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Stratigraphy and evolution of a long-lived fluvial system in the southeastern Alps (NE Italy): the Tagliamento conglomerate

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KEYWORDS

Eastern Southern Alps
Messinian-Quaternary
Clast composition
Tagliamento River
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Abstract

The Tagliamento River, located in the eastern Southern Alps, represents a unique opportunity to study the evolution of this sector of the chain over the last 6 Ma because of its relatively well preserved deposits. The development of the fluvial system has been reconstructed for the period since the Messinian, when the valley was deeply carved and uphead eroded, and the drainage basin was widened. The deposits preserved along or close to the present valley have been subdivided into five allostratigraphic units on the basis of bounding unconformities, supported also by petrographic (pebble and sandstone) data, facies and structural analysis. The units are characterized by different composition and sources, permitting a reconstruction of the changes in the drainage areas. The angular unconformities that bound the units as well as the deformations affecting the deposits indicate that the eastern Southalpine Chain has been tectonically active since the Messinian.

Der Tagliamento und seine Ablagerungen (östlichen Südalpen) bieten ideale Voraussetzungen zum Studium der Entwicklung der letzten 6 Millionen Jahre dieses Sektors der Alpen. Die Entwicklung des fluvialen Systems wurde ab dem Messinium rekonstruiert, einem Zeitintervall, in dem das Tal tiefgreifend ausgeschürft und frontal erodiert wurde und sich das Einzugsbecken weitete. Die Ablagerungen entlang beziehungsweise nahe des Tales wurden auf der Basis diskordanter Lagerungsverhältnisse, sowie petrographischer (Gerölle und Sandsteine), faziesanalytischer, und struktureller Daten in fünf allostratigraphische Einheiten unterteilt. Diese unterscheiden sich in Zusammensetzung und Herkunft, und erlauben eine Rekonstruktion der sich verändernden Einzugsgebiete. Die Diskordanzen, welche die unterschiedlichen Einheiten begrenzen, sowie die unterschiedlichen Deformationen der Ablagerungen, bezeugen, dass die östlichen Südalpen seit dem Messinium tektonisch aktiv waren.

1. Introduction

The evolution of a river system in a thrust belt is commonly inferred from the stratigraphic and petrographic analyses of thick sedimentary successions filling the associated foreland basins (i.e. Johnson et al., 1986; DeCelles et al., 1991; Jordan et al., 1993; Mather, 1993; Pivnik and Johnson, 1995). However, sediments trapped inside drainage basins and transfer zones (sensu Schumm, 1977) within mountain belts can also provide an important, though less continuous, record of fluvial evolution (i.e. Galloway and Hobday, 1983; Schumm and Ethridge, 1994; Vincent and Elliott, 1997; Jones et al., 1999; Vincent, 2001; Jones, 2004). In spite of their low preservation potential, deposits in long-lived palaeovalleys are especially important in unravelling the evolution of drainage basins and mountain belts (Friend et al., 1999; Vincent, 2001), providing a sensitive sedimentary record of changes in different primary controls.

As far as the Alps are concerned most of the stratigraphic records of valley fillings were removed by glacial advances during the middle-late Pleistocene, and few discontinuous remains are preserved (e.g. Keil and Neubauer, 2009; Sanders et al., 2009). The fragmentation of these records makes the reconstruction of the evolution of the valleys rather difficult. Moreover, river-sourced units located inside mountain chains are usually characterized by a coarse-grained texture and consequently are difficult to date and to correlate downstream with the fine-grained continental and marine units in the foreland.

The present paper attempts to reconstruct the development of the Tagliamento fluvial system by unravelling the stratigraphy of the Tagliamento conglomerate, a rather rare example of a well preserved sedimentary unit along a trunk valley in the Southern Alps.

2. Geological setting

The Tagliamento valley is located on the southern side of the Alps (Fig. 1), where streams dramatically deepened their valleys during the sea level drop of the Messinian Salinity Crisis (Bini et al., 1978; Felber et al., 1992; Krijgsman et al., 1999; Roveri et al., 2008). The transgression which followed at the end of the Zanclean led to some of these valleys being filled (i.e. Ghielmi et al., 2009).

The Messinian valley of the Tagliamento River, is recognizable on seismic survey lines crossing the Friulian plain, which show that downstream from the present mouth of the valley, the incision is 300 m deep and 3-4 km wide (Zanferrari et al., 2008a), with a NE-SW trend. Upstream, the Tagliamento valley cannot be seismically resolved, probably because of tectonic disturbances.

The eastern Southalpine Chain (ESC, Fig. 1), in which the catchment is located, is a SE verging thrust-fold belt developed during the Neoalpine Phase (Serravallian to Present) of the Alpine orogeny, whose evolution has been studied in detail over the last few decades (Doglioni and Bosellini, 1987; Massari, 1990; Castellarin et al., 1992; Rantitsch, 1997; Bressan et al., 1998; Castellarin and Cantelli, 2000; Galadini et al., 2005; Caputo et al., 2010). This chain was formed by the indentation of the Adriatic Foreland beneath the Alps and the contemporary dextral strike-slip movement of the Insubric Lineament (Massari, 1990; Ratschbacher et al., 1991; Fodor et al., 1998). The Neoalpine Phase is usually subdivided into a series of events:

1) the Serravallian-Messinian event, which recorded the most significant uplift rate, when the main stress direction varied from NNW-SSE to NW-SE (Castellarin et al., 1992);
2) and four events recognized in the Pliocene-Quaternary period (Caputo et al., 2010), which had a N-S main stress direction. Local stress was distributed fanwise from NNW-SSE to ENE-WSW in the Friulian area because of the subsidence of the wedge-shaped foreland beneath the eastern Southalpine front, producing local deformations with different directions, as marked by minor seismicity (Bressan et al., 1998). Along the Tagliamento valley the presence of strike-slip earthquakes (Burrato et al., 2008) are thought to be related to the western migration of the Idrija Fault (Poli M.E., personal communication).

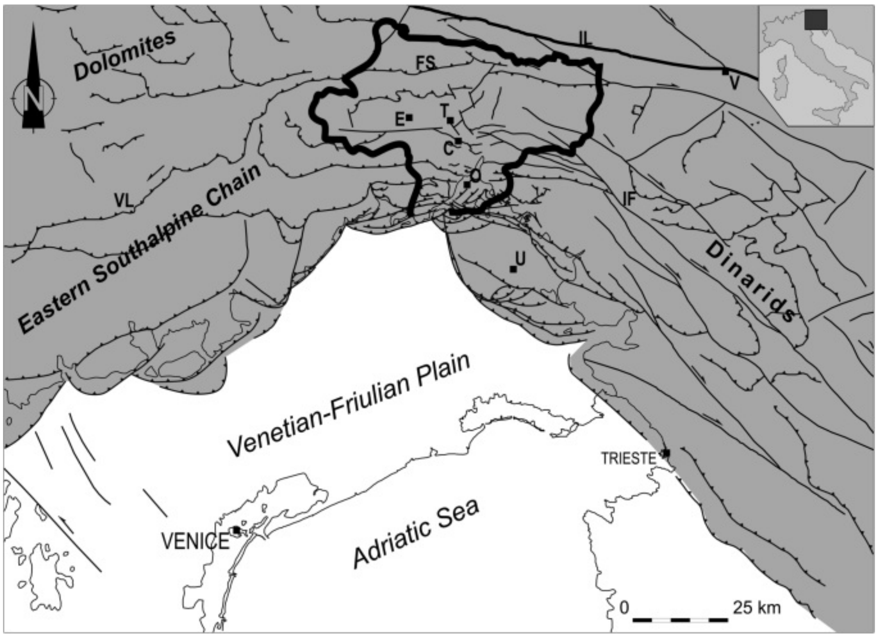

Figure 1: Regional tectonic sketch of northeastern Italy and western Slovenia modified from Zanferrari et al. (in press) with the location of the Tagliamento drainage basin shown by the thick line. Black lines: strike–slip faults; hachured lines: thrusts. Active faults and regional tectonic features are highlighted with thicker lines. Legend: FS, Fella-Sava Line; IF, Idrija Fault; IL, Insubric Lineament; VL, Valsugana Line. C, Cavazzo Carnico; E, Enemonzo; O, Osoppo; T, Tolmezzo; U, Udine; V, Villach.

The modern drainage basin of the Tagliamento River cut the ESC and its tectonic structures (Fig. 1) dividing the river catchment into three adjoining sectors with different source rocks which are, from north to south (Fig. 2):

- O-P sector (Ordovician-Permian) limited by the northern watershed and the E-W structures of the Fella-Sava fault; Palaeozoic units of the so-called Palaeocarnic Chain (Selli, 1963; Spalletta et al., 1982; Venturini, 1990; 2009) crop out in this sector;
- P-T_2 sector (Permian to Middle Triassic) bounded by the Fella-Sava and Tagliamento-Fella alignments; Permo-Triassic sedimentary rocks are exposed here (Carulli et al.,

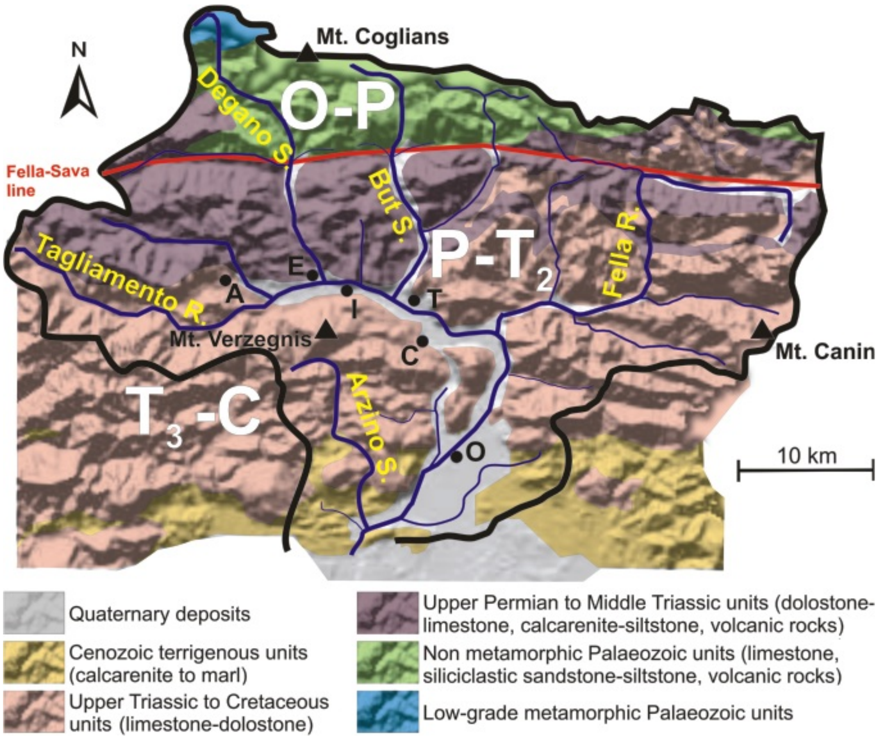

Figure 2: Bedrock map of the Tagliamento drainage basin with its main tributaries; the area is subdivided from north to south into sectors O-P, P-T_2, T_3-C characterized by different geologic successions. A: Ampezzo; E: Enemonzo; I: Invillino; T: Tolmezzo; C: Cavazzo Carnico; O: Osoppo

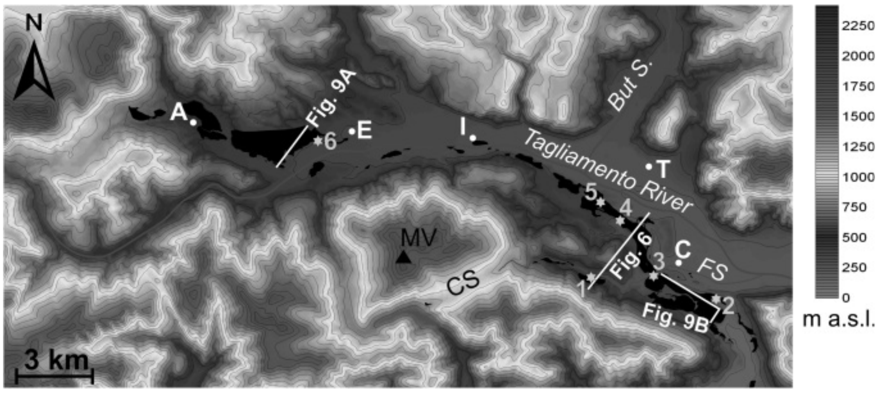

Figure 3: Distribution of the TC outcrops (black) and location of the measured sections (numbered white stars). The traces of the geological sections of Figures 6 and 9 are marked. MV: Mount Verzegnis, CS: Chianzutan saddle; FS: Faeit stream. A: Ampezzo; E: Enemonzo; I: Invillino; T: Tolmezzo; C: Cavazzo Carnico.

1987, 2000; Venturini, 2009);

- T_3-C sector (Upper Triassic to Cenozoic) includes the Carnic and Julian Prealps, where upper Triassic to Miocene formations crop out (Massari et al., 1986; Carulli et al., 2000; Carulli, 2006).

3. The Tagliamento conglomerate

3.1 Outline

The Tagliamento conglomerate (TC) is a succession dominated by pebble to cobble-size conglomerates, with subordinate sandstones, mudstones and breccias which unconformably overlies the bedrock. The sedimentary succession is internally subdivided into five allostratigraphic units (sensu NACSN, 1983), 30-100 m thick, bounded mainly by angular unconformities. Starting from the oldest and working down to the youngest, they are: Faeit, Ambiesta, Cesclans, Ampezzo and Invillino (Tab. 1).

The main outcrops appear in a series of ridges (Fig. 3) that are the remnants of the ancient valley-fill and that, taken together, represent a 25 km long, 0.6-1.2 km wide and 200 m thick belt, along the modern Tagliamento valley (Fig. 4); the elevation of the outcrops range from 200 to 550 m a.sl., with the exception of the Faeit Unit that has remnants up to 820 m a.sl. (Fig. 5). The ridges are almost continuous, interrupted only by short, narrow gorges, except in the central segment of the valley, where deposits are more discontinuous.

The main basal surface of the TC is that of the Ambiesta Unit (Fig. 6), thought to correspond to the intra-Messinian unconformity (Roveri et al., 2008), recognized in the Venetian-Friulian foreland using industrial seismic lines and results from boreholes (Nicolich et al., 2004; Mancin et al., 2007; Zanferrari et al., 2008b; Ghielmi et al., 2009). At the mouth of the Tagliamento Valley, near Ragogna, this surface crops out as an angular unconformity above the Montello Conglomerate, whose topmost part is Messinian. The sections with the best stratigraphic continuity and clearest exposure of the basal surface are shown in Figure 7, while the longitudinal and cross profiles of the basal surfaces show the relationships amongst the units (Figs. 6, 8 and 9).

Stratigraphic unit	Distribution (see Fig. 4)	Bounding unconformities	Tectonic features
Faeit	Chianzutàn saddle, Faeit valley	Lower angular discordances and onlap on the bedrock; upper diachronic erosion surface	Decametric folds with N-S axis and decametric folds with 105/10° axis and pressure-solution cleavage
Ambiesta	From Cavazzo Carnico to Invillino and near Enemonzo	Lower angular discordances and onlap on the bedrock; upper erosion surface marked by angular unconformities	Decametric anticline with 200/10° axes, decametric folds with NNE-SSW axis dip towards NNE; pressure-solution tracks showing NW-SE and ENE-WSW compression; SE-verging reverse faults; WNW-ESE strike-slip faults
Cesclans	From Cavazzo Carnico to Invillino and from Enemonzo to Ampezzo	Lower angular unconformity and lateral onlap on the bedrock; upper erosion surface marked by angular unconformities	Kilometric syncline with N110° axis and reverse faults on the sides; monocline dipping at 30/30°; pressure-solution tracks showing NNE-SSW compression; WNW-ESE strike-slip faults
Ampezzo	From Cavazzo Carnico to Invillino and from Enemonzo to Ampezzo	Lower angular unconformity and lateral onlap on the bedrock; upper diachronic erosion surface	WNW-ESE strike-slip faults, N-S vertical joint systems; pressure-solution tracks showing N-S compression
Invillino	From Invillino to Ampezzo	Lower angular discordances with the bedrock; upper diachronic erosion surface	N-S vertical joint systems sub-vertical fractures with WNW-ESE strike and sub-vertical strike-slip faults oriented N100°

Table 1: Summary of the TC stratigraphy.

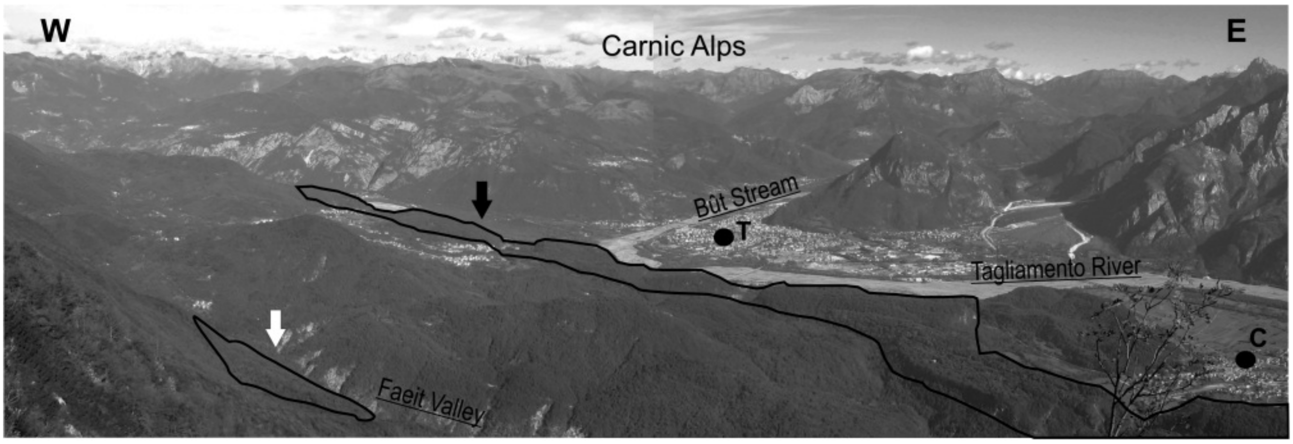

Figure 4: Northwestward panoramic view of the Tagliamento valley from the Carnic Prealps; the TC distribution is highlighted in the large outlined area; the white arrow indicates the Faeit Unit, the black arrow indicates the ridge made of other units as in Fig. 8; T: Tolmezzo; C: Cavazzo Carnico.

3.2 Previous works

Investigations on the TC started with Taramelli (1875; 1881) and focused on determining its age and sorting out the question of single versus multiple sedimentary episodes. The TC was divided into two units, based on pre-glacial and fluvioglacial evolution, by the earliest authors (Taramelli, 1875, 1881; Gortani, 1912) and more recently by Venturini and Tunis (1992); whereas other authors have considered it a single unit of preglacial (Stefanini, 1915) or interglacial origin (Penck and Brückner, 1909; Gortani and Desio, 1926; Feruglio, 1929; Gortani, 1935; Carulli et al., 2000; Venturini, 2009).

The age assignment of the conglomerate succession differs between various authors from Pliocene (Taramelli, 1875, 1881; Stefanini, 1915) to middle Pleistocene (Penck and Brückner, 1909; Gortani and Desio, 1926; Feruglio, 1929; Gortani, 1935; Carulli et al., 2000; Venturini, 2009). However, none of these age interpretations have been supported by age constraining data; but they derive from speculation regarding pebble composition, degree of cementation and stratigraphic position.

Within the Tagliamento drainage basin there are also some remains of ancient fluvial conglomerates located at elevations of up to 1550 m a.s.l. in the Carnic Prealps (Stefanini, 1911; Venturini, 2009) which are ascribed to the palaeo-Tagliamento and tentatively attributed to the Pliocene (Stefanini, 1911) or to the late Miocene - Early Pliocene (Venturini, 2009). These deposits, which are not considered in this study, probably represent the last remnants of a Miocene drainage network, similar to those found in other areas of the Dolomites (Doglioni and Siorpaes, 1990).

Deltaic conglomerates, known as "Osoppo conglomerates" (Venturini, 1992), are located at the mouth of the valley. Recent studies, based on sedimentological interpretations (Venturini, 1992; 2000) and mammal track-ways on silty levels (Dalla Vecchia and Rustioni, 1996; Dalla Vecchia, 2008), have suggested the presence of a sea inlet or alternatively of a large lake, ascribed to the "lago-mare" paleoenvironment of the late Messinian. For these deposits pollen data (Monegato et al., 2006) indicate a Zanclean age.

Downstream from Osoppo, in the piedmont plain near Ragogna, thick conglomerate sequences of the Montello Conglomerate, ascribed to the lower Messinian, crop out (Zanferrari et al., 2008b).

4 Methods

Geomorphological, sedimentological, composition and structural analyses have been carried out on the TC. Facies analyses have been made on outcrops at the decimetre scale; facies have been recognized based on a two-tier system of grain size and sedimentary structures, supplemented by grain fabric (summarized in Tab. 2) referring to the schemes of Miall (1996) with extensions by Eyles et al. (1983) and Vincent (2001).

Provenance analyses examined samples taken from the same segment of the palaeovalley to avoid differences in tributary supply; close to Cavazzo Carnico four stations for each unit

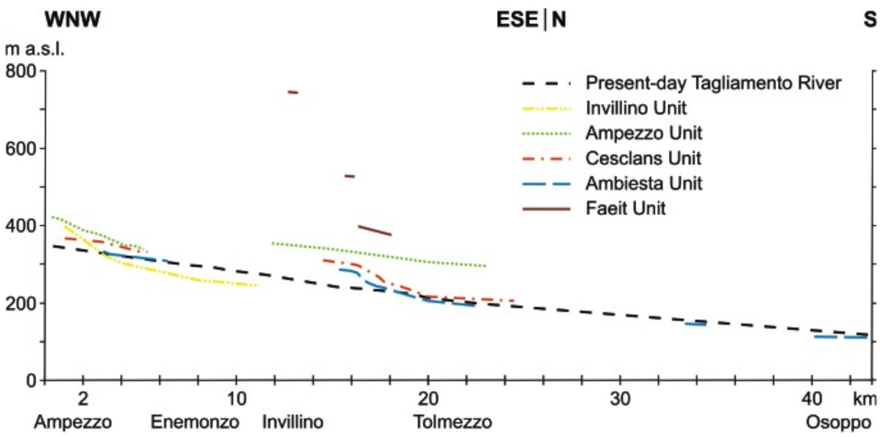

Figure 5: Longitudinal profile for each sedimentary unit along the Tagliamento valley; the different elevation of the basal surface is recognizable between Enemonzo and Tolmezzo suggesting uplift of the bedrock.

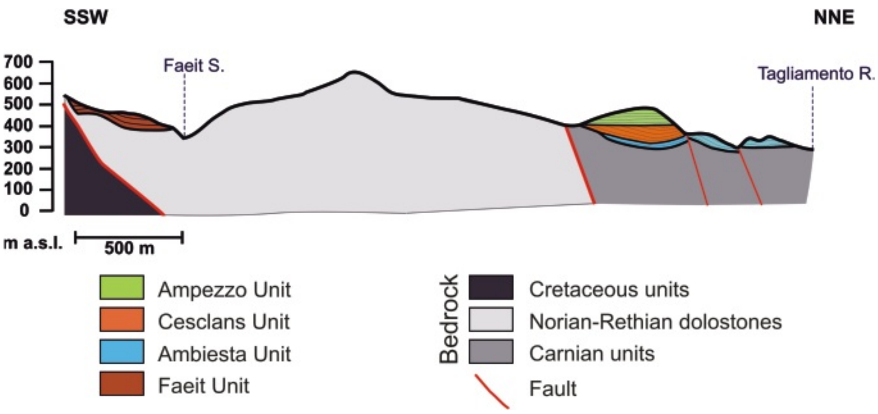

FIGURE 6: Geological cross section through the Faeit and the Tagliamento valleys close to Cavazzo Carnico (see Fig. 3 for the location).

were selected for pebble compositional analyses. At least 100 gravel-size clasts were collected during each sampling so as to have at least 400 counted clasts per station, as suggested by Howard (1993). The ribbon method has been adopted (Galehouse, 1971), this involves selecting pebbles with b axis greater than 3 cm within an area whose band is greater than the diameter of the largest pebble. All stations are located in facies Gh where conglomerates are typically well cemented by sparry pore-filling calcite with a mosaic texture; locally, some micritic matrix is present. Clasts are mostly sub-rounded to sub-angular. Locally, some bodies are affected by dissolution of dolostone clasts, and have consequently been avoided.

Percentages of different lithologies for each stratigraphic units are represented in Figure 10.

In order to obtain more accurate data inside the valley, forty-seven sand samples relative to the main stratigraphic sections of the valley fill and some samples from the present-day river were analysed (Tab. 3). The entire sand fraction (0.0625-2 mm) was split and impregnated with an epoxy resin according to the methodology described by Gazzi et al. (1973) to obtain thin sections for analyses. These were stained with alizarine-red solution in order to determine the carbonate phases. Sandstone and sand counts were carried out following Gazzi-Dickinson procedures (Gazzi, 1966; Dickinson, 1970). For each section 500 (sandstones) or 300 points (sands) were determined, using a 0.5 mm grid spacing. To improve the information on the source rocks, a separate count of almost 200 coarse- plus fine-grained rock fragments was performed on each sample. The Zuffa (1985) classification for extra-basinal fraction (Q,F,L+CE, Fig. 11A) has been adopted because of the abundance of carbonate clasts. The common

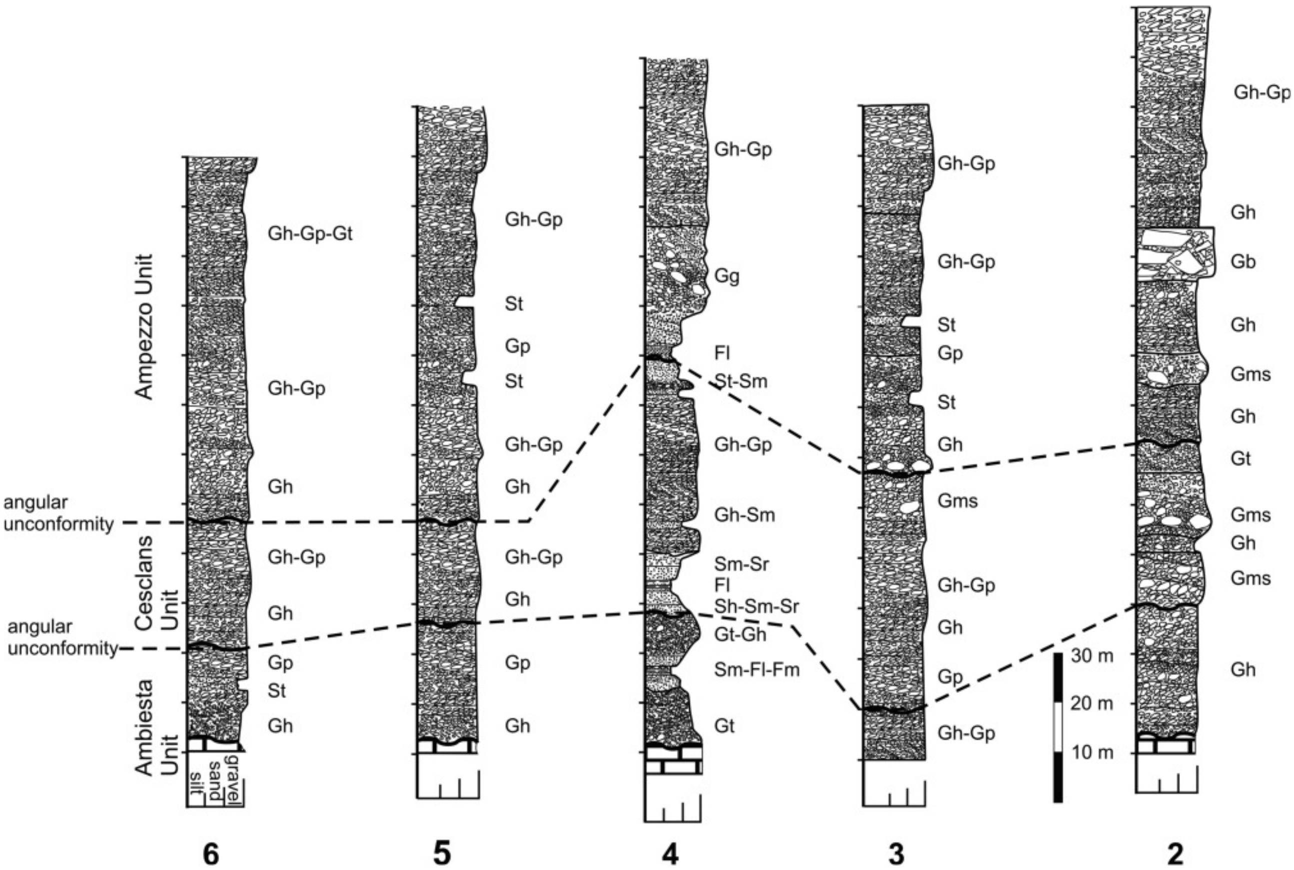

FIGURE 7: Proximal to distal (from left to right) graphic logs through the TC; numbers refer to the logged sections located in Figure 3. Letters indicate the recognized facies (see Tab. 2).

scarcity of feldspar grains has led us to add them to the quartz fraction, while carbonate and non-carbonate rock fragments have been separated, as proposed by Lugli et al. (2007), adopting the Q+F, L, CE diagram (Fig. 11B). In addition the total lithic population is represented in Figure 11C.

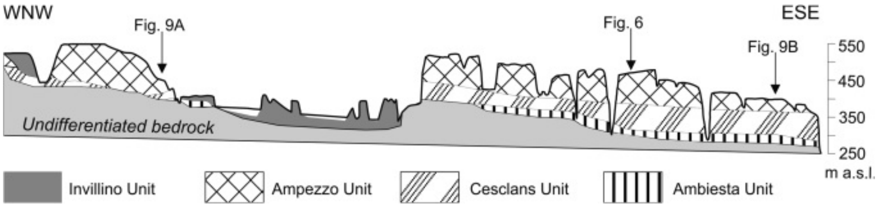

Figure 8: Geological cross section along the Tagliamento valley showing the stratigraphic relationships among the different TC units; junction with cross sections of figures 6 and 9 are marked.

5. Conglomerate clast lithologies

The following lithotypes were recognized:

1) quartzite. White to pale pink quartz pebbles are commonly reworked from the Palaeozoic conglomerates, as well as from low-grade metamorphic rocks of the Palaeocarnic Chain basement (Poli and Zanferrari, 2002);
2) chert. This clast type includes microcrystalline siliceous pebbles which are commonly brown to red, grey, black and only rarely brownish yellow. Their principal sources are the Mesozoic successions;
3) volcanic rocks. This category is made up of rounded acid volcanic pebbles derived from Palaeozoic and Triassic volcanic successions;
4) volcanic arenite. This type includes green to grey coarse-grained arenites made up of volcanic grains characteristic of both Palaeozoic and Triassic successions of the Carnic Alps;
5) low-grade metamorphic rocks. They are fine-grained metaphyllites, usually disc shaped or round, sourced from the Palaeocarnic Chain basement;
6) Palaeozoic siliciclastic siltstone/sandstone. This class includes red Val Gardena Sandstone and Carboniferous-Permian siltstones and sandstones of the Pramollo Group (Venturini, 1990), commonly very rich in quartz grains;
7) Triassic siltstone/sandstone. They come from lower-middle Triassic successions and can be distinguished from the previous group by the abundance of white mica and the higher carbonate content;
8) limestone. Limestone clasts show a wide range of textures and colours and are generally sub-rounded. They have been distinguished in the field from dolostones using diluted hydrocloric acid (10%). No distinction has been made between Palaeozoic and Mesozoic limestones;
9) dolostone. Dolostones are abundant in the pebble spectra; they are mainly of Triassic age, sub-rounded and normally white, pale to dark grey or brown. In the present Tagliamento drainage basin this is the most common outcropping rock type (Carulli, 2006).
10) other rocks. This class includes clasts that do not fall into any of the previously mentioned categories.

6. Stratigraphy of the Tagliamento conglomerate

6.1 The Faeit Unit

The Faeit Unit crops out inside the Faeit Creek valley (Figs. 3 and 6), a present-day dextral tributary of the Tagliamento River, and in isolated remnants at Chianzutàn saddle, several kilometers to the west (Fig. 3). The unit extends discontinuously for about 5 km, and is 30 to 80 m thick. The lower boundary is defined by the bedrock floor of the valley. Its present elevation differs from that of the Chianzutàn saddle (810 m a.s.l.) to the east to that of the Faeit valley (600 to 410 m a.s.l.), following the irregular surface of the deformed Mesozoic bedrock (Fig. 12). In all its outcrops the upper boundary is the present-day erosional surface.

The unit is made up of basal breccias (Gb, Tab. 2) characterized by angular to sub-angular carbonate clasts, reflecting the composition of the surrounding bedrock (Carulli et al., 2000). Planar crudely bedded conglomerates (Gh) are the most representative facies, locally interfingering with coarser breccia bodies. Palaeocurrent indicators suggest an average flow towards the east. Conglomerate petrography (Fig. 10) highlights the prevalence of carbonate classes (~76%) and the relative abundance of clasts belonging to the lower Triassic reddish siltstone/sandstone (16%) and volcanic sandstones (~4%); chert is also present. Sandstone petrography (Fig. 11A) shows a very well defined lithic composition characterized by the abundant sedimentary, mainly carbonate, rock fragments (Fig. 11B).

Deposits are deformed by a series of asymmetric anticline/synclines with N110-130 axes (Fig. 12), subsequently gently deformed by hectometric folds with N-S axes; the former are associated with a south-verging reverse fault and pressure-solution cleavage oriented N105-110/75°, genetically related to the fold system.

The Faeit Unit is related to a palaeo-Tagliamento river as its petrographic composition cannot be attributed to a local source, because of the abundance of Lower Triassic sandstones and volcanic arenites that have been exposed in the northernmost sector of the chain since the Miocene according to tectono-stratigraphic reconstructions (Carulli and Ponton, 1992). Clast petrography indicates that the catchment was south of the Fella-Sava fault, as suggested by the lack of clasts coming from the Palaeozoic succession of the Palaeocarnic chain; moreover the composition is similar to the upper portion of the Montello Conglomerate (Early Messinian) which crops out at the mouth of the present Tagliamento valley (Zanferrari et al., 2008b). The distribution of the deposits indicates that the river crossed the Chianzutàn saddle and flowed down through the present Faeit valley. The facies associations indicate a braided fluvial system dominated by high-energy tractional currents and shallow channels; the river-bed was probably about 400 m wide with small alluvial fans and a slope talus on the valley sides. The unit appears undisturbed at the Chianzutàn saddle; nevertheless, the difference in elevation of the basal boundary (Figs. 5 and 6), compared to the eastern outcrops along the Faeit valley, suggests a displacement by faulting.

The Faeit Unit can be considered an intravalley member of the Montello Conglomerate. The valley floor has probably been carved during the growth of the eastern Southern Alps since the Tortonian. According to Massari et al. (1986, 1994), the Venetian-Friulian Basin was probably isolated from the Mediterranean during the first phases of the Messinian Salinity Crisis; however, the up-head erosion from the Mediterranean reached the region later, probably as the result of the major drop occurring around 5.6 Ma. The abandonment of this trunk valley could be tentatively related to this trenching as described in adjacent sectors of the foreland of the Southern Alps (Mancin et al., 2007; Ghielmi et al., 2009).

6.2 The Ambiesta Unit

This unit extends for about 20 km downstream of Enemonzo along the Tagliamento valley and displays an average thickness of 30 m (Fig. 8), while the deltaic conglomerates at Osoppo, which crop out to the south, have a maximum thickness of 100 m.

Scattered bodies of oligomictic breccia (Gb) of bedrock carbonates are usually present in the basal portions, covered by fluvial deposits. Planar crudely bedded conglomerates (Gh) are mostly represented (Figs. 7 and 13A, Tab. 2), with scarce interfingering of colluvial breccias along the valley side. Local floodplain deposits made of fine-grained facies (Sh-Sm-Sr), up to 5 m thick, are present (Fig. 13B). Palaeocurrent indicators suggest an average flow towards the south-east.

Conglomerate pebbles (Fig. 10) show a clear decrease in carbonate content (~58%) in respect to the Faeit Unit, while abundances of lower-middle Triassic sandstone/siltstone (14%), volcanic sandstones (~5%) and quartz and chert (2%) are quite similar. A significant change is linked to the appearance of siliciclastic sandstone/siltstone (~6%) and low-grade metamorphic rocks (~6%) derived from the Palaeozoic succession, as well as acidic volcanites (~6%).

Sandstone petrography (Fig. 11B) indicates the same compositional changes as the gravel fraction with a relative increase of fine-grained siliciclastic grains (L).

The basal boundary of the unit is carved in the bedrock (Fig. 6) and is commonly visible on the valley sides and scarcely in the middle of the valley section, while the upper boundary is

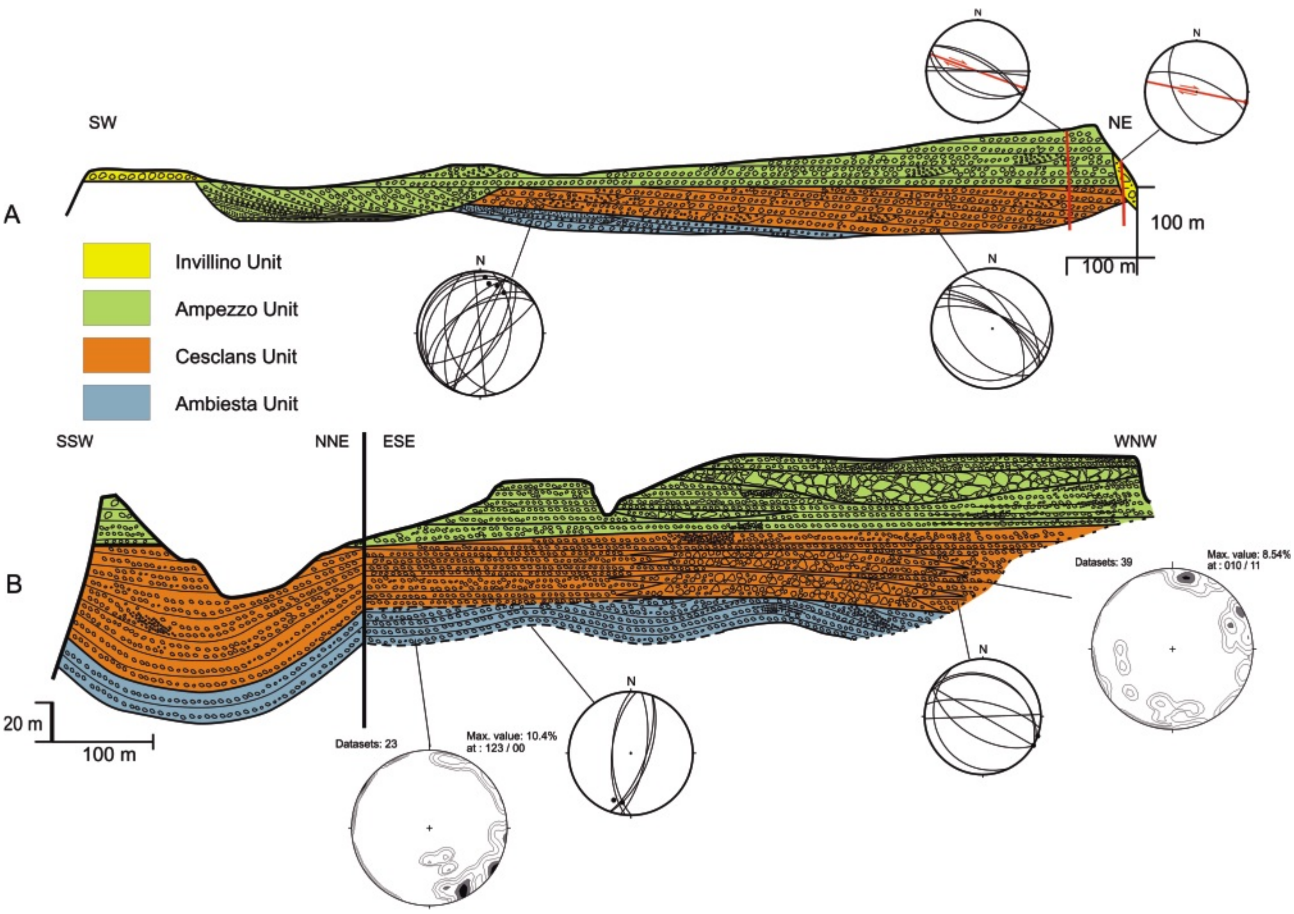

Figure 9: Sketched geological sections: A) transect through the TC succession at Enemonzo; B) Cesclans outcrop site in composite view highlighting the differences between the two angular unconformities. Stereonet diagrams, for folds and associated fractures, faults (red colour) and density diagrams for pressure-solution pits on pebbles highlight the change of tectonic deformation with time.

marked by an angular unconformity.

In the inner outcrops (Fig. 9A), the Ambiesta Unit is deformed by a system of open folds with axes oriented from N-S to NNE-SSW and dipping 20° northwards. The striation pattern of fold axes and several fractures associated with the folds suggest that the deformation occurred after cementation. Downstream, the decametric N-S folds appear subsequently folded by a hectometric syncline with N110° axis (Fig. 9B). Subvertical faults, WNW-ESE oriented also cut the two-folded unit.

Pressure-solution pits on pebbles indicate a NW-SE local maximum of compression, comparable to the deltaic conglomerates cropping out at Osoppo (Caputo et al., 2003).

Pollen analysis of the bottomset beds of the Osoppo delta indicates that trees and shrubs exceed 97%, dominated by subtropical forest taxa, such as Taxodiaceae (24.7%) with the occurrence of Sequoia Type (3.8%) and Taxodium Type (1.9%), Cupressaceae (15.8%), Symplocos (2%) and Myrica (2.5%), and the presence of Loranthus and Engelhardia. Temperate broad-leaved deciduous forest taxa are represented by Corylus (9.5%), Carya (5.7%), Platycarya (3%), Castanea Type (3.2%), with the occurrence of Fagus and Alnus. Coniferae are characterized by Pinus (14.5%) and Cathaya (2.5%). This association, rich in subtropical taxa, is comparable to those des-

Facies	Code	Description	Sedimentary environment and interpretation
Matrix-supported disorganized diamictite	Dmm	Generally thick; poorly sorted; angular to sub-rounded clasts, granule to boulder size, scratched and faceted. Matrix-supported; poorly sorted silty-sandy matrix	Lodgement and undifferentiated till
Angular disorganized breccia	Gb	Thick; poorly sorted; angular clasts composed of adjacent bedrock lithologies, granule to boulder size with megaclasts (>1 m in diameter, exceeding 10 m). Ungraded massive, clast-supported. Poorly sorted sandy matrix	Landslide
Clast-supported graded conglomerate	Gg	Generally thick; sorted; angular to sub-rounded clasts, granule to cobble size; clast-supported; poorly sorted silty-sandy matrix. Crudely-bedded to graded, a-axis imbricated	Subacqueous-subaerial cohesionless grain-flow
Clast-supported to matrix-supported disorganized conglomerate	Gms	Generally thick; poorly sorted; angular to sub-rounded clasts, granule to boulder size; clast-supported to matrix-supported; poorly sorted silty-sandy matrix. Crudely-bedded to graded, partly a-axis imbricated	Subaerial debris flow, cohesive debris-flow
Crudely bedded coarse conglomerate to sandstone	Gh	Thin to thick; moderately sorted; sub-rounded to rounded clasts, granule to cobble size. Clast-supported; imbricated; sorted sandy matrix	Gravel bar
Trough cross-bedded conglomerate	Gt	Thin to thick; partly b-axis imbricated; granule to cobble size clasts; sorted sandy matrix; clast-supported; rounded to sub-rounded	Gravel dune
Planar cross-bedded conglomerate	Gp	Thin to thick; partly b-axis imbricated; granule to cobble size clasts; sorted sandy matrix; clast-supported; rounded to sub-rounded	Gravel bar
Horizontally bedded sandstone	Sh	Generally thin; planar laminated sandstone	Plane-bed flow
Ripple cross bedded sandstone	Sr	Generally thin; ripple cross-bedded well-sorted sandstone	Lower flow regime
Massive sandstone	Sm	Sorted to well-sorted fine to coarse sand; rip-up mud clasts, widely dispersed gravels, charcoal debris; loading and pseudonodules	High- or low-density turbidity current; sandy debris flow
Trough cross-bedded sandstone	St	Sorted to well-sorted fine to coarse sand, normally graded	Sand dune
Massive to laminated mud	Fm-Fl	Fine laminated mud; massive mud, containing charcoal debris and mud-cracks	Abandoned channel, lacustrine bottomset

Table 2: Lithofacies identified in the Tagliamento conglomerate; codes are extended from Miall (1996), Eyles et al. (1983) and Vincent (2001); terminology for thickness of beds and lamina from Tucker (1988).

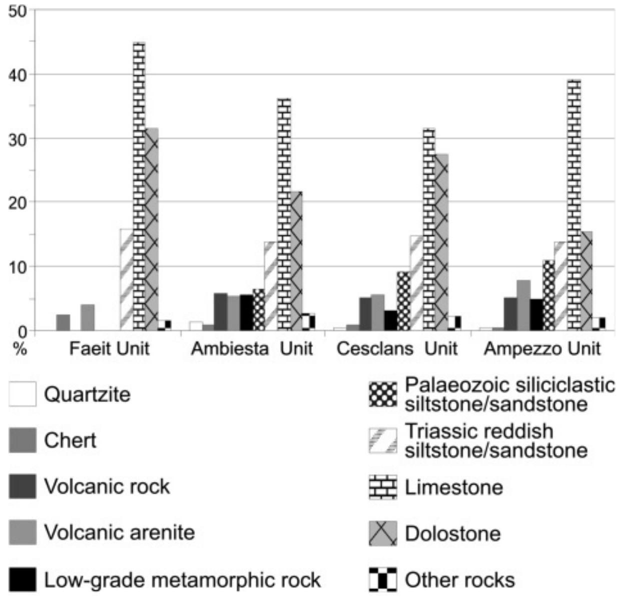

Figure 10: Composition diagrams of the rudite fraction of four units of the TC reported in stratigraphic order from left to right. Note the appearance and increasing of metamorphic and other Palaeozoic siliciclastic rock fragments from the Ambiesta Unit onwards.

cribed for the Zanclean of Northern Italy (Bertini and Martinetto, 2008) and represents an important chronological reference for this unit and the entire TC.

The basal boundary of the Ambiesta Unit, compared with that of the Faeit Unit (Fig. 6), shows that the valley was affected by a 200-m deep incision during the elapsed time-span as well as a shift towards the north. Facies associations suggest that the river was mostly characterized by a high-energy braided regime and that small alluvial fans and slope talus bodies were present on the valley sides.

Clast petrography differs from the Faeit Unit and points to a northward extension of the catchment area, which led to the inclusion of the Palaeozoic successions of the Palaeocarnic Chain in the drainage basin. The Gilbert-type delta of Osoppo indicates that the mouth of the valley was interested by a sea inlet during the late Zanclean transgression in the Venetian-Friulian foreland (Venzo, 1977; Favero and Grandesso, 1983); the Ambiesta Unit records the Zanclean infilling of the valley.

6.3 The Cesclans Unit

This unit is developed for about 25 km along the present Tagliamento valley; it occurs as isolated remnants within the inner valley, whereas more extensive outcrops are located downstream of Invillino (Fig. 5). The unit has an average thickness of about 50 m. Both basal and upper boundaries are marked by angular unconformities, the lower above the deformed Ambiesta Unit (Fig. 9B). The upper boundary is an erosional surface.

Planar-bedded conglomerates (Gh) are the most representative facies, interfingering near Cesclans on both sides of the valley with coarse-grained conglomerates (Gms) up to 10 m thick, related to alluvial fan bodies (Fig. 7, log 2; Tab. 2). Fine-grained deposits (Sh to Fl), with a thickness of up to 10 m, are locally present at the base of the unit (Fig. 7, log 4) and are related to floodplain deposition. Colluvial breccia (Gb) laterally interfingers with the fluvial deposits at Somplago. Palaeocurrent indicators suggest an average flow towards the south-east, concordant with the trunk valley axis.

Conglomerate petrography (Fig. 10) shows a persistence in the abundance of the carbonate categories (~58%) with an increase in dolostones, which reach 27.4% of the total composition. The other categories do not vary significantly, except for a clear decrease in low-grade metamorphic rocks (~3%) and a slight increase in the amounts of Palaeozoic siliciclastics (~9%). Alluvial fan deposits are characterized by up to 90% of sub-angular to angular carbonate clasts, with minor amounts of sub-rounded clasts of the various lithologies. Sandstone petrography indicates a slight increase of the CE fraction (Fig. 11B).

Some badly-preserved Taxodiaceae pollen grains have been recognized in the finest sediments, but on the whole all these levels are barren of pollens.

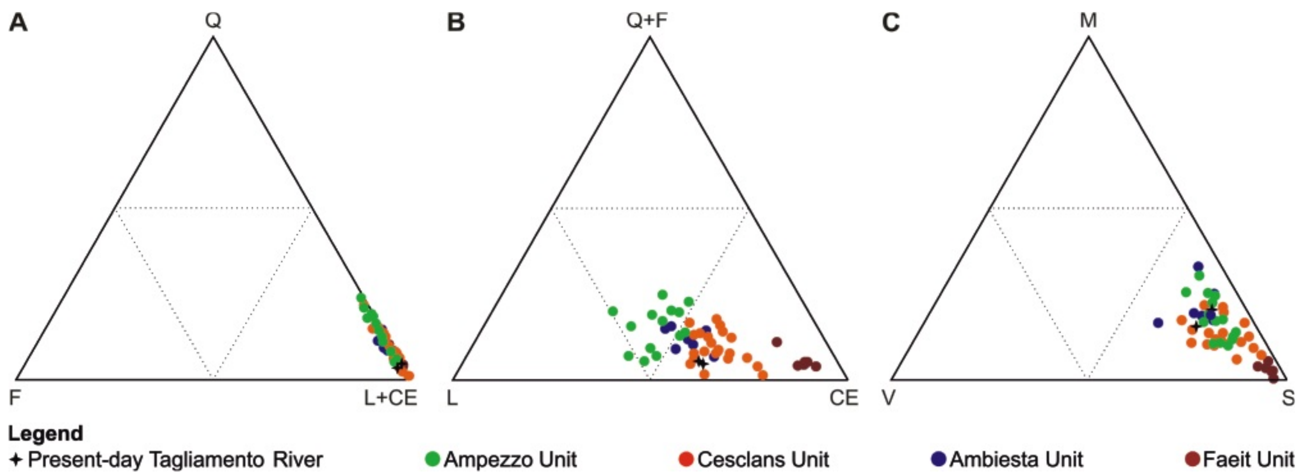

Figure 11: : Ternary diagrams of the sandy fraction of the TC; see text for explanation; the recognized units are quite distinct. Q, quartz; F, feldspars; L, fine-grained non-carbonate r.f.; CE, carbonate rock fragments; M, total (coarse- plus fine-grained) metamorphic r.f.; V, total volcanic r.f.; S, total sedimentary r.f.

Unit	No.	Q	F	L	CE	*Tot.*	M	V	S	*Tot.*
	105	2.7	1.2	6.3	89.8	*100.0*	2.6	2.6	94.8	*100.0*
	106	4.2	1.0	8.5	86.3	*100.0*	5.5	2.1	92.4	*100.0*
	107	3.8	0.3	10.8	85.1	*100.0*	3.3	4.0	92.8	*100.0*
	123	4.4	-	9.1	86.5	*100.0*	2.3	3.0	94.8	*100.0*
	201	4.5	0.6	7.8	87.0	*100.0*	0.3	3.5	96.2	*100.0*
Faeit	202	10.4	0.6	12.6	76.3	*100.0*	3.9	5.7	90.4	*100.0*
	195	5.7	0.9	30.8	62.6	*100.0*	17.5	10.1	72.4	*100.0*
	102	9.2	2.6	34.7	53.5	*100.0*	25.1	6.0	68.9	*100.0*
	103	8.5	1.9	34.1	55.5	*100.0*	18.7	12.3	69.0	*100.0*
	31	14.7	0.9	37.0	47.4	*100.0*	19.6	14.0	66.4	*100.0*
	237	11.3	3.1	28.8	56.9	*100.0*	19.0	9.9	71.1	*100.0*
Ambiesta	147	14.7	0.3	38.9	46.2	*100.0*	32.9	6.1	61.0	*100.0*
	145	15.9	0.9	31.9	51.3	*100.0*	12.5	3.5	84.0	*100.0*
	135	12.9	0.8	30.8	55.5	*100.0*	21.3	5.7	72.9	*100.0*
	136	11.3	1.4	29.3	58.0	*100.0*	11.9	12.3	75.8	*100.0*
	138	13.7	0.3	24.8	61.1	*100.0*	7.2	3.0	89.7	*100.0*
	139	12.5	0.5	32.8	54.3	*100.0*	16.7	2.6	80.7	*100.0*
	158	21.9	1.3	42.9	33.9	*100.0*	23.3	11.8	64.9	*100.0*
	159	15.0	2.6	24.7	57.7	*100.0*	11.1	11.1	77.7	*100.0*
	164	15.1	0.9	24.5	59.5	*100.0*	10.2	10.2	79.7	*100.0*
	162	6.4	-	22.5	71.1	*100.0*	9.4	3.9	86.7	*100.0*
	172	7.6	0.6	29.0	62.7	*100.0*	10.1	13.5	76.4	*100.0*
	171	8.0	0.7	28.7	62.7	*100.0*	10.2	15.3	74.5	*100.0*
	168	7.0	0.8	26.1	66.1	*100.0*	6.0	9.8	84.2	*100.0*
	169	9.9	0.8	29.4	59.9	*100.0*	13.5	9.6	76.9	*100.0*
	196	5.9	0.3	27.5	66.4	*100.0*	12.5	7.6	79.9	*100.0*
	197	2.4	1.4	21.2	75.1	*100.0*	11.7	8.2	80.1	*100.0*
	198	1.0	0.3	21.0	77.7	*100.0*	11.1	6.2	82.6	*100.0*
	199	6.0	0.3	35.9	57.8	*100.0*	19.8	6.4	73.9	*100.0*
	241	3.5	1.3	37.7	57.6	*100.0*	14.6	16.9	68.4	*100.0*
	242	1.2	0.3	35.7	62.8	*100.0*	21.9	10.0	68.1	*100.0*
	117	6.1	1.6	29.8	62.5	*100.0*	13.5	13.2	73.3	*100.0*
	118	8.3	-	32.3	59.3	*100.0*	10.9	18.9	70.2	*100.0*
Cesclans	120	11.0	1.2	23.5	64.2	*100.0*	10.1	10.1	79.8	*100.0*
	121	18.0	2.3	34.7	45.0	*100.0*	17.3	18.1	64.5	*100.0*
	128	11.1	1.7	36.3	50.9	*100.0*	17.0	12.7	70.3	*100.0*
	161	21.1	1.6	29.0	48.2	*100.0*	10.6	13.5	75.9	*100.0*
	165	19.3	0.6	49.9	30.3	*100.0*	24.5	6.1	69.4	*100.0*
	166	23.9	0.9	34.7	40.5	*100.0*	10.8	11.6	77.5	*100.0*
	167	12.6	1.2	34.5	51.7	*100.0*	13.9	6.1	80.0	*100.0*
	240	8.2	1.2	45.5	45.2	*100.0*	30.4	7.1	62.5	*100.0*
	180	16.3	0.9	38.5	44.3	*100.0*	22.5	7.7	69.7	*100.0*
	144	18.4	0.5	40.4	40.7	*100.0*	17.8	7.4	74.8	*100.0*
	183	14.4	1.3	47.3	37.0	*100.0*	25.3	7.6	67.1	*100.0*
	182	18.6	1.1	33.1	47.2	*100.0*	17.3	9.5	73.2	*100.0*
	204	5.3	1.8	52.2	40.7	*100.0*	25.6	12.8	61.7	*100.0*
Ampezzo	203	6.0	0.9	45.1	48.0	*100.0*	19.2	10.4	70.4	*100.0*

Table 3: Sandstone compositional data and adopted parameters.

In the upstream reaches there are several fractures associated with the tilting of the unit towards the north-west (Fig. 9A), while downstream it is deformed by a hectometric syncline with a N110° axis (Fig. 9B); the striation pattern of the reverse fault plane matches the folding. Dip angles decrease towards the unit top and measurements on pitted pebbles indicate a NNE-SSW local maximum of compression (Fig. 9B). Subvertical faults, WNW-ESE oriented, also cut the folded unit.

The angular unconformity at the bottom of the Cesclans Unit points to a significant stratigraphic gap, representing periods of enhanced erosion and tectonic deformation along the valley before fluvial deposition was restored. The palaeo-Tagliamento valley more or less maintained its path during this time span as suggested by the overlap of Ambiesta and Cesclans units. The main river was characterized by a high-energy braided regime, while the basal floodplain facies could be compared to those described for the Ambiesta Unit. The presence of alluvial fan bodies in the Cavazzo Carnico outcrops suggests the existence of some small tributaries draining from the surrounding slopes. The increase in the abundance of dolostone clasts could be related to the enhancement of detrital supply from small tributaries.

Tectonic deformations show that there were changes in the local stress directions, in particular their rotation from NW-SE to NNE-SSW, during the time span implied by the angular unconformity at the base of the unit.

6.4 The Ampezzo Unit

This unit is the most extensive of the whole succession and has an overall extent of about 25 km along the valley (Fig. 8), with an average thickness of 100 m. The lower boundary is marked by an angular unconformity above the Cesclans Unit (Fig. 6), locally exposed along the axis of the valley and better distinguishable on the sides. Conglomerates are from planar (Gh) to cross-bedded (Gp-Gt) (Fig. 7). Palaeocurrent indicators point to an average flow towards the south-east, matching that of the trunk valley.

Two breccia bodies (Gb), ascribed to massive landslides, are interbedded with the fluvial deposits (Fig. 7, log 2); the better preserved body reaches 30 m in thickness (Fig. 13C). Breccias are exclusively made up of carbonate elements with many coarse boulders (sensu Blair and McPherson, 1999).

Two Gilbert-type deltas are recognizable in the succession. The first which is 30 m thick, is located in the lowermost part of the unit and is exposed in a gorge south of Tolmezzo (Fig. 7, log 4). Foreset beds are visible in both cliffs of the gorge whereas foreset-toeset transition and laminated bottomsets (Fig. 13D) are visible in the eastern section. The other delta is located upstream of Enemonzo and reaches 40 m in preserved thickness (Fig. 9A); conglomerate foresets dip towards NE at 15°-20°, while the bottomsets are mostly sandy, small slump features are present.

Pollen analysis in an organic level from the bottomsets of the first delta indicates mixed forest (Arborean Pollen: 75%)

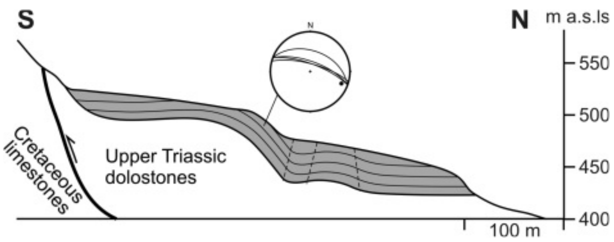

Figure 12: : Sketch profile of the Faeit Unit (site 1 in Figure 3) and particular of a 50° steep fold with stereonet diagram of fold axis and associated fractures.

dominated by Quercus caducifolia (10.5%), Ostrya (10.3%), Quercus ilex (6%), Corylus (6%) and Ulmus (5%), with subordinate Fagus (1.5%), Carpinus betulus (1.5%), Alnus glutinosa type (1.2%) and occurrence (<1%) of Acer, Alnus Viridis, Betula, Salix and Tilia. Conifers are represented by Pinus sylvestris/mugo (17.9%), Picea (9.6%) and Abies (1%). Herbs are about 25%, and consist mostly of Cruciferae (10.5%) and Ranuncolaceae (7.4%). This association is lacking of subtropical taxa and according to several authors (e.g. Bertini, 2006; Pini et al., 2008) this absence is characteristic of the upper part of the middle Pleistocene temperate flora in Northern Italy, marking an age constraint for the Ampezzo Unit.

Pebble composition (Fig. 10) indicates a slight decrease in carbonate clasts (~54%), while volcanic arenites (~8%) and Palaeozoic siliciclastics (~11%) show slight increases marking the transition between the Cesclans and Ampezzo units. Sandstone composition points to the same changes shown by gravel-size data, in particular the Q+F, L, CE ternary plot shows a 10-30% decrease in CE (Fig. 11B).

The Ampezzo Unit is crossed by several sub-vertical faults (Fig. 9A) with N110°-130° strike and faint sub-horizontal striae along the strike. Weakly pitted pebbles are rare.

The distribution of the sedimentary bodies in the inner segment indicates a widening of the valley floor and a shift southwards during the deposition of the Ampezzo Unit. The fluvial facies association suggests that the river was still dominated by high-energy streams, with locally deepening braided channels probably caused by the narrowing of the valley section. The two Gilbert-type deltas and the lacustrine fines are thought to reflect a temporary damming of the valley by landslides, testified by thick breccia bodies near Cavazzo Carnico at the same elevation as one the lacustrine deposits. Pollen analyses from the first delta suggest a middle Pleistocene age for the base of the unit. The increase in the amount of clasts sourced from the northern portion of the catchment may reflect the onset of glacier advances as a consequence of glacial phases which occurred at the end of the early Pleistocene (Muttoni et al., 2003).

Strike-slip faults are probably linked to the strike-slip movements along the Tagliamento valley related to the western propagation of the Idrija Fault (Burrato et al., 2008; Zanferrari et al., in press).

6.5 The Invillino Unit

This is the upper unit of the TC located inside the present valley between Ampezzo and Invillino (Fig. 8), which crops out mostly in isolated ridges within the river bed. The unit has an overall development of about 10 km and an average thickness of 50 m. The lower boundary is an erosional surface carved in older units (Fig. 8) and mostly located in the lowermost topographic areas with respect to the other units. The upper boundary is difficult to trace because of the discontinuity of the remnants; nevertheless glacial deposits related to the LGM rest on the surface. The fluvial facies is characterized by very coarse conglomerates (Gh) interfingering with diamictites, which consist of unsorted and commonly striated material from pebble to boulder size supported by a fine-grained silty-sandy matrix (Dmm). Foreset beds and topset beds of a delta body crop out at Invillino.

Pebble petrography is not comparable with that of older units due to the lack of outcrops downstream of the Tagliamento/Bût junction (Fig. 3), where the main and most complete sections of the other units are located.

The Invillino Unit, like the previous ones, is cut by several sub-vertical fractures with N100°-130° strike and sub-vertical strike-slip faults oriented N100° (Fig. 9A).

The Invillino Unit is the youngest of the TC and is the only one with clear glacial-fluvioglacial features: diamictites can be interpreted as tillites, while fluvial facies associations indicate high-energy streams. The delta body near Invillino is probably related to a lake caused by downstream damming, although no remnants of this damming have been found; glacial damming cannot be excluded.

The elevation of the basal surface is lower than that of the others and the unit is nested inside the older ones (Fig. 5). These facts suggest a deep carving of the valley before the deposition of the Invillino unit and a shift of the river towards the north-east to its present day course. This change in the drainage pattern probably occurred during the middle Pleistocene, as the age of the unit lies between that of the Ampezzo Unit and that of the deposits related to the Last Glacial Maximum (Venturini, 2009).

7. Discussion

7.1 Synthesis of the correlations and chronological bearings

Although the age of the Tagliamento conglomerate is poorly defined the allostratigraphic subdivision of the succession, strengthened by petrographic and structural analyses, indicates some chronological constraints, which are summarized here (Tab. 1).

The clast composition of the Faeit Unit could be linked with that of the Montello Conglomerate of Tortonian – Early Messinian age (Zanferrari et al., 2008b); the structural deformations affecting the unit, as well as the high topographic level of the basal surface, strengthen the assumption that this is of Early Messinian age.

As regards the Ambiesta Unit, the pollen data and the stratigraphic position of the Gilbert-type delta near Osoppo indicate that it represents the infilling of the valley at the end of the late Zanclean, when a widespread transgression occurred across the Venetian-Friulian plain (Venzo, 1977; Favero and Grandesso, 1983). This transgression was driven by a tectonic event in the Northern Apennines that caused a flexural subsidence in the southeastern Alpine foreland (Ghielmi et al., 2009).

The two angular unconformities bounding the Cesclans Unit indicate a long time span before and after its deposition; moreover the unconformities can be related to the two main tectonic events affecting the chain during the Gelasian and the Middle Pleistocene (Caputo et al., 2010); hence, because of its stratigraphic position, the unit could be referred to the Gelasian – Calabrian time span.

Pollen data indicate a Middle Pleistocene age for the Ampezzo Unit, which also appears to be more recent than the previous units as suggested by its stratigraphical position and weaker structural deformations.

The Invillino Unit is the youngest member of the succession

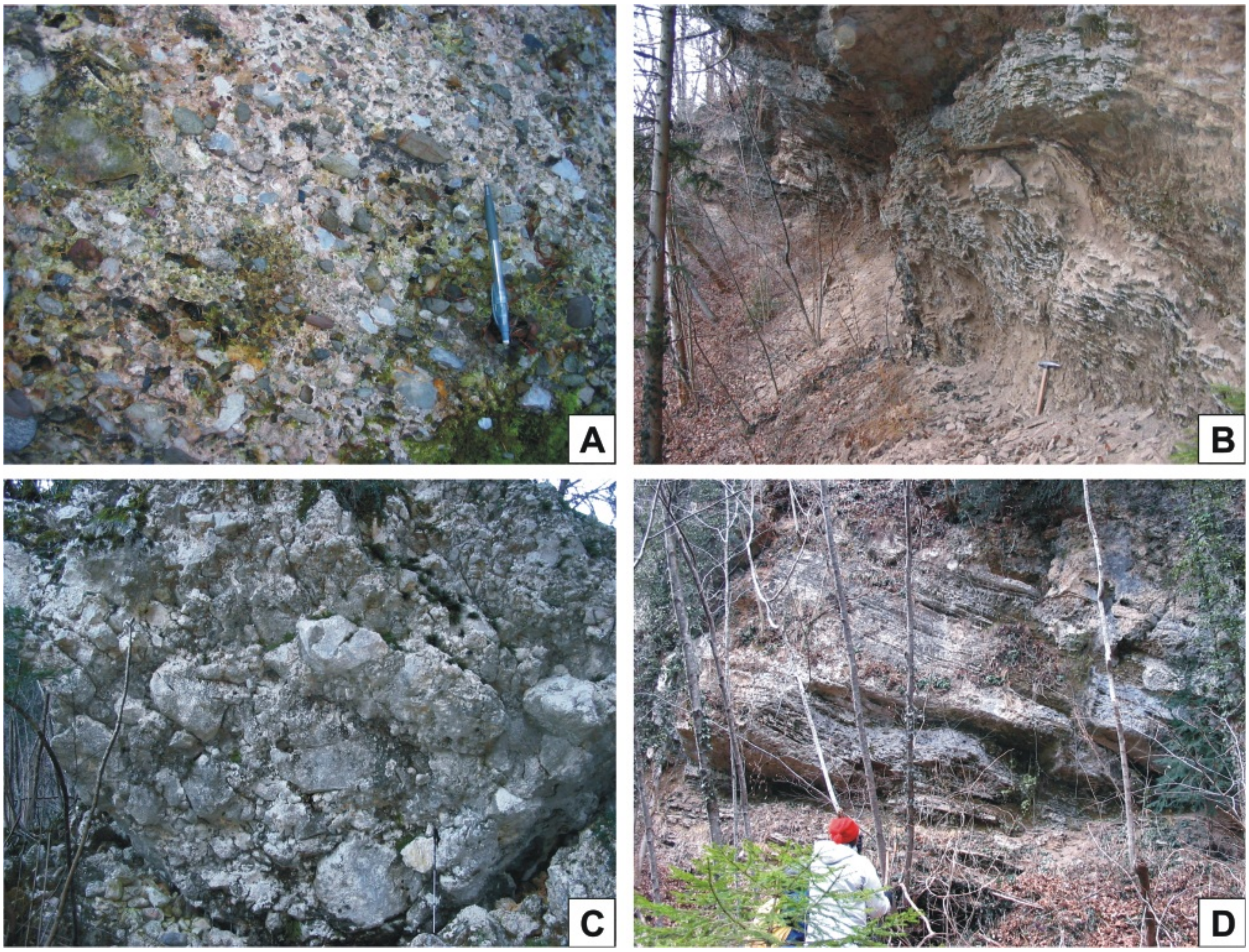

Figure 13: Photos of facies referred to logged sections of Figure 7; A) outcrop of poorly sorted, sub-rounded conglomerates of fluvial facies (Gh) of the Ambiesta Unit (pen is 10 cm long; log 2 in fig. 7); B) folded sandstone beds of fine-grained fluvial facies (St) of the Ambiesta Unit (hammer is 40 cm long; log 6 in fig. 7); C) Carbonate landslide breccia (log 2 in fig. 7) in the Ampezzo Unit (scale 1.5 m long) D) foreset beds of a Gilbert-type delta (log 4 in fig. 7) in the Ampezzo Unit.

and is nested in the previous ones. Common glacial features point to a Middle Pleistocene age for these deposits.

The new stratigraphic subdivision of the TC markedly differs from previous interpretations (Penck and Brückner, 1909; Gortani and Desio, 1926; Feruglio, 1929; Gortani, 1935; Carulli et al., 2000; Venturini, 2009), which considered the TC to be the sedimentary expression of an interglacial valley-fill of the middle Pleistocene. The presence of angular unconformities unequivocally points to the fact that this sedimentary stack has had a long history; this is further reinforced by the different levels of deformation affecting the single units (Tab. 1), as well as by changes in composition and provenance (Figs. 10 and 11). New Apatite Fission Track data (Monegato et al., 2010) indicate that the chain has experienced a slow uplift since the Late Miocene; this fact is strengthened by the presence of ancient deposits along the valley floor and not at very high elevation. According to recent structural data (Zanferrari et al., in press) the E-W reaches of the valley have been affected by strike-slip movement of the western portion of the Idrija fault system, producing reaches with local subsidence or displacement (Barnaba et al., 2010) prone to sedimentation and conservation of ancient sediments.

7.2 The evolution of the Tagliamento drainage basin in the last 6 Ma

The stratigraphic reconstruction of the valley fill, the composition of sediments and changes in the morphology of the valley itself contribute to outline the evolution of the drainage basin of the Tagliamento River.

Based on the stratigraphic succession of the foreland basin it would seem that the continental fluvial sedimentation became prevalent at the Tortonian-Messinian boundary with the deposition of the Montello Conglomerate (Zanferrari et al., 2008b). The compositional data of the conglomerate of the Faeit Unit indicate that it was the intra-mountain feeder system of the easternmost portion of the Montello Conglomerate. As the Montello Conglomerate is older than the intra-Messinian event, it is suggested that before this event, the Tagliamento drainage basin was restricted to the northwestern part of the Carnic Prealps, where Lower Triassic successions extensively crop out, and did not reach the northern Carnic Alps at that time (Fig. 14A). The watershed, however, was located south of the Fella-Sava fault, along which an east-west oriented river that probably flowed eastwards into the Slovenian Basin (Dunkl et al., 2005).

During the Messinian, the drop of the Mediterranean sea level at 5.6 Ma (Ryan and Cita, 1978; Krijgsman et al., 1999; Rouchy and Caruso, 2006; Roveri et al., 2008) determined the deep incision of valleys along the southern side of the Alps (Bini et al., 1978; Gargani, 2004). New studies of the Venetian–Friulian foreland basin (Nicolich et al., 2004; Mancin et al., 2007; 2009; Ghielmi et al., 2009) reveal that it was deeply trenched during the Messinian Salinity Crisis, as were the valleys in the mountain catchments.

The Tagliamento River also deepened its catchment. The distribution of the Ambiesta Unit indicates that the trunk valley shifted to the north and dropped down about 300 m (Fig. 6) during this period. Tectonic activity along the valley could have contributed to the migration, as suggested by the displacement of the basal boundary of the different remnants of the Faeit Unit (Fig. 5). The deepening also caused the wide northward extension of the drainage basin (Fig. 14B), noticeable in the sharp change in clast petrography (Fig. 10) of the fluvial deposits of the Ambiesta Unit. The deposits of the Ambiesta

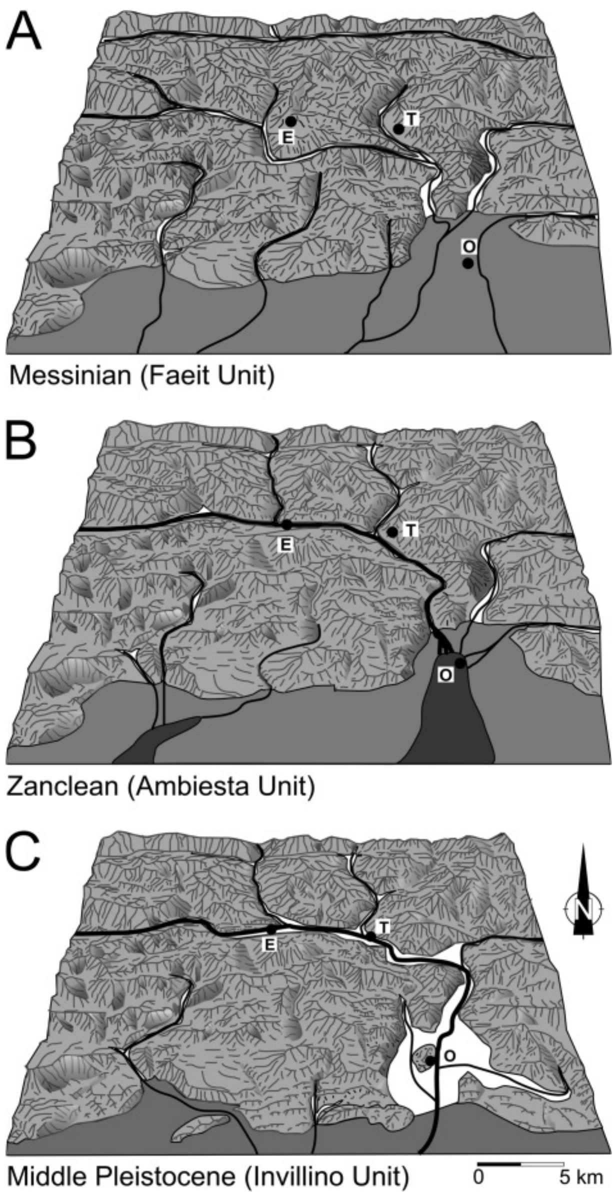

Figure 14: Palaeogeographic reconstruction of the main phases in the evolution of the Tagliamento valley: (A) during the Messinian the catchment was restricted to the central part of the relief, an E-W river flowed along the Fella-Sava fault lineament; (B) after the deep incision, caused by the sea-level drop of the late Messinian, the drainage basin extended northwards, capturing the E-W drainage, while the Tagliamento abandoned the reach south of Enemonzo; during the upper Zanclean transgression the river flowed into the sea forming the Osoppo delta; (C) during the middle Pleistocene, in response to glaciations, the trunk valley was incised, widened and forced to shift northwards abandoning the previous track; the valley mouth shifted southwards and the junction with Fella river was located inside the catchment; E: Enemonzo; O: Osoppo; T: Tolmezzo.

Unit were stored during the final part of the Zanclean, during a transgression phase that involved the whole Venetian-Friulian Basin (Ghielmi et al., 2009); the mouth of the river was located at Osoppo where it flowed into a marine inlet feeding a Gilbert-type delta (Venturini, 2000; Monegato et al., 2006).

In the subsequent period, till the middle Pleistocene, during the deposition of the Cesclans and Ampezzo units, the main trunk of the Tagliamento valley did not change. Nevertheless, changes in pebble petrography (Fig. 10) between the Cesclans and Ampezzo units indicates enhanced transport from the northern part of the catchment. This could be related with the onset of glaciations in the Alps (Muttoni et al., 2003), that affected the highest mountains located close to the northern watershed. At that time the valley mouth and the junction with the Fella River were still located at Osoppo.

During the middle Pleistocene the valley experienced entrenchment ascribed to glacial advances; these determined the fall of the threshold with the Fella Valley. The axis of the trunk valley shifted northwards and eastwards, forcing the Tagliamento River to merge with the Fella River inside the catchment (Fig. 14C). The valley section was also widened, reaching 2 km. The Invillino unit was deposited into this new thalweg, whose elevation was much lower than the older one, and nested in the older units (Fig. 8). Tectonic influence of this important change is cryptic; however, it is supported by recent geophysical data below the present riverbed downstream of Cavazzo Carnico (Barnaba et al., 2010). In addition, the presence of strike-slip faults throughout the TC succession implies that it cannot be underestimated and that tectonic activity continued during the Plio-Pleistocene.

8. Summary and conclusions

The five allostratigraphic units into which the Tagliamento conglomerate can be subdivided record the sedimentary and tectonic history of its drainage basin since the late Miocene. As far as the eastern Southalpine Chain is concerned this is the first example of a Messinian to Pleistocene stratigraphic reconstruction of a valley fill and of the evolution of a drainage basin linked to tectonic uplift. In fact, the presence at different elevations of abandoned segments of the valley related to the Tagliamento River highlights the changes that have occurred in the drainage network during the last 6 millions of years, during the exhumation of the eastern Southalpine Chain.

Based on petrographic (pebble and sandstone) data, tectonic deformations and stratigraphy the following steps have been recognized: the history of the valley, started during the Late Miocene with the first carving and downfilling caused by the deposition of coarse-grained fluvial deposits. The Messinian Salinity Crisis caused rapid uphead erosion and the widening of the drainage basins towards the Carnic Prealps; subsequently the Zanclean sea level rise allowed the retrogressive infilling of the river basin. Hereinafter, from the Middle Pliocene to the Middle Pleistocene, several phases of aggradation and erosion took place until the onset of glaciations in the Alps. During the Middle Pleistocene, probably due to subglacial carving and possibly favoured by strike-slip tectonics in the Tolmezzo area, the valley shifted north-eastwards, abandoning the previous westerly path.

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References

Barnaba, C., Marello, L., Vuan, A., Palmieri, F., Romanelli, M., Priolo, E., and Breitenberg, C., 2010. The buried shape of an alpine valley from gravity surveys, seismic and ambient noise analysis. Geophysical Journal International, 180, 715-733.

Bertini, A., 2006. The Northern Apennines palynological record as a contribute for the reconstruction of the Messinian palaeoenvironments. Sedimentary Geology, 188-189, 235–258.

Bertini, A. and Martinetto, E., 2008. Messinian to Zanclean vegetation and climate of Northern and Central Italy. Bollettino della Società Paleontologica Italiana, 47, 105-121.

Bini, A., Cita, M.B. and Gaetani, M., 1978. Southern Alpine lakes. Hypothesis of an erosional origin related to the Messinian entrenchment. Marine Geology, 27, 271–288.

Blair, T.C. and McPherson, J.G., 1999. Grain-size and textural classification of coarse sedimentary particles. Journal of Sedimentary Research, 69, 6-19.

Bressan, G., Snidarcig, A. and Venturini, C., 1998. Present state of tectonic stress of the Friuli region (eastern southern Alps). Tectonophysics, 292, 211-227.

Burrato, P., Poli, M.E., Vannoli, P., Zanferrari, A., Basili, R. and Galadini, F., 2008. Sources of Mw 5+ earthquakes in northeastern Italy and western Slovenia: An updated view based on geological and seismological evidence. Tectonophysics, 453, 157–176.

Caputo, R., Poli, M.E. and Zanferrari, A., 2003. Neogene-quaternary twist tectonics in the eastern southern Alps, Italy. Memorie di Scienze Geologiche, 54, 155-158.

Caputo, R., Poli, M.E., and Zanferrari, A., 2010. Neogene-Quaternary Tectonic Stratigraphy of the eastern Southern Alps, NE Italy. Journal of Structural Geology, 32, 1009-1027.

Carulli, G.B., 2006. Carta Geologica del Friuli Venezia Giulia (scala 1:150.000). S.EL.CA., Firenze.

Carulli, G.B. and Ponton, M., 1992. Interpretazione strutturale profonda del settore centrale carnico-friulano. Studi Geologici Camerti, vol. spec., 2, CROP1-1A, 275-284.

Carulli, G.B., Frizzo, P., Longo Salvador, G., Semenza, E., Bianchin, G., Mantovani, F. and Mezzacasa, G., 1987. La geologia della zona fra il T. Chiarzò e il F. Fella (Alpi Carniche). Giornale di Geologia, 49, 1-32.

Carulli, G.B., Cozzi, A., Longo Salvador, G., Pernarcic, E., Podda, F. and Ponton, M., 2000. Carta Geologica delle Prealpi Carniche. Museo Friulano Storia Naturale, Udine.

Castellarin, A. and Cantelli, L., 2000. Neo-Alpine evolution of the eastern Southern Alps. Journal of Geodynamics, 30, 251-274.

Castellarin, A., Cantelli, L., Fesce, A.M., Mercier, J., Picotti, V., Pini, G.A., Prosser, G. and Selli, L., 1992. Alpine compressional tectonics in the southern Alps. Relations with the N-Apennines. Annales Tectonicae, 6, 62-94.

Dalla Vecchia, F.M., 2008. Vertebrati fossili del Friuli. Pubblicazione n. 50, Edizioni Museo Friulano di Storia Naturale, Udine, 303 pp.

Dalla Vecchia, F.M. and Rustioni, M., 1996. Mammalian trackways in the Conglomerato di Osoppo (Udine, NE Italy) and their contribution to its age determination. Memorie di Scienze Geologiche, 48, 221-232.

DeCelles, P.G., Gray, M.B., Ridgway, K.D., Cole, R.B., Srivastava, P., Pequera, N. and Pivnik, D.A., 1991. History and kinematics of foreland uplift from synorogenic conglomerate, Beartooth Range, Wyoming and Montana. GSA Bulletin, 103, 1458–1475.

Dickinson, W.R., 1970. Interpreting detrital modes of greywacke and arkose. Journal of Sedimentary Petrology, 40, 695-707.

Doglioni, C. and Bosellini, A., 1987. Eoalpine and mesoalpine tectonics in the Southern Alps. Geologische Rundschau, 76, 735-754.

Doglioni, C. and Siorpaes, C., 1990. Polyphase deformation in the Col Bechei area (Dolomites - Northern Italy). Eclogae Geologicae Helvetiae, 83, 701-710.

Dunkl, I., Kuhlemann, J., Reinecker, J. and Frisch, W., 2005. Cenozoic relief evolution of the Eastern Alps – constraints from apatite fission track age-provenance of Neogene intramontane sediments. Austrian Journal of Earth Science, 98, 92-105.

Eyles, N., Eyles, C.H. and Miall, A.D., 1983. Lithofacies types and vertical profile models; an alternative approach to the description and environmental interpretation of glacial diamict and diamictite sequences. Sedimentology, 30, 393-410.

Favero, V. and Grandesso, P., 1983. Nuovi affioramenti di Pliocene marino nei dintorni di Bassano del Grappa (Vicenza). Memorie della Società Geologica Italiana, 24, 71-77.

Felber, M., Frei, W. and Heitzmann, P., 1992. Seismic evidence of pre-Pliocene valley formation and filling in the region of Novazzano (Southern Ticino, Switzerland). Eclogae Geologicae Helvetiae, 84, 753-761.

Feruglio, E., 1929. Nuove ricerche sul Quaternario del Friuli. Giornale di Geologia, 4, 1-36.

Fodor, L., Jelen, B., Martor, E., Skaberne, D., Car, J. and Vrabec, M., 1998. Miocene-Pliocene tectonic evolution of the Slovenian Periadriatic fault: implication for Alpine-Carpathian extrusion model. Tectonics, 17, 690-709.

Friend, P.F., Jones, N.E. and Vincent, S.J., 1999. Drainage evolution in active mountain belts: extrapolation backwards from present-day Himalayan river patterns. In: N.D. Smith and J. Rogers (eds.), Fluvial Sedimentology VI. International Association Sedimentologists Special Publication 28, pp. 305-313.

Galadini, F., Poli, M.E. and Zanferrari, A., 2005. Seismogenic sources potentially responsible for earthquakes with M≥6 in the eastern Southern Alps (Thiene-Udine sector, NE Italy). Geophysical Journal International, 161, 739-762.

Galehouse, J.S., 1971. Point counting. In: R.E. Carver (ed.) Procedures in Sedimentary Petrology. Wiley Interscience, New York, pp. 385-407.

Galloway, W.E. and Hobday, D.K., 1983. Terrigenous Clastic Depositional Systems: Applications to Petroleum, Coal, and Uranium Exploration. Springer, Berlin, 489 pp.

Gargani, J., 2004. Modelling of the erosion in the Rhone valley during the Messinian crisis (France). Comptes-rendus Geoscience, 121, 13-22.

Gazzi, P., 1966. Le arenarie del flysch sopracretaceo dell'Appennino modenese: correlazioni con il Flysch di Monghidoro. Mineralogica Petrographica Acta, 12, 69-97.

Gazzi, P., Zuffa, G.G., Gandolfi, G. and Paganelli, L., 1973. Provenienza e dispersione litoranea delle sabbie delle spiagge adriatiche fra le foci dell'Isonzo e del Foglia: inquadramento regionale. Memorie della Società Geologica Italiana, 12, 1-37.

Ghielmi, M., Minervini, M., Nini, C., Rogledi, S., Rossi, M. and Vignolo, A., 2009. Sedimentary and Tectonic Evolution in the Eastern Po Plain and Northern Adriatic Sea Area from Messinian to Middle Pleistocene (Italy). Rendiconti online della Società Geologica Italiana, 9, 32-35.

Gortani, M., 1912. Sull'età delle antiche alluvioni cementate nella valle del Tagliamento. Bollettino della Società Geologica Italiana, 31, 388-394.

Gortani, M., 1935. I terrazzi del bacino montano del Tagliamento e nelle valli contigue. Giornale di Geologia, 9, 1-41.

Gortani, M. and Desio, A., 1926. Note illustrative della Carta geologica delle Tre Venezie. Foglio "Pontebba". Ufficio Idrografico Regio Magistrato Acque di Venezia, 86 pp.

Howard, J.L., 1993. The statistics of counting clasts in rudites: a review, with examples from the upper Palaeogene of southern California, USA. Sedimentology, 40, 157-174.

Johnson, G.D., Raynolds, R. and Burbank, D., 1986. Late Cenozoic tectonics and sedimentation in the northwestern Himalayan foredeep: I. Thrust ramping and associated deformation in the Potwar region. In: P.A. Allen and P. Homewood (eds.), Foreland basins. International Association Sedimentologists Special Publication, 8, pp. 273–291.

Jones, S.J., 2004. Tectonic controls on drainage evolution and development of terminal alluvial fans, southern Pyrenees, Spain. Terra Nova, 16, 121–127.

Jones, S.J., Frostick, L.E. and Astin, T.R., 1999. Climatic and tectonic controls on fluvial incision and aggradation in the Spanish Pyrenees. Journal Geological Society London, 156, 761-769.

Jordan, T.E., Allmendinger, R.W., Dmanti, J.F. and Drake, R.E., 1993. Chronology of motion in a complete thrust belt: The Precordillera, 30–318S, Andes Mountains. Journal of Geology, 101, 135-156.

Keil, M. and Neubauer, F., 2009. Initiation and development of a fault-controlled, orogen-parallel overdeepened valley: the Upper Enns Valley, Austria. Austrian Journal of Earth Sciences, 102, 80-90.

Krijgsman, W., Hilgen, F.J., Raffi, I., Sierro, F.J. and Wilson, D.S., 1999. Chronology, causes and progression of the Messinian salinity crisis. Nature, 400, 652-655.

Lugli, S., Marchetti Dori, S. and Fontana, D., 2007. Alluvial sand composition as a tool to unravel late Quaternary sedimentation of the Modena Plain, northern Italy. In: J. Arribas, S. Critelli and M.J. Johnsson (eds.), Sedimentary Provenance and Petrogenesis: Perspectives from Petrography and Geochemestry. GSA Special Paper, 420, pp. 57-72.

Mancin, N., Cobianchi, M., Di Giulio, A. and Catellani, D., 2007. Stratigraphy of the Cenozoic subsurface succession of the Venetian-Friulian Basin (NE Italy): a review. Rivista Italiana di Paleontologia e Stratigrafia, 113, 401-418.

Mancin, N., Di Giulio, A. and Cobianchi, M., 2009. Tectonic vs. climate forcing in the Cenozoic sedimentary evolution of a foreland basin (Eastern Southalpine system, Italy). Basin Research, 21, 799–823.

Massari, F., 1990. The foredeeps of the Northern Adriatic margin: evidence of diachroneity in deformation of the Southern Alps. Rivista Italiana di Paleontologia e Stratigrafia, 96, 351-380.

Massari, F., Grandesso, P., Stefani, C. and Zanferrari, A., 1986. The Oligo-Miocene Molasse of the Veneto- Friuli region, Southern Alps. Giornale di Geologia, 48, 235-255.

Massari, F., Mellere, D. and Doglioni, C., 1994. Cyclicity in nonmarine foreland-basin sedimentary fill: the Messinian conglomerate-bearing succession of the Venetian Alps (Italy). In: M. Marzo and C. Puigdefabregas (eds.) Alluvial Sedimentation. International Association Sedimentologists Special Publication, 17, pp. 501-520.

Mather, A.E., 1993. Basin inversion: some consequences for drainage evolution and alluvial architecture. Sedimentology, 40, 1069-1089.

Miall, A.D., 1996. The Geology of Fluvial Deposits. Springer-Verlag, Berlin Heidelberg, 582 pp.

Monegato, G., Zanferrari, A. and Gliozzi, E., 2006. Stratigraphy, sedimentology and age of the Osoppo Hill deposits. In: R. Melis, R. Romano and G. Fonda (eds.), Giornate di Paleontologia 2006: guida alle escursioni. EUT Trieste, pp. 81-83.

Monegato, G., Stefani, C., and Zattin, M., 2010. From present rivers to old terrigenous sediments: the evolution of the drainage system in the eastern Southern Alps. Terra Nova, 22, 218-226.

Muttoni, G., Carcano, C., Garzanti, E., Ghielmi, M., Piccin, A., Pini, R., Rogledi, S. and Sciunnach, D., 2003. Onset of major Pleistocene glaciations in the Alps. Geology, 31, 989-992.

NACSN North American Commission on Stratigraphic Nomenclature, 1983. North American Stratigraphic Code. American Association Petroleum Geology Bulletin, 67, 841-875.

Nicolich, R., Della Vedova, B., Giustiniani, M. and Fantoni, R., 2004. Carta del sottosuolo della Pianura Friulana. L.A.C., Firenze.

Penck, A. and Brückner, E., 1909. Die Alpen im Eiszeitalter. Tauchnitz, Leipzig, 393 pp.

Pini, R., Donegana, M. and Ravazzi, C., 2008. Il sondaggio CARG – FVG S5 Azzano Decimo. Indagine palinostratigrafica. In: A. Zanferrari, R. Avigliano, A. Fontana and G. Paiero (eds.), Note illustrative della Carta Geologica d'Italia alla scala 1:50.000, Foglio 086, San Vito al Tagliamento, Servizio Geologico d'Italia, pp. 27–36.

Pivnik, D.A. and Johnson, G.D., 1995. Depositional response to Pliocene–Pleistocene foreland partitioning in northwest Pakistan. GSA Bulletin, 107, 895-922.

Poli, M.E. and Zanferrari, A., 2002. La catena ercinica a falde metamorfiche (Basamento Sudalpino Orientale). In: G.B. Vai, C. Venturini, G.B. Carulli and A. Zanferrari (eds.), Alpi e Prealpi Carniche e Giulie. BE-MA editrice, Milano, pp. 68-70.

Rantitsch, G., 1997. Thermal history of the Carnic Alps (Southern Alps, Austria) and its palaeogeographic implications. Tectonophysics 272, 213-232.

Ratschbacher, L., Frisch, W. and Linzer, H.G., 1991. Lateral extrusion in the eastern Alps, part 2: structural analysis. Tectonics, 10, 257-271.

Rouchy, J.M. and Caruso, A., 2006. The Messinian salinity crisis in the Mediterranean basin: A reassessment of the data and an integrated scenario. Sedimentary Geology, 188–189, 35–67.

Roveri, M., Bertini, A., Cosentino, D., Di Stefano, A., Gennari, R., Gliozzi, E., Grossi, F., Iaccarino, S.M., Lugli, S., Manzi, V. and Taviani, M., 2008. A high-resolution stratigraphic framework for the latest Messinian events in the Mediterranean area. Stratigraphy, 5, 323-342.

Ryan, W.B.F. and Cita, M.B., 1978. The nature and distribution of the Messinian erosional surface—indicators of a several-kilometers deep Mediterranean in the Miocene. Marine Geology, 27, 193–230.

Sanders, D., Ostermann, M. and Jan Kramers, J., 2009. Quaternary carbonate-rocky talus slope successions (Eastern Alps, Austria): sedimentary facies and facies architecture. Facies, 55, 345-373.

Schumm, S.A., 1977. The Fluvial System. Wiley, New York, 338 pp.

Schumm, S.A. and Ethridge, F.G., 1994. Origin, evolution, and morphology of fluvial valleys. In: R.W. Darlymple, R. Boyd and B.A. Zaitlin (eds.), Incised-valley systems: origin and sedimentary sequences. Society Sedimentary Geologists Special Publication, 51, pp. 11-27.

Selli, R., 1963. Schema geologico delle Alpi Carniche e Giulie occidentali. Giornale di Geologia, 30, 1-136.

Spalletta, C., Vai, G.B. and Venturini, C., 1982. La Catena Paleocarnica. In: A. Castellarin and G.B. Vai (eds.), Guida alla geologia del Sudalpino centro-orientale. Guide geologiche Regionali Società Geologica Italiana, pp. 281-292.

Stefanini, G., 1911. Sulla stratigrafia e sulla tettonica dei terreni miocenici del Friuli. Uff. Idrogr. Regio Magistrato Acque, Venezia.

Stefanini, G., 1915. Il Neogene Veneto. Memorie Istituto Geologia Mineralogia Regia Università di Padova, 3, 340-624.

Taramelli, T., 1875. Dei terreni morenici e alluvionali del Friuli. Annali Regio Istituto Tecnologico Udine, 8, 1-91.

Taramelli, T., 1881. Carta geologica del Friuli. Fusi, Pavia.

Tucker, M., 1988. Tecniques in Sedimentology. Blackwell Scientific Publications, Oxford, 394 pp.

Venturini, C., 1990. Geologia delle Alpi Carniche centro-orientali. Museo Friulano Storia Naturale, Udine, 220 pp.

Venturini, C., 1992. Il conglomerato di Osoppo. Gortania, Atti Museo Friulano Storia Naturale, 13, 31-49.

Venturini, C., 2000. Significato dei conglomerati. In: G.B. Carulli (ed.), Guida alle escursioni dell'81 Riunione estiva della SGI, pp. 118-120.

Venturini, C., 2009. Note illustrative della Carta Geologica d'Italia alla scala 1:50.000: Foglio 031 "Ampezzo". APAT-Servizio Geologico d'Italia. LAC, Firenze, 240 pp.

Venturini, S. and Tunis, G., 1992. La composizione dei conglomerati cenozoici del Friuli: dati preliminari. Studi geologici Camerti, Volume Speciale, CROP 1/1A, 285-295.

Venzo, S., 1977. I depositi quaternari e del Neogene superiore della bassa valle del Piave da Quero al Montello e del paleoPiave nella valle del Soligo (Treviso). Memorie Istituto Geologia Mineralogia Università di Padova, 30, 1 – 62.

Vincent, S.J., 2001. The Sis palaeovalley: a record of proximal fluvial sedimentation and drainage basin development in response to Pyrenean mountain building. Sedimentology, 48, 1235-1276.

Vincent, S.J. and Elliott, T., 1997. Long-lived transfer zone paleovalleys in mountain belts: an example from the Tertiary of the Spanish Pyrenees. Journal of Sedimentary Research, 67, 303-310.

Zanferrari, A., Avigliano, R., Fontana, A., Paiero, G. and Mozzi, P. 2008a. Note illustrative della Carta Geologica d'Italia alla scala 1:50.000: Foglio 086 "San Vito al Tagliamento". APAT-Servizio Geologico d'Italia – Regione Autonoma Friuli Venezia Giulia, GraphicLinea, Udine, 190 pp.

Zanferrari, A., Avigliano, R., Grandesso, P., Monegato, G., Paiero, G., Poli, M.E. and Stefani, C., 2008b. Note illustrative della Carta Geologica d'Italia alla scala 1:50.000: Foglio 065 "Maniago". APAT-Servizio Geologico d'Italia – Regione Autonoma Friuli Venezia Giulia, GraphicLinea, Udine, 224 pp.

Zanferrari, A., Poli, M.E., Monegato, G., Masetti, D., Romano, R., Podda, F., Russo, S., Ponton, M., and Stefani, C., in press. Note illustrative della Carta Geologica d'Italia alla scala 1:50.000: Foglio 049 "Gemona del Friuli": APAT-Servizio Geologico d'Italia – Regione Autonoma Friuli Venezia Giulia.

Zuffa, G.G., 1985. Optical analyses of arenites: Influence of methodology on compositional results, In: G.G. Zuffa (ed.), Provenance of arenites. Dordrecht, Netherlands, D. Reidel, NATO Advanced Study Institute Series 148, pp. 165-189.

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