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THE VILLAFRANCHIAN DEPOSITS OF THE CASTELNUOVO GARFAGNANA AND BARGA BASINS (LUCCA, TUSCANY, ITALY): FACIES ANALYSIS AND PALEOENVIRONMENTAL RECONSTRUCTION

Abstract - A facies analysis of the Villafranchian continental deposits outcropping in the Castelnuovo Garfagnana and Barga basins allow the reconstruction of their paleoenvironmental evolution that differs significantly from the traditional fluvio-lacustrine interpretation. We identify, at different stratigraphic positions, two main river systems and some tributaries which flowed longitudinally and laterally to the axis of the two basins respectively, the latter fed both by the Apuan and Apennine margins. The mapped deposits were subdivided in five lithostratigraphic units (U_{1-5}). Lying in disconformity on the substratum U_1 corresponds to a cohesive sediment anabranching river (sub-type organo-clastic) developed longitudinally to the axis of the two basins in a humid subtropical climate phase. It is characterized by abundant fine organic-rich deposits and lignite accumulation (overbank elements) and by conglomeratic facies (channel-belt elements). An abrupt facies change characterizes the contact between U_1 and overlying U_2 that is constituted by prevalent conglomeratic deposits (channel-belt elements) and interpreted as a gravel bed-load braided river. U_3, U_4 and U_5 correspond to coalescent fan systems developing transversally to the axis of the two basins. U_3 and U_4 were interpreted as debris flow dominated fans exclusively, (U_3), or prevalently, (U_4), constituted by «Macigno» clasts while U_5 corresponds to a braided fluvial fan mainly characterized by a high variety of metamorphic clasts. Their influence, as transversal tributaries of the main longitudinal river systems, results both from compositional statistical analyses of conglomeratic deposits and from survey evidences. This paleoenvironmental reconstruction implies that Monte Perpoli high («Soglia di Monte Perpoli» *Auctt.*) acted as a sedimentary by-pass since the opening of the Castelnuovo Garfagnana and Barga basins.

Key words - Facies analysis, continental deposits, fluvial architectural elements, Villafranchian.

Riassunto - *I depositi Villafranchiani dei bacini di Castelnuovo Garfagnana e Barga (Lucca, Toscana, Italia): analisi di facies e ricostruzione paleoambientale*. È stata condotta, attraverso un rilevamento alla scala 1:10.000, un'analisi di facies sui depositi continentali Villafranchiani affioranti nei bacini di Castelnuovo Garfagnana e di Barga e proposta una ricostruzione paleoambientale che differisce da quella tradizionalmente accettata di progressivo riempimento di due laghi da parte di depositi fluviali. Sono stati individuati, a diverse altezze stratigrafiche, due sistemi fluviali principali ed alcuni sistemi tributari, a decorso rispettivamente longitudinale e trasversale all'asse dei due bacini, questi ultimi alimentati sia dal margine Apuano sia Appenninico. Questi sistemi sono stati cartografati e suddivisi in cinque unità litostratigrafiche U_{1-5}. U_1 giace in discordanza sul substrato ed è stata attribuita ad un sistema fluviale del tipo «cohesive sediment anabranching» del sottotipo «organo-clastic» a decorso longitudinale rispetto all'asse dei due bacini. U_1 è costituita da abbondanti depositi fini di tracimazione («overbank elements»), caratterizzati da diffusa presenza di lignite e da intercalazioni di conglomerati («channel-belt elements»). Questo sistema è sormontato in disconformità da depositi (U_2) principalmente conglomeratici («channel-belt elements») con sporadiche intercalazioni di depositi fini («overbank elements»), coerenti con un sistema fluviale a prevalente trasporto al fondo del tipo «gravel bed-load braided». U_3, U_4 e U_5 sono principalmente costituite da conglomerati grossolani e corrispondono a sistemi coalescenti di conoidi sviluppatesi trasversalmente all'asse dei due bacini. U_3 e U_4 sono state interpretate come conoidi dominate da processi di tipo massivo («debris-flow dominated fans») costituite esclusivamente (U_3) o prevalentemente (U_4) da clasti di «Macigno», mentre U_5 corrisponde ad una conoide dominata da processi trattivi («braided fluvial fan») costituita da un'ampia varietà composizionale di clasti metamorfici. Le analisi comparate dei dati composizionali, eseguite con metodo statistico sui litosomi conglomeratici, insieme ai dati di rilevamento, evidenziano le interazioni tra i sistemi a decorso trasversale e longitudinale. In base alla ricostruzione paleoambientale proposta la «Soglia di Monte Perpoli» avrebbe agito da zona di *by-pass* sedimentario fin dall'impostazione dei due bacini.

Parole chiave - Analisi di facies, depositi continentali, elementi architetturali, Villafranchiano.

INTRODUCTION

The Castelnuovo Garfagnana and Barga basins are located about 25 km north of Lucca along the intramontane valley of the Serchio river. They are about 5 Km wide and 15 and 10 Km long respectively and are separated by a structural high, known in literature as «Soglia di Monte Perpoli» (Puccinelli, 1987). These basins represent tectonical extensional depressions, elongated in a NW-SE direction, delimited southwest by the Apuan Alps and northeast by the Apennines (Fig. 1). The geological history of the Castelnuovo Garfagnana and Barga basins, as well as that of other depressions formed along the Tyrrhenian margin of the Apennines, is related to the Tyrrhenian rifting, which has been active since Late-Tortonian, and to the counter-clockwise migration of the chain-foredeep-foreland system (Elter *et al.*, 1975; Malinverno and Ryan, 1986; Sartori, 1989; Patacca *et al.*, 1990). Studied since 1800

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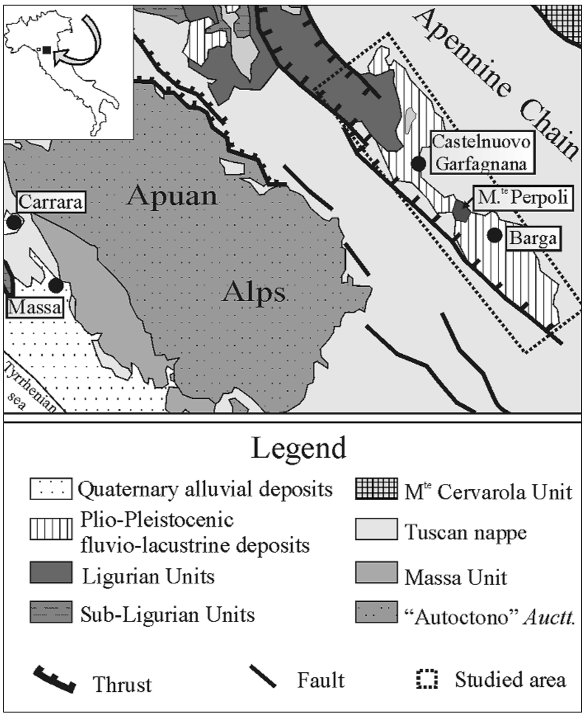

Fig. 1 - Structural and stratigraphic scheme of Northern Apennines, modified after Carmignani et al. (2000).

for mining of lignite and quarrying of clay both basins are filled with a remarkable thickness of continental deposits, mainly of Villafranchian age, generically interpreted, in previous studies, as fluvio-lacustrine (De Stefani, 1889; Masini, 1936; Calistri, 1974; Nardi *et al.*, 1987; Puccinelli, 1987; Antiga, 1988; Torre, 1988). In their opinion, during the early Villafranchian, the Monte Perpoli high acted as a shallow sill separating two lakes (corresponding to the Castelnuovo Garfagnana and Barga basins respectively).
On the basis of the facies analysis this study aims at offering a more detailed reconstruction of the depositional history of these deposits. It significantly differs from the traditional fluvio-lacustrine interpretation.

Methods

The 1:10.000 scale geological survey and the facies analysis allow the location of five (U_{1-5}) informal litostratigraphic units (Fig. 3), whose geometrical relationships are shown in Fig. 6. Within each litostratigraphic unit, a various number of lithofacies can be distinguished (Miall, 1996 and Sanchez-Moya *et al.*, 1996 lithofacies code are used) and their associations allow the definition of some architectural elements (Miall, 1996). Seventeen conglomeratic, heterolithic, sandy and silty-clay lithofacies were differentiated (Fig. 2) and grouped in ten architectural elements belonging to overbank elements (Fig. 4) and channel-belt elements (Fig. 5). A compositional statistical analysis of conglomeratic deposits was made applying the Howard's (1993) counting method. Nineteen sampling sites, at different stratigraphic positions, were selected in the Castelnuovo Garfagnana and Barga basins (Figs. 8, 9 and 10) and 9.600 clasts were counted. Applying the Howard's method, four closely spaced replicate counts of 100 clasts each were performed in all the sites and then the results combined. In order to decrease errors, introduced by using a definite number of clasts as representative of the whole population of the clasts and to increase the accuracy by increasing clast percentages, five clast assemblages were established on the basis of macroscopic and microscopic observations (Tab. 1). The data obtained permit: i) the calculation of the confidence interval, ii) the evaluation of the analysis of variance and thus the statistical comparison between counts of different sites belonging to the same lithostratigraphic unit and finally, iii) the estimation of the effects of dilution by comparing the compositional data of each unit of the two basins. The confidence interval permits the evidence of possible statistical differences by a quick visual ispection. The analysis of variance allows the comparison between two or more sampled sites in regard to the composition. The purpose is to verify that the means of all groups of count are the same compared with the possibility that at least one mean could be different. The effects of dilution can be estimated applying the ratio analysis that is useful to evaluate changes in the relative abundance of clast types which take place if a tributary introduces an abundant percentage of determinate lithologies in a fluvial system. In this case lithologies carried downstream the confluence point experience a proportional decrement, in respect to lithologies carried upstream this point, while the count ratio will remain unaltered.

Description of mapped lithostratigraphic units

In the study area five litostratigraphic units, referable to four depositional alluvial systems (cohesive sediment anabranching river, gravel bed-load braided river, debris flow dominated fan, braided fluvial fan), were recognized. The stratigraphic relationships among U_{1-5} are illustrated in Fig. 6.

U_1 (cohesive sediment anabranching river system)
Sedimentological analysis. The oldest fluvial system recorded, corresponding to U_1 (Fig. 3), lies in disconformity on the substratum (Fig. 6) made by the metamorphic units (Autoctono *Auctt.*) and non-metamorphic units (Tuscan nappe) and subordinate Ligurian Units. The thickness of U_1 was measured, on the basis of seismic and geological evidences, in about 200 m (Cancelli *et al.*, 2002; De Marco & Caielli, 1995). U_1 is constituted by widespread fine-grained deposits (Fig. 7a) related to overbank architectural elements (Fig. 4: swamp, SW; pond, PO; levee, L and muddy floodplain, M) with intercalations (*a* member, Fig. 3) of conglomeratic and sandy lithosomes associated to channel-belt architectural elements (Fig. 5: simple channel fill, CH

Lithofacies code		Facies description
C		Peat and organic-rich clay
P		Massive dark gray silt and clay-silt containing land fossils. Pedogenic features like calcareous nodule, slikenside rizoconcretions are observed
Silty-clay	Fh	Horizontal lamination of fine to very fine sand silt and clay
	Fsm	Massive or crudely laminated silt and mud
	Fm	Massive silt and clay
Sandy	Sh	Fine to coarse sand showing horizontal lamination
	St	Fine to coarse sand showing through-cross lamination
	Sp	Fine to coarse sand showing planar-cross lamination
	Sr	Fine to coarse sand showing ripple cross lamination
	Sm	Massive fine to coarse sand
Etherolitic	Et	Trough cross-bed conglomerate and sand
	Ep	Planar cross-bed conglomerate and sand
Conglomeratic	Gmm	Massive matrix-supported, poorly sorted conglomerate
	Gcm	Massive or faintly stratified clast-supported conglomerate; imbricated clasts
	Gt	Clast-supported trough cross-bed conglomerate
	Gp	Clast-supported planar cross-bed conglomerate
	Gh	Clast-supported horizontal bedding conglomerate

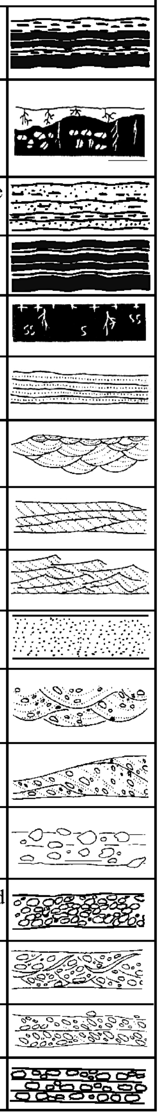

Fig. 2 - Identified lithofacies. Lithofacies code is slightly modified after Miall, 1996 and Sanchez-Moya et al., 1996.

and heterolitic bar, HB). SW deposits, 0.5 to 3.5 m thick, are characterized by widespread presence of well-preserved lignified trunks (C lithofacies, Fig. 2) lacking any evidence of transport (e.g. iso-orientation of trunks), and by subordinate thin intercalations of clays (Fm lithofacies, Fig. 2). Tree trunks in a life-wise position were observed. These data, attesting the absence of traction currents, are consistent with a swamp environment (Fig. 4), characterized by a continuous storage in *situ* of vegetal debris (Martini and Glooschenko, 1985). This interpretation is also consistent with the presence of *Glyptostrobus* (De Stefani, 1887; Masini, 1936) that is also indicative of humid-subtropical climatic conditions. Litofacies Fm (Fig. 2, Fig. 7a) also suggests a moderate silicoclastic input. The occasional presence of centimetric to decimetric sharp-based sandy levels (Sm, St lithofacies, Fig. 2, Fig. 7a) indicates phases characterized by a relative increase in sedimentary supply probably related to crevasse-splay processes. Analogous deposits in the Fossil Forest of Dunarobba (Italy, Umbria) have been described by Ambrosetti *et al.* (1995). PO element, 1.5 m to 3 m thick, is characterized by centimetric to decimetric rhythmical alternations of clay and silt (Fh, Fsm and Fm lithofacies) containing fresh-water taxa: ostracods (*Candona* spp., *Ilyocypris gibba*), gastropodes (*Melanoides curvicosta*, *Prososthenia paulae*, *Theodoxus* sp., *Laminifera villafranchiana*), teeth of fish (*Tinca* sp., *Leuciscus cephalus*, Carnevale *et al.*, 2003a), charophytes oogonia (*Nitellopsis* cfr. *megarensis*, Carnevale *et al.*, 2003b) and leaves. Sedimentological and paleontological features point to a low-energy sedimentary environment mainly subject to fall-out or weakly traction depositional mechanisms. The preservation of both subtle sedimentary structures and vegetal remains is suggestive of bottom anoxic conditions, below the depositional interface, also confirmed by the common presence of siderite glaebulae (Flores, 1981; Ambrosetti *et al.*, 1995). Relative higher rates of sedimentation are consistent with soft deformation structures (load casts, ball and pillows and convolute laminations) sometimes observed in these deposits (Fig. 7a), even if a direct relationship with paleoseismic events (e.g. Mills, 1983; Mohindra & Bagati, 1996; Alfaro *et al.*, 1997; Rossetti, 1999) can not be excluded. The paleontological content is coherent with fresh, shallow, standing or slightly moving waters. The widespread presence of *Glyptostrobus* attests the closeness to the swamp environments. This lithofacies association is indicative of deposition in pond or small shallow lake environments and it finds analogies both in present-day alluvial plain settings (e.g. Tye and Coleman, 1989; Aslan & Autin, 1998) and in some ancient deposits (e.g. Ambrosetti *et al.*, 1995; Sarti *et al.*, 2001). L and M elements consist of rhythmical alternations of fine sand, silt, clay (Sh, Sr, Fsm and Fm lithofacies) and bioturbated clay and silty-clay respectively (Fm, Fsm lithofacies). The thickness of L element is up to 1 m while M element ranges from 0.5 to 7 m (Fig. 7a). The widespread presence of hydromorphic paleosols (P lithofacies), 20-30 cm thick, containing land taxa (e.g. *Helix* sp., *Pomatias elegans*, *Discus rotundatus*), was observed mainly in M element. Paleosols with analogous characteristics have been detected and described in the Ponte Naja Unit located in Umbria (Basilici, 1995) and in the Villafranchian deposits of the Lucca basin (Sarti *et al.*, 2001). The common presence of lithofacies P observed in M element and the fine-grained correlate lithofacies indicating settlement processes, are consistent with an alluvial floodplain depositional environment. The increase in sediment grain-size, the lower development of paleosols and the appearance of weakly tractive structures observed in L element are indicative of a depositional environment relatively closer to the channels activity like levee. Channel-belt elements (*a* member) consist of

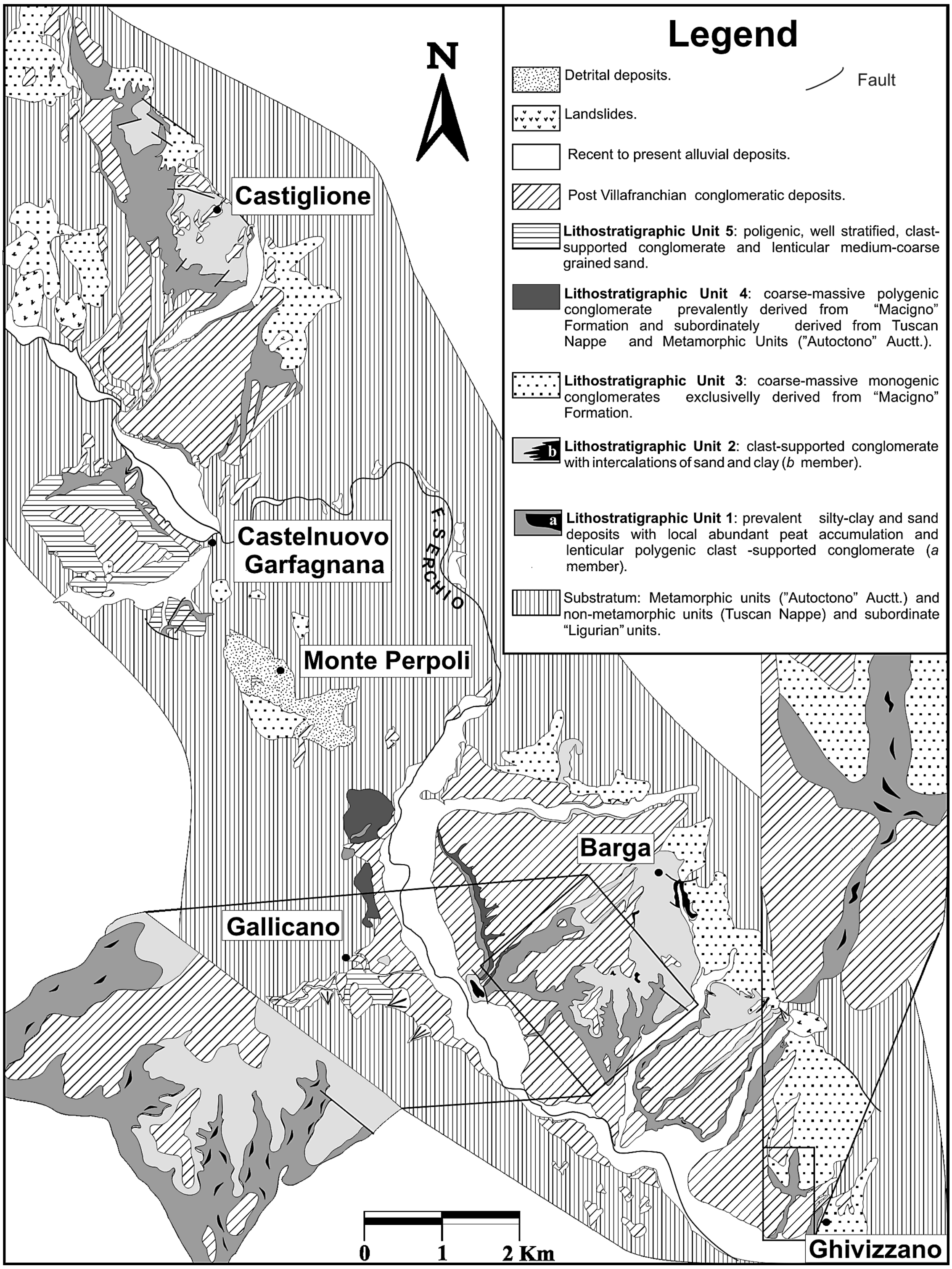

Fig. 3 - Geological map of the continental Villafranchian deposits of the Castelnuovo Garfagnana and Barga basins.

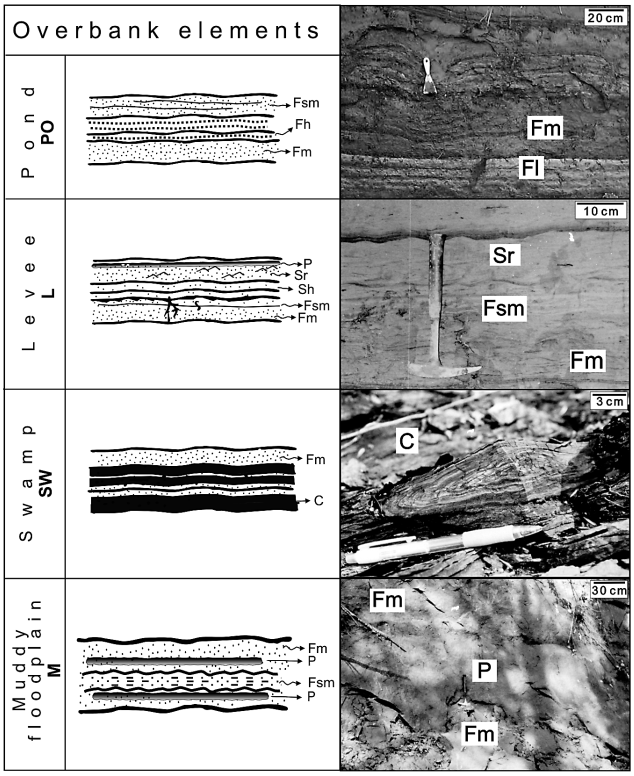

Fig. 4 - Detected channel belt architectural elements. Architectural code modified after Sanchez-Moya *et al.*, 1996.

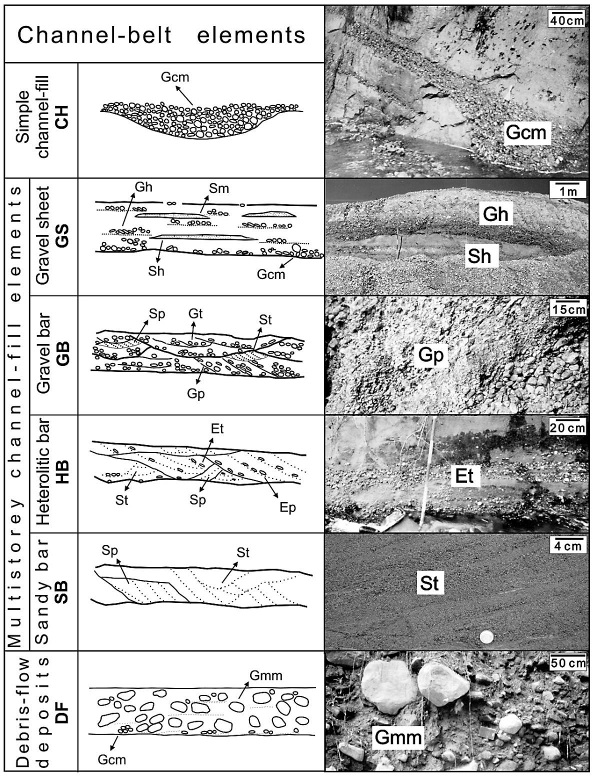

Fig. 5 - Recognised overbank architectural elements. Architectural code modified after Sanchez-Moya *et al.*, 1996.

simple channel-fill and heterolithic bar elements (CH and HB respectively). CH element, 4-15 m wide and 1-3 m deep, shows a ribbon geometry and frequent «ailes d'etalement» (*sensu* Friend *et al.*, 1979; see photo in Fig. 5). This architectural element is exclusively made by medium to coarse/massive, well or sub-rounded polygenic conglomerates belonging to Gcm lithofacies (Fig. 2). They show a clast-supported texture and a low percentage of silt to fine sand interstitial matrix. Clasts, with long-axes oriented parallel to the flow direction (a_p; a_i imbrication of Harms *et al.*, 1982) were observed. Gcm conglomerates are commonly organized in abrupt fining-upward sequences and show a strong basal scour surface cutting into overbank elements. These data are suggestive of hyperconcentrated flood-flows (*sensu* Smith, 1986). HB element, 1 to 3 m thick, shows a plane-convex upward geometry characterized by many reactivation surfaces. It consists of alternations between sand and conglomerate (Ep, Et, St, Sp lithofacies, Fig. 2), organized in a fining-upward trend sometimes showing mudclasts at the base of each cycle. Reworked specimen of *Unio* sp. were collected from these deposits indicating fresh and standing or slightly moving shallow water. HB element is interpreted to represent bars migration within the channel. Paleocurrents are indicative of a northwest to southeast direction, from the Castelnuovo Garfagnana to the Barga basin (Fig. 8). Downstream, a slight decrease in clast grain-size is also observed. The acquired data match with the features of a cohesive sediment anabranching river system, organo-clastic sub-type (*sensu* Nanson & Knighton, 1996), that represents braided river forming relatively wide flood-plain areas. It consists of gravelly channel and adjacent fine overbank areas characterized by continuous storage *in situ* of organic matter. According to Azzaroli (1977) and De Giuli & Masini (1983) the presence of molluscs belonging to the species *Laminifera villafranchiana*, *Prososthenia paulae, Teodoxus* cf. *groyanus* and the characean species (*Nitellopsis* cf. *megarensis*, Carnevale *et al*., 2003b) matches with the lower-middle Villafranchian age of these deposits corrensponding to Late Pliocene (Gliozzi *et al*., 1997; Esu & Girotti, 2001).

Compositional analysis. U_1 outcropping in the Castelnuovo Garfagnana basin is composed of non-metamorphic clasts (44.8% and 54.3% of A and B clast assemblages respectively) except for a very small percentage (1%) of metamorphic ones (C clast assemblage, Tab. 2). Because of the presence of only one site (site 4, Fig. 8) suitable to carry out statistical compositional analyses, these data may not be considered completely representative for the whole U_1 cropping out in the Castelnuovo Garfagnana basin. However, an

Tab. 1 - Established clast assemblages on the basis of Carmignani et al. (2000) geological map: A and B are referred to non-metamorphic Tuscan nappe; C and D are referred to metamorphic units whilst E regards the unidentified clasts.

	Clasts assemblages
A	Calcare Cavernoso Fm., Calcari e Marne a *Rhaetavicula contorta* Fm., Calcare Massiccio Fm., Rosso Ammonitico Fm., Calcari Selciferi Inferiori Fm., Marne a Posidonia Fm., Calcari Selciferi Superiori Fm., Diaspri Fm., Maiolica Fm., Scaglia Toscana Fm., Calcari a Nummuliti Fm.
B	Macigno Fm.
C	Marmi a Megalodonti, Brecce di Seravezza, Scisti a Cloritoide, Marmi Dolomitici Fm., Marmi Fm.
D	Calcari Selciferi Fm., Diaspri Fm., Calcari Selciferi ad Entrochi Fm., Calcari a Nummuliti, Cipollini, Scisti Sericitici Fm.
E	Non-recognizable clasts.

increase in metamorphic clasts (up to 10%) was qualitatively observed by rising in the stratigraphic position. In the Barga basin the mean value of non-metamorphic clasts reaches 73% (35.4% and 37.9% of A and B clast assemblages respectively) while the mean value of metamorphic clasts correspond to 22.1% (14.9% and 7.2% of C and D clast assemblages respectively). Anomalous high values of the B clast assemblage (68%) were recordered at site 14 (Figs. 8, 11). These anomalous values and the compositional difference noticed between the two basins will be debated later in the last chapter.

U_2 (Gravel bed-load braided river system)

Sedimentological analysis. U_2 (Fig. 3), up to 170 m thick, corresponds to a gravel bed-load braided system (*sensu* Sanchez-Moya *et al.*, 1996). The contact between this unit and the underlying U_1 is an abrupt facies change. U_2 shows latero-vertical stratigraphic relationships with U_3 and U_5 (Fig. 6). It is mainly composed of conglomerates (channel-belt elements), while fine-grained deposits (overbank elements, *b* member in Fig. 3) are subordinate (Fig. 7b). Gravelly sheet (GS), gravelly bar (GB) and sandy bar (SB) elements constitute channel-belt elements (Fig. 5). GS element (up to 3 m thick) is made by pebble to cobble well-rounded clast-supported conglomerates and subordinate sandy lithosomes showing a tabular or weakly erosive base. It includes (Fig. 2): disorganized (Gcm lithofacies) to poorly organized conglomerate (Gh lithofacies) and lenticular massive (Sm lithofacies) to horizontally stratified sand (Sh lithofacies). Gcm conglomerates are poorly sorted with rare a_p; a_i imbrications (*sensu* Harms *et al.*, 1982) whilst Gh lithofacies comprises moderately sorted imbricated gravel clasts, with a_t; b_i imbrication (long axes transverse to paleo-flow direction; Harms *et al*., 1982). The lateral relationship between these lithofacies (Fig. 7b) suggests deposition during waning flood-flows: Gcm lithofacies is interpreted as the deposition of hyperconcentrated high-magnitudo flood-flow (Smith, 1986; Jo *et al*., 1997) able to carry a mixture of gravels and sands (Reid & Frostick, 1987), while Gh lithofacies shows the characteristic of a waning flow, probably on low-to moderate-magnitude floods. The sheet-like geometry of conglomeratic lithosomes confirms a rapid sedimentation from a high-concentrated stream flood and suggests a low stream depth with respect to grain size in transport (Jo *et al*., 1997). GB element is made up of openwork and matrix-filled well-sorted medium to coarse conglomerates, showing trough and planar cross-bedding (Gp and Gt lithofacies). The amount of sandy-silty matrix is very small and sometimes absent. Reactivation surfaces are frequently observed. The thickness of GB element ranges from 0.5 to 3 m. SB element consists of medium to coarse-grained reddish sand, up to 1 m thick, strongly bioturbated and characterized by a well developed trough and planar cross-bedding (St and Sp lithofacies). These deposits show a fining-upward trend (gradual transition from St to Sp lithofacies, Fig. 7b) also observed at the set scale. Alignments of mudclasts, up to 2 cm in size, are common along the base of foreset.

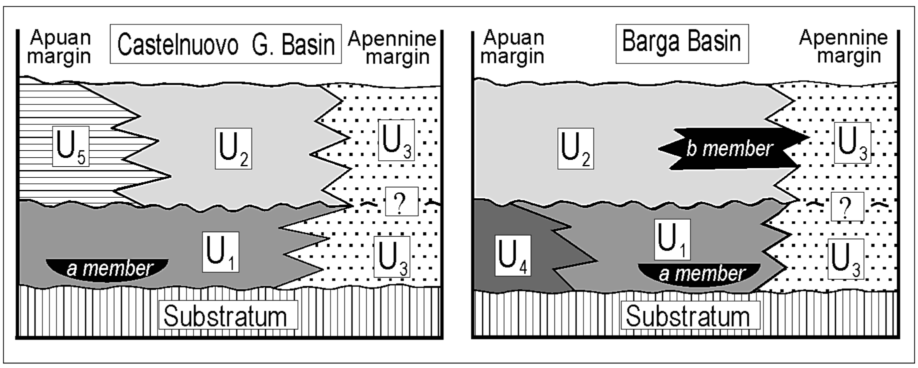

Fig. 6 - Inferred stratigraphic relationships among the identified lithostratigraphic units and members (see legend in Fig. 2).

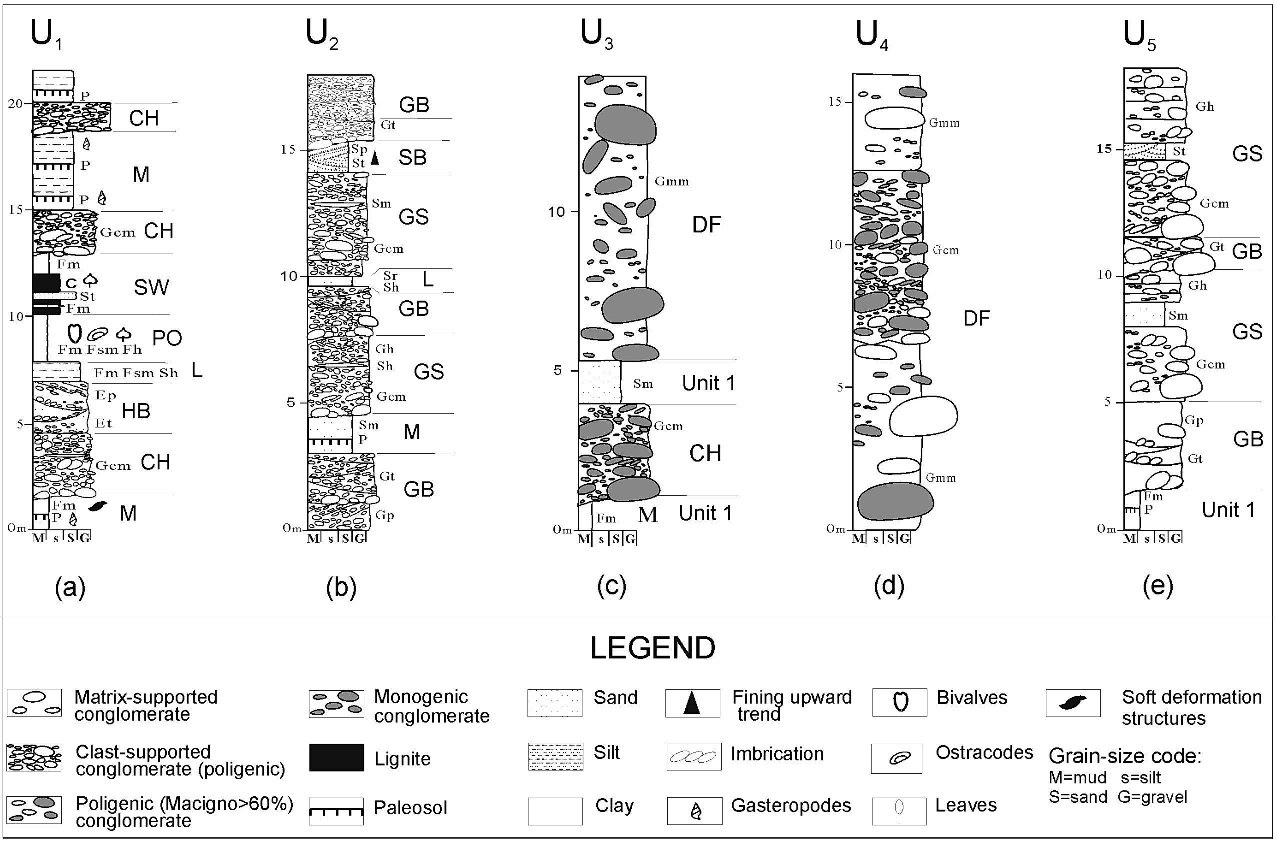

Fig. 7 - Representative stratigraphic sections of the studied lithostratigraphic units. Lithofacies code and architectural elements are referred to Tab. 1 (e.g. P, Fm, Gcm etc.) and Tabb. 2-3 (e.g. SW, CH, M etc.) respectively.

GS, GB and SB element associations (Figs. 5, 7b) are interpreted to represent multistorey channel-fill deposits (*sensu* Friend *et al.*, 1979; Miall, 1985). L and M overbank elements, up to 1 m thick with the exception of two outcrops located in the Barga basin reaching 20 m of thickness (*b* member, Fig. 3), are characterized by fine to medium-grained sand (Sh and Sr lithofacies) and by drapes of clay respectively (Fm lithofacies), and they show lateral stratigraphic relationships with channel-fill elements (Fig. 7b). Some ostracod valves assigned to *Cyprideis torosa* were collected in these deposits. Immature paleosols (P lithofacies) are prevalently developed in M element. L and M deposits show strong analogies with the present-day overbank deposits of the Serchio river. The paleocurrent analysis points out approximately a northwest to southeast paleoflow direction (Fig. 9). Clast grain-size slightly decreases in the same direction from the Castelnuovo Garfagnana to Barga basins. The sedimentological features and the architectural element relationships are consistent with a gravel bedload braided system (*sensu* Sanchez-Moya *et al.*, 1996) corresponding to the braided stream deposits of Reineck and Singh (1980) and the gravel-bed braided river of Miall (1996). In our reconstruction, this river system flowed the two basins through the Monte Perpoli high which role in respect to depositional processes will be discussed later in this paper. The finding of *Cyprideis torosa* in the basal portion of U_2 permits the assignment of these deposits to the Late Villafranchian according to Gliozzi *et al.* (1997).

Compositional analysis. In the Castelnuovo Garfagnana basin U_2 shows an higher clast percentages of metamorphic lithologies compared to the underlying U_1: collected data exhibit (Tab. 3) an higher mean of clast assemblages A (60.7%) and D (32.8%) and subordinately B (4.3%) and C (1.9%). Besides at different stratigraphic positions a significant compositional change was not observed. Compositional data acquired in the Barga basin differ for higher values of B and C clast assemblages (23.3% and 37% respectively, Tab. 3, Fig. 9). An anomalous relative higher percentage of «Macigno» clasts (B clast assemblage) was recorded at site 12 and 13 (Fig. 9, Tab. 3). Plotting data with their relative confidence intervals (Fig. 12), a gradual increasing trend of «Marble» proportion (C clast assemblage), corresponding to a decrement of «Macigno» clasts (B clast assemblage), was also observed. The meaning of the difference between

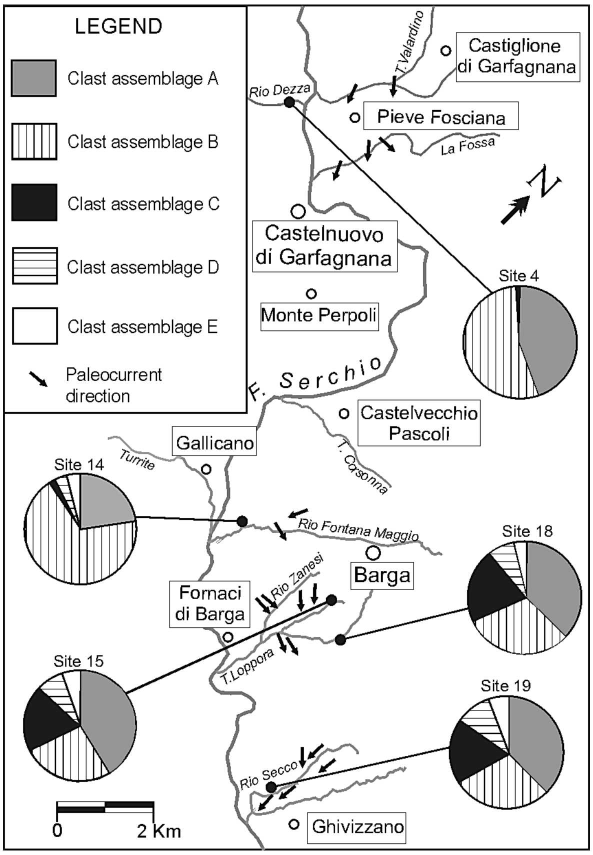

Fig. 8 - Location of the clast-count sites, provenance data and paleocurrent directions related to U_1 in the Castelnuovo Garfagnana and Barga basins.

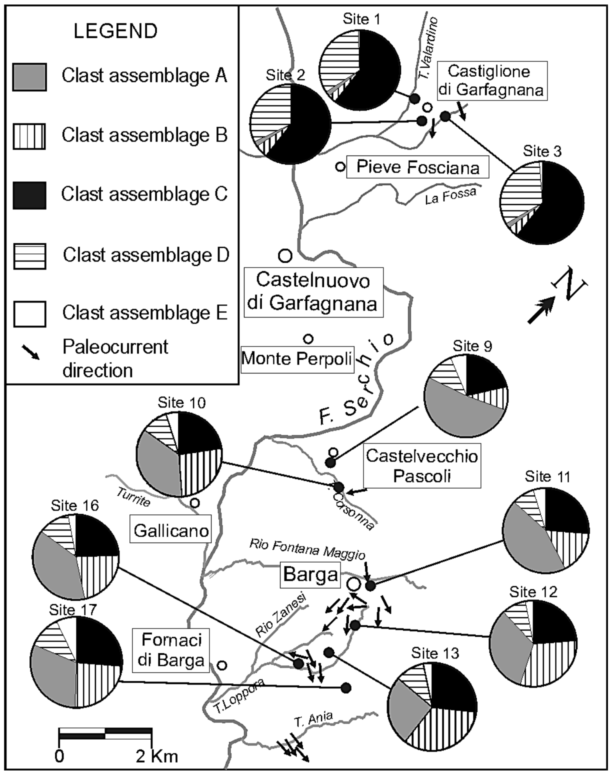

Fig. 9 - Location of the clast-count sites, provenance data and paleocurrent directions related to U_2 in the Castelnuovo Garfagnana and Barga basins.

the clast composition detected in the Castelnuovo Garfagnana and Barga basins will be discussed later in the last chapter.

U_3 and U_4 (Debris-flow dominated fan)

Sedimentological analysis. Along the Castelnuovo Garfagnana and Barga margins (Fig. 3), spatially limited conglomeratic lithosomes, showing latero-vertical relationships with U_1 and U_2 were mapped (Fig. 6). U_3 patchily outcrops along the Apennine margin of the two basins and subordinately along the Apuan margin of the Castelnuovo Garfagnana basin. The thickness ranges from few meters up to about 100 m. It consists mainly of DF architectural element, which is sometimes observed to grade downstream to CH element (Figs. 5, 7c). U_3 includes very coarse to medium-grained monogenic, massive conglomerates entirely derived from the surrounding «Macigno» Fm., showing a poor sorting and sub-angular to rounded clasts. The texture ranges from clast to matrix-supported with coarse to medium sand matrix (Gcm and Gmm lithofacies, Fig. 2). Clasts showing a_p; a_i imbrication were sometimes observed in Gcm litofacies. Both lithofacies occur in DF element while CH element is exclusively made by Gcm lithofacies. DF element differs from CH element for its sharp or weakly erosive base and a larger lateral extension suggesting a deposition ranging from true plastic debris-flow to hyperconcentrated flood-flow (*sensu* Smith, 1986). This last depositional mechanism is also consistent with the textural characteristics of CH element. U_4 (Fig. 3) crops out in a small area around the southwest margin of the Barga basin and displays strong textural affinity with U_3 but i) is made only by DF element and ii) show a slightly different clast composition (see the following *Compositional analysis* paragraph). North of Gallicano the thickness of U_4 reaches 60 m and thins eastward to 25 m. The close proximity of the source area and the textural features observed in these deposits are consistent with a debris-flow dominated fan (*sensu* Stanistreet & McCarthy, 1993) developed transversally to the axis of the two basins.

Compositional analysis. U_3 consists exclusively of «Macigno»-derived clasts (B clast assemblage) and thus statistical compositional count analysis was not necessary. U_4 is instead composed mainly of «Macigno» clasts (B assemblage, Tab. 1) except for a very little proportion of Tuscan nappe (A clast assemblage) and metamorphic-derived clasts (D clast assemblage) with a very little interpretative value.

U_5 (Braided fluvial fan system)

Sedimentological analysis. Cropping out in the southwest margin of the Castelnuovo Garfagnana basin (Fig. 3), U_5 lies in disconformity above U_1 and shows latero-vertical relationships with U_2 and U_3 (Fig. 6). Its thickness reaches 100 m at Monte Alfonso and thins to about 40 m northeastward. It entirely consists of channel-belt elements (Fig. 5): lithofacies Gcm, Gh, Gp, Gt, Sm, Sh, St e Sp (polygenic, clast-supported conglomerate and medium-coarse grained sand) are associated in GS and GB elements, showing latero-vertical relationships (Fig. 7e). GS element (0.5-3 m thick) displays a tabular geometry and represents the predominant element (Fig. 5), constituted by poorly-sorted medium to very coarse (clasts up to 50 cm are sometimes observed) conglomerates. A characteristic feature of GS element, detected within U_5, is the presence of portions with a chaotic aspect alternated to portions displaying a better organization where it is possible to observe clasts showing a_p; a_i imbrication. Lateral abrupt grain-size changes, reactivation surfaces and massive fine to coarse sand lenses, up to 1-2 m thick (Sm lithofacies), are also identified. We mean that the acting physical processes characterizing these deposits are similar to those described for GS element within U_2 suggesting a deposition by hyperconcentrated flood-flows (sensu Smith, 1986). GS element grades downstream to GB element. GB element (Fig. 5) is made by fine grained to medium (up to 5 cm), well sorted conglomerates, showing trough and planar cross-bedding (Gp and Gt litofacies, Fig. 2) and common a_t; b_i imbrication. The sedimentological features of GB element match with stream-flow deposition. The paleocurrent analysis points out a radial pattern with flow-despersion from west (Apuan margin) to east (Fig. 10). In the same directions a decrement of the clast grain-size was observed. U_5 is interpreted as a braided fluvial fan system (sensu Stanistreet & McCarthy, 1993) developed transversally to the axis of the Castelnuovo Garfagnana basin.

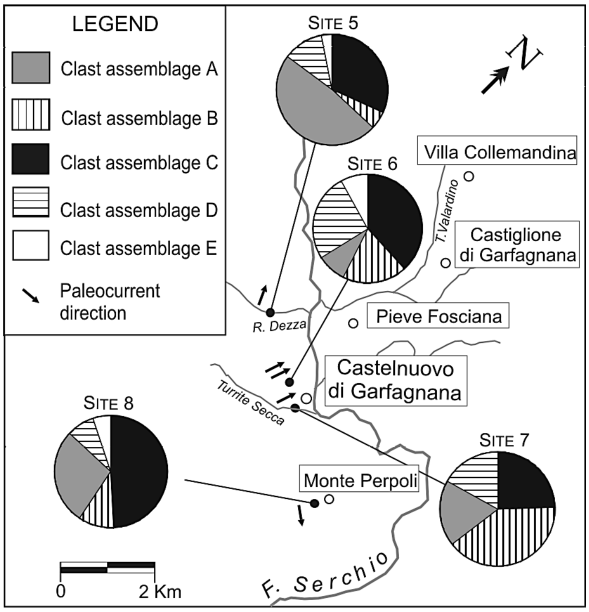

Fig. 10 - Location of the clast-count sites, provenance data and paleocurrent directions related to U_5 in the Castelnuovo Garfagnana and Barga basins.

Compositional analysis. U_5 consists of a variable proportion of the five clast assemblages (Tab. 4). Plotting clasts percentage as function of the stratigraphic position, an increment of A clast assemblage and a simoultaneous decrement of B clast assemblage were observed (Fig. 13). A higher value of marble-derived clasts (C clast assemblage) associated with an anomalous lower value of «Macigno»-derived clasts (B clast assemblage), was recorded at site 5. These fluctuactions in the reciprocal abundance of the five compositional clasts are interpreted to reflect depositional changes

Tab. 2 - Compositional analysis of conglomerate lithosomes belonging to U_1 outcropping in Castelnuovo Garfagnana and Barga basins.

	Site	A		B		C		D		E	
		X	CE	X	CE	X	CE	X	CE	X	CE
Castelnuovo G.	4	44.8	4.9	54.3	4.9	1	0.5	0	0	0	0
Barga	19	39.8	4.8	27.0	4.4	17.8	3.7	9.8	2.9	5.8	2.3
	18	37.5	4.8	30.3	4.5	20.5	4.0	7.5	2.6	4.0	1.9
	15	41.6	4.8	26.3	4.3	19.3	3.9	7.8	2.6	5.3	2.2
	14	22.8	4.1	68.0	4.6	1.8	1.3	3.8	1.9	3.8	1.9
	M	**35.4**		**37.9**		**17.9**		**7.2**		**4.7**	

X: mean in percentage; CE: counting error; A, B, C, D, E: clast assemblages; M: mean.

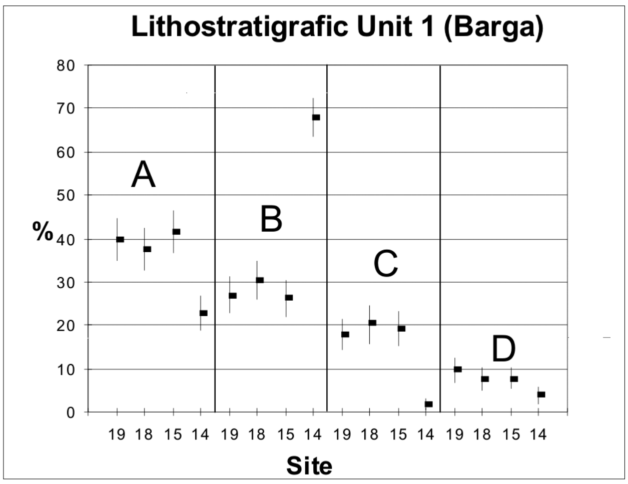

Fig. 11. Confidence interval observed in U_1 in the Barga basin. A, B, C, D: clast assemblages.

Tab. 3 - Compositional analysis of U_2 outcropping in the Castelnuovo Garfagnana and the Barga basins.

		A		B		C		D		E	
		X	**CE**	**X**	**CE**	**X**	**CE**	**X**	**CE**	**X**	**CE**
Castelnuovo G.	**Site**										
	1	60.8	4.8	3.3	1.7	1.8	1.3	33.8	4.6	0.5	0.7
	2	60.8	4.8	5.3	2.2	1.8	1.3	32.3	4.6	0.0	0
	3	60.5	4.8	4.3	2.0	2.0	1.4	32.3	4.6	1.0	10
	M	**60.7**		**4.3**		**1.9**		**32.8**		**0.5**	
Barga	**Site**										
	16	24.5	4.2	22.3	4.1	38.3	4.8	12.0	3.2	3.0	1.7
	12	23.8	4.2	31.0	4.5	33	4.6	9.0	2.8	3.0	1.7
	10	22.8	4.1	26.5	4.3	36.0	4.7	10.3	3.0	5.0	2.1
	17	26.5	4.3	24.0	4.3	31.0	4.5	11.3	3.1	7.3	2.5
	13	26.8	4.3	33.8	4.6	25.5	4.3	11.0	3.1	3.0	6.4
	11	26.1	4.4	15.8	3.6	43.8	4.9	8.3	2.7	4.8	2.1
	9	21.8	3.9	8.8	2.8	51.8	5.2	11.3	3.2	6.5	2.4
	M	**24.6**		**23.1**		**37.1**		**10.5**		**4.7**	

X: mean in percentage; CE: counting error; A, B, C, D, E: clast assemblages; M: mean.

over time related to both the relative variation of the fluvial base-level and the great geological complexity and etherogeneity of the source area.

DISCUSSION AND CONCLUSION

The depositional history of the Villafranchian continental deposits cropping out in the Castelnuovo Garfagnana and Barga basins, inferred in the previous studies, consists of a transition from lacustrine to fluvial environments (De Stefani, 1887, 1889; Calistri, 1974; Nardi *et al.*, 1987; Puccinelli, 1987; D'Amato Avanzi & Puccinelli, 1988; Antiga, 1988; Torre, 1988). The achieved data lead to delineate a different depositional history and to identify distinct sedimentary environments and sub-environments. The results can be summarized in the following points:

– development of a fluvial system (U_1) in a humid subtropical climate regime. It flows through the two basins and is related to a cohesive sediment anabranching river (sub-type organo-clastic) characterized by an abundant fine-grained overbank organic-rich sedimentation. At the same time coalescent debris-flow dominated fans (U_3 and U_4), mainly derived from the Apennine margin, develop transversally to the axis of the two basins. Their influence as transversal tributaries of the anabranching river (U_1) can be well detected for example at site 14. In this area I) an high percentage (53.7%) of B («Macigno» Fm.) clast assemblage (Fig. 8; Tab. 2) was observed; II) a lateral stratigraphic transition between conglomeratic deposits related to U_1 and U_4 occurred and III) a bimodal distribution of «Macigno»-derived clast grain-size (B clast assemblage) was identified: one consistent with A, C and D clast assemblage-sizes of U_1, and the other consistent with the granulometric range observed in U_4. The same type of observations may be extended to the other portions of the two basins. Even if in this context the increment of C clast assemblage observed in the Barga basin should imply a transversal supply derived from the Apuan margin the geological survey and compositional data may not allow the evaluation of this hypothesis.

– Development of a gravel bed-load braided fluvial system (U_2), characterized by prevalent gravelly channel-belt deposits, flowing through the two

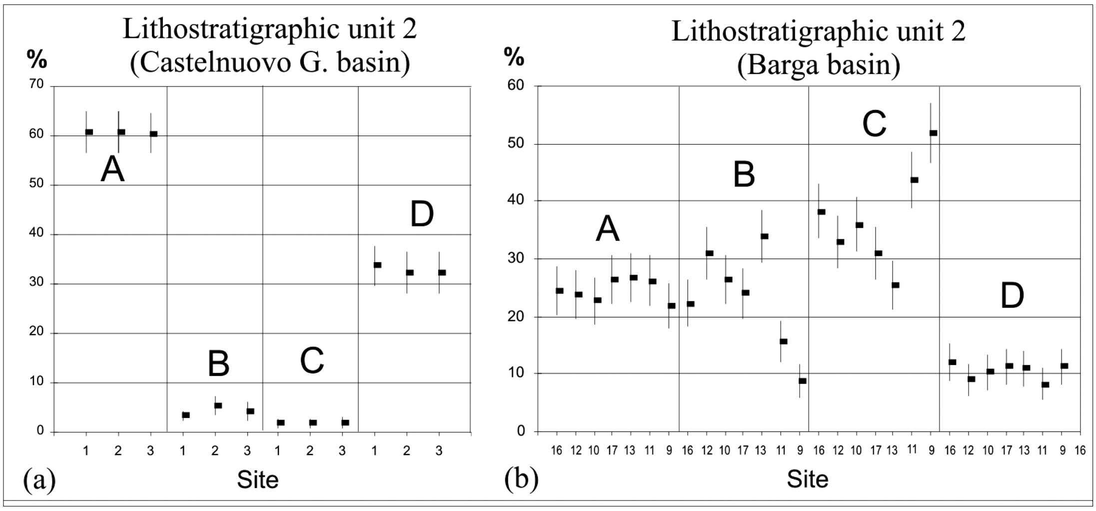

Fig. 12 - Confidence interval observed in U_2 in the Castelnuovo Garfagnana basin (a) and the Barga basin (b). A, B, C, D: clast assemblages.

basins. The contact between this fluvial system and the underlying one is an abrupt facies change inferring a possible disconformity surface. Debris-flow dominated fans (U_3), derived from the Apennine margin, persist in their transversal tributary activity as perhaps evidenced by the higher values of B clast assemblage detected at sites 12 and 13 (Fig. 9) and by geological survey data (lateral transition between U_2 and U_3, Fig. 3). Although the proposed reconstruction involves the necessity of a disconformity surface within deposits belonging to U_3, the spatially limited outcrops and the frequent weathering do not permit the evaluation of this hypothesis. At the same time a braided fluvial fan (U_5) fed by the Apuan Alps also develops transversally in the Castelnuovo Garfagnana basin as a tributary of the gravel bedload braided fluvial system (U_2). This interpretation is supported by the ratio analysis (Howard, 1993) as well as by the same compositional and geological evidence described for U_1. Besides the ratio analysis permits the clarification of the apparent discrepancy between the clast composition of U_2 observed in the deposits of the Castelnuovo Garfagnana and Barga basins respectively. The A clast assemblage can be subdivided into two groups (A_1 and A_2 in Tab. 5) and the ratio between the two most abundant compositional classes (A_1 and D), observed in the Castelnuovo Garfagnana basin, can be calculated considering that A_1 and D approximately represent the composition of the longitudinal fluvial system (U_2) upstream the confluence point with the transversal tributary (U_5). Table 6 doesn't show significant statistical differences between the ratio A_1/D calculated upstream and downstream this confluence point confirming that the introduction of variable proportions of B and C clast assemblages by the tributary system (U_5), causes a change in the relative proportion among the clast assemblages observed upstream, but the ratio A_1/D results unaltered. Finally, some previous works interpret the conglomeratic lithosome outcropping in the surroundings of Gallicano, located a few km west of Barga (Fig. 1, U_2 in this work), as deposits of fan and fan delta, supplied by the Apuan margin (Calistri, 1974; D'Amato Avanzi & Puccinelli, 1988). Although we do not share the interpretation of progressive infilling of a lake by fan delta and fan deposits, we consider realistic the possibility that the Gallicano conglomeratic lithosome can represent deposits of a transversal tributary. In fact, even if at the presenttime the outcrops permit neither an accurate facies analysis nor a statistical compositional count, we consider significant, as documented by previous Authors a) the presence of grain-sizes up to 50 cm, b) the decrease in grainsize observed eastward and finally c) the paleocurrent and compositional data implyng a westward (Apuan Alps) supply.

In conclusion we identify, at different stratigraphic position, two river systems and some tributaries that, during the Villafranchian, flowed longitudinally and laterally (fed both by the Apuan and Apennine margins) to the axis of the two basins respectively. This paleoenvironmental reconstruction differs from that of the two ancient lakes (corresponding to the Castelnuovo Garfagnana and Barga basins), progressively infilled by fluvial deposits, proposed by the other Authors (De Stefani, 1889; Masini, 1936; Calistri, 1974; Nardi *et al.*, 1987; Puccinelli, 1987; Antiga, 1988; Torre, 1988). This disagreement in the paleoenvironmental interpretation lead us to assign, to the Monte Perpoli high, a different role with respect to the sedimentation. While

Tab. 4 - Compositional analysis of U_5 outcropping in the Castelnuovo Garfagnana basin.

		A		B		C		D		E	
Castelnuovo G. basin	Site	X	CE	X	CE	X	CE	X	CE	X	CE
	7	23.8	4.2	39.0	4.8	18.3	4.2	16.5	3.6	0.0	0
	5	31.8	4.6	5.3	2.2	48.3	4.9	11.8	3.2	3.0	1.8
	6	38.8	4.8	20.0	3.9	8.8	2.8	26.3	4.3	8.3	3.1
	8	49.1	4.9	10.5	3.0	27.5	4.4	8.0	2.7	5.0	2.5
	M.	**24.8**		**18.7**		**24.7**		**15.5**		**4.1**	

X: mean in percentage; CE: counting error; A, B, C, D, E: clast assemblages; M: mean.

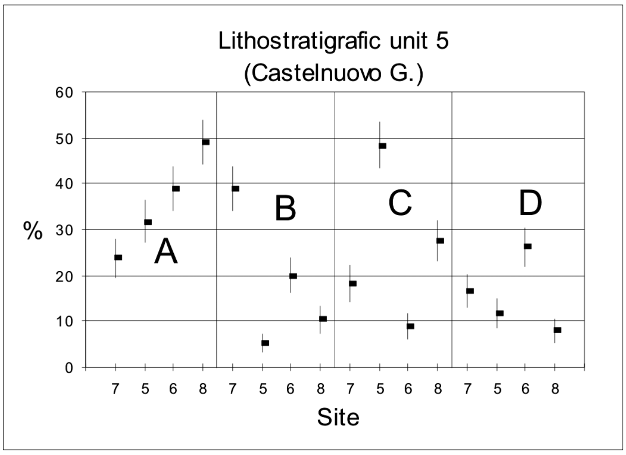

Fig. 13 - Confidence interval observed in U_5. A, B, C, D: clast assemblages.

Tab. 5 - Further subdivision within A clasts assemblage into two groups A_1 and A_2 representing Triassic-Jurassic units and Cretaceous units respectively.

	A clasts assemblage
A_1	Calcare Cavernoso Fm., Calcari e Marne a *Rhaetavicula contorta* Fm., Calcare Massiccio Fm., Rosso Ammonitico Fm., Calcari Selciferi Inferiori Fm., Marne a Posidonia Fm., Calcari Selciferi Superiori Fm., Diaspri Fm.
A_2	Maiolica Fm., Scaglia Toscana Fm., Calcari a Nummuliti Fm.

Tab. 6 - Ratio analysis of A_1 and D clast assemblages detected in U_2.

	Castelnuovo G. Basin	**Barga basin**
A_1/D		
$X_{x/y}$	1,76	1,69
C.I.	0,02	0,10
$S_{x/y}$	0,05	0,11

$X_{x/y}$: mean of count ratios; C.I.: confidence interval; $S_{x/y}$: standard deviation.

Puccinelli, 1987 interpreted this high as a shallow sill confining, during the Villafranchian, the two ancient lakes, we think, on the basis of (1) paleocurrent and compositional analisys (Sodini *et al*., 2002) and (2) survey evidences (absence in Monte Perpoli high of deposits indicating sedimentation associated with the two longitudinal river systems, U_1 and U_2), that this area has acted as a sedimentary by-pass since the opening (Lower Villafranchian) of the Castelnuovo Garfagnana and Barga basins analogously to what at present occurs for the Serchio river. The variation over the time of the fluvial level base, driven by tectonics, has lead to erosion and fluvial incision without depositional processes. This interpretation is also in agreement with the evidence of the Monte Perpoli high tectonic uplift inferred by Puccinelli (1987) and consistent with the most recent data about uplift times of the Apuan Alps (Molli *et al*., 2001).

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