2005).

6.1.4 The alluvial sedimentation in the upper VRC Synthem

After the VRC.c tectonic pulse, a progressive morphological re-equilibration of the basin margins took place (**Fig. 7.1I**), leading to establishment of an axial fluvial drainage (unit VRC.d) with associated alluvial-fan systems along the margins (unit VRC.g). Identification of an axial fluvial drainage in the middle part of the Montevarchi Synthem succession highlights the occurrence of a fluvial outlet, providing noteworthy insights to the previous paleogeographic reconstructions (e.g. Bartolini and Pranzini, 1981; Albianelli et al., 1995), which ascribed units VRC.d-f to a lacustrine setting. At this stage the basin reached its present-day architecture, with a well-defined bounding normal fault along the NE margin. Basin emissary was reasonably located to NNW given the distribution of alluvial-fan systems along the margins. The basal FU trend of VRC.g unit attests backstepping of the alluvial-fan systems due to the progressive morphological re-equilibration of the basin margins. Alluvial fans backstepping culminated in an overall starvation of the axial areas, where floodplain lakes (**Fig. 7.1L**) developed during deposition of unit VRC.e during the Early Pleistocene (Albianelli et al., 1995). Formation of these lakes was possibly enhanced by the emergence of the water table (Gumbricht et al., 2004; McCarthy, 1993) induced by a further subsidence pulse, which affected the whole basin and triggered a new morphological disequilibrium along the margins. The progradation of the marginal alluvial fans, which stemmed out as response to this disequilibrium, formed the CU interval of the VRC.g unit. In places, alluvial fans prograded into the shallow floodplain lakes developing isolated fan-delta systems (Billi et al., 1991), which filled the floodplain lakes establishing conditions for accumulation of unit VRC.f (**Fig. 7.1M**). Finally, during the Middle Pleistocene (Albianelli et al., 1995), the progressive morphological re-equilibration of the basin margins caused backstepping of the alluvial fan systems, with consequent formation of the FU interval at top of unit VRC.g. The local absence of this FU interval was due to its erosion during development of the unconformity capping the VRC Synthem deposits (see next section).

6.1.5 From the VRC to the UFF Synthem

The progressive broadening of the basin during accumulation of VRC Synthem was associated with an expansion of its catchment. As a consequence of this expansion, the headwall of one of the tributaries entering the basin in the Levane area caught the southward flowing Arno River. The Arno River entered the basin from the East (**Fig. 7.1N**) during the Middle Pleistocene (Albianelli et al., 1995; Sagri and Magi 1992). Since most of the Arno bedload was trapped upstream of the newly formed knickpoint, the river started to erode the VRC deposits in order to get its appropriate bedload (Lane, 1955). Such erosion propagated upstream along the Arno's tributaries causing their embanking and erosion of the FU interval capping unit VRC.g. Therefore, the unconformity capping the VRC Synthem is thought to have been mainly generated by a hydrological disequilibrium due to the entrance of the Arno River into the basin, although a tectonic component cannot be *a priori* ruled out.

6.1.6 The alluvial sedimentation in the UFF Synthem

After the early erosional phase, the Arno River settled in the Valdarno and Palazzolo Basins and started to accumulate sediments of unit UFF.a (**Fig. 7.1N**) during the Middle Pleistocene (Napoleone et al., 2003). In particular, it formed a gravelly braided system in the proximal areas (Billi et al., 1987; see Chapter 2) and relatively sinuous sandy channels in the more distal portions (**Fig. 7.1N**). The progressive adjustment of Arno River profile, associated with the upstream migration of the knickpoint developed during the capture, is highlighted by the FU trend of the UFF.a unit. A similar FU trend is also shown by the alluvial-fan succession of unit UFF.b, which developed during profile re-equilibration of the Arno tributaries. The final depositional stage is associated with the accumulation of a muddy interval (UFF.c), which marks the final stage of morphological re-equilibrium both on the axial (UFF.a) and transverse (UFF.b) alluvial successions. This muddy interval was intensely pedogenized during the following embanking of the Arno River, which eroded the Incisa rocky shoulder cutting and terracing the whole Plio-Pleistocene succession (see Chapter 4).

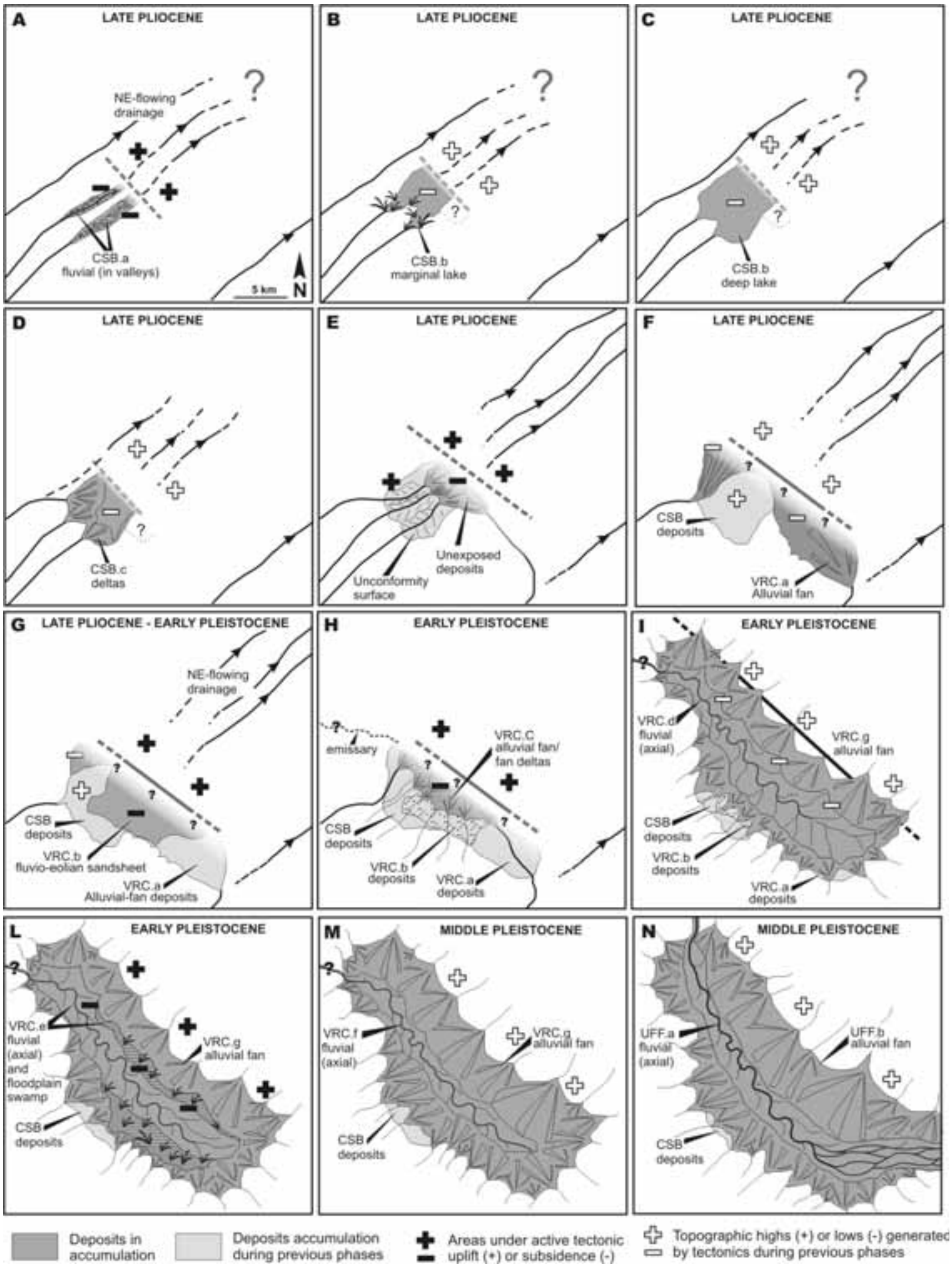

Fig 7.1 – Sketch for the Upper Valdarno Basin evolution (see text for details).

6.2 CONCLUSIONS

The evolution of the Upper Valdarno Basin can be summarized in the following points:

1. The Upper Valdarno basin-fill succession consists of three unconformity bounded units (Castelnuovo, Montevarchi and Torrente Ciuffenna Synthem) accumulated between Late Pliocene and Middle Pleistocene in alluvial and lacustrine setting.

2. The basin was generated during Late Pliocene through a tectonic damming of a NE flowing drainage. The onset of this damming is documented by the alluvial infill of several valleys at the base of the basin-fill succession, whereas the definitive damming is indicated by development of fully lacustrine conditions. The lake was progressively filled by deltas fed from the SW margin.

3. Between 3 and 2.5 My a tectonic phase, documented in several basins of the Northern Apennines, caused uplift and erosion of the Castelnuovo Synthem deposits, which were probably re-deposited below the modern Arno River.

4. Deposition of the lower part of the Montevarchi Synthem testifies a marked basin broadening and re-equilibrium of the rivers morphological profiles resulted from the previous tectonic deformation. Such a re-equilibrium allowed accumulation of FU alluvial fan successions, which were capped by eolian-reworked sand developed as a consequence of a marked climatic deterioration occurred at about 2.5 My.

5. Syn-sedimentary tectonics which affected eolian-reworked sand culminated in a new deformative phase, which caused erosion along the SE margin and deposition in distal areas. As a consequence of this tectonic pulse, a topographic low developed in the S. Cipriano area where lacustrine facies accumulated.

6. Deposition of the upper part of the Montevarchi Synthem started at about 2.3 My and testifies re-equilibrium of the morphological profile stemmed out from the previous tectonic deformation. Such a basin reorganization led to the establishment of an axial fluvial drainage and marginal alluvial fans.

7. During the Early Pleistocene, a further subsidence pulse triggered a new morphological disequilibrium along the margins and subsidence in the axial portion, where floodplain lakes developed. The alluvial-fans progradation, which stemmed out as response to the morphological disequilibrium, led to development of isolated fan-delta systems.

8. During Middle Pleistocene, the entrance of the Arno river into the basin caused development of a marked unconformity, whereas the subsequent re-equilibrium led to the formation of a FU trend both in fluvial and alluvial fans successions.

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