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Neogene–Quaternary tectonic stratigraphy of the eastern Southern Alps, NE Italy

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ABSTRACT

In order to reconstruct the Neogene–Quaternary Tectonic Stratigraphy of the eastern Southern Alps, the late Tortonian-lower Pleistocene foredeep clastic sequences, cropping out in the Veneto and Friuli piedmont areas have been extensively investigated focusing on the contractional features observed in the frequent conglomerate layers (pitted pebbles). The eastern Southern Alps is the result of a typical polyphase tectonic activity initiated in Late Oligocene, characterised by the occurrence of several non-coaxial stress regimes. Based on careful analyses of the pebbles' surfaces (shape and orientation of the indented features) and following a systematic and statistical approach, the mean orientation of the maximum compressive stress axis (σ_1) has been obtained for more than 30 sites of measurements along the ca. 120 km-long investigated piedmont area. The affected lithostratigraphic units and the orientation (pre- *versus* post-tilting) of the stereonets density peaks make it possible to recognize four distinct deformational events and characterize them in terms of mean σ_1 direction and timing: late Tortonian ($\sigma_1 = 313°/00°$), late Messinian-Early Pliocene (338°/04°), Late Pliocene (314°/03°), and Early-Middle Pleistocene (160°/03°). The Tectonic Stratigraphy of the eastern Southern Alps during the last ca. 10 Ma shows the occurrence of several variations of the stress field characterized by a repeated oscillation of the σ_1 axis between an NNW-SSE and NW-SE directions (Twist Tectonics). Taking also into account literature data about older deformational events (Chattian–Burdigalian and Serravallian-Tortonian), we analyse the Neogene–Quaternary tectonic evolution in the frame of the central Mediterranean realm and compare it with the convergence direction between the Adria–Africa and Europe lithospheric plates. We show that compressional directions within the eastern Southern Alps are basically governed by the remote plate convergence, though since late Messinian, the approaching Northern Apennines started to play a crucial role within the investigated area. Alternating short-lived phases (1–2 Ma) of coupling and decoupling along the basal detachment of the Apennines accretionary wedge probably caused temporary perturbations of the 'local' stress field and complex accommodation structures in this region of ongoing crustal collision.

1. Introduction

Every orogen is commonly characterized by several deformational events that affect the crust and the sedimentary cover by successive and distinct tectonic phases. The Southern Alps, Northern Italy (Fig. 1), are not an exception and the first major goal of the present research is to reconstruct the 'Tectonic Stratigraphy' of the investigated area. In particular, the aims of Tectonic Stratigraphy (Caputo and Pavlides, 1993) are, firstly, the recognition of how many tectonic events occurred and, secondly for each event, the reconstruction of the stress trajectories, the areal distribution of the associated deformation as well as the relative and absolute chronology. For the sake of simplicity, in the following sections, we will uniformly use the term of tectonic (or deformational) "event" regardless the dimension of the affected crustal volume and its duration.

The Southern Alps is a major structural subdivision of the broader Alpine Chain and it is conventionally limited to the north by the Periadriatic Lineament (Fig. 1b). From a tectonic point of view, the Southern Alps correspond to a distinct late Cretaceous–Quaternary orogen (Doglioni and Bosellini, 1987; Massari, 1990; Castellarin et al., 1992, 2006a), while the Periadriatic Lineament represents its polyphased (though mainly oblique-slip) back-stop (Castellarin et al., 1992, 2006b; Schmid et al., 1996). This south-verging fold-and-thrust belt was generated during the complex crustal collision and indentation of the Adria promontory underneath the Alpine chain (Roeder, 1989; Polino et al., 1990; Schmid et al., 1996; Beaumont et al., 1996; Castellarin et al., 2006b).

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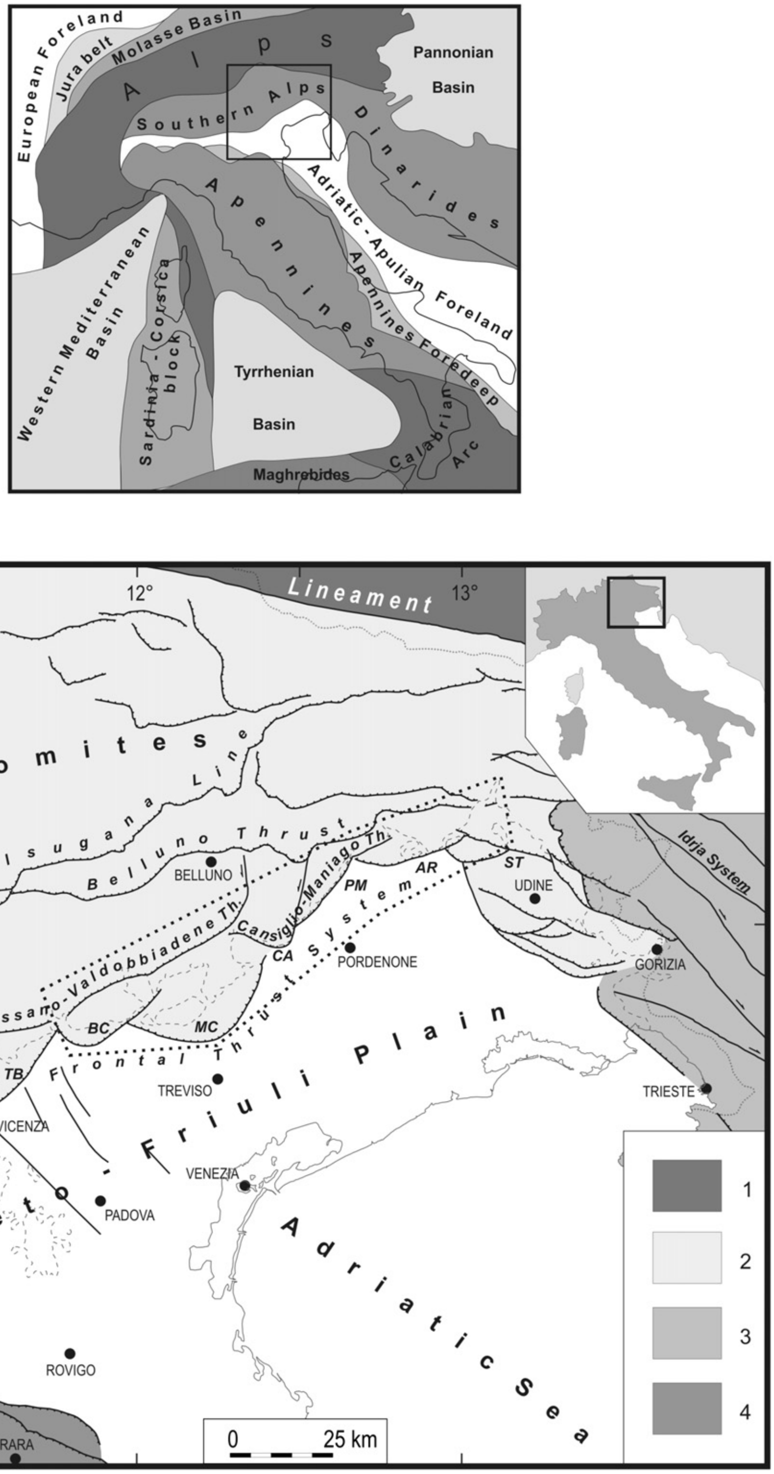

Fig. 1. a) The North Italian geodynamic framework (modified from Bigi et al., 1990) showing the position of the Southern Alps within the Europe-Africa convergent system. b) Simplified tectonic map of the eastern Southern Alps. The thin dashed line represents the morphological hills-plain boundary, while the dotted line indicates the investigated area (Fig. 2). 1 = Austroalpine; 2 = eastern Southern Alps; 3 = Northern Dinarides; 4 = Apennines; TB = Thiene-Bassano Thrust; BC = Bassano-Cornuda Thrust; MC = Montello Thrust; CA = Cansiglio Thrust; PM = Polcenigo-Maniago Thrust; AR: Arba-Ragogna Thrust; ST: Susans-Tricesimo Thrust.

Based on the fact that the available chronology and stratigraphy of the Neogene–Quaternary sedimentary succession within the eastern Southern Alps is now very detailed (Zanferrari et al., 2008a,b; and references therein), we investigated the external sector of the eastern Southern Alps and performed structural and stratigraphic mapping of the Tortonian–Quaternary sedimentary units outcropping within a 120 km-long zone along the foothills of the mountain chain in Veneto and Friuli regions (Fig. 2). Therefore, it has been possible to reconstruct a similarly detailed Tectonic Stratigraphy for the study region. Moreover, the principal results obtained from the mesoscopic structural analyses were correlated with the large-scale tectonic setting of the investigated area, while in a later section of this paper

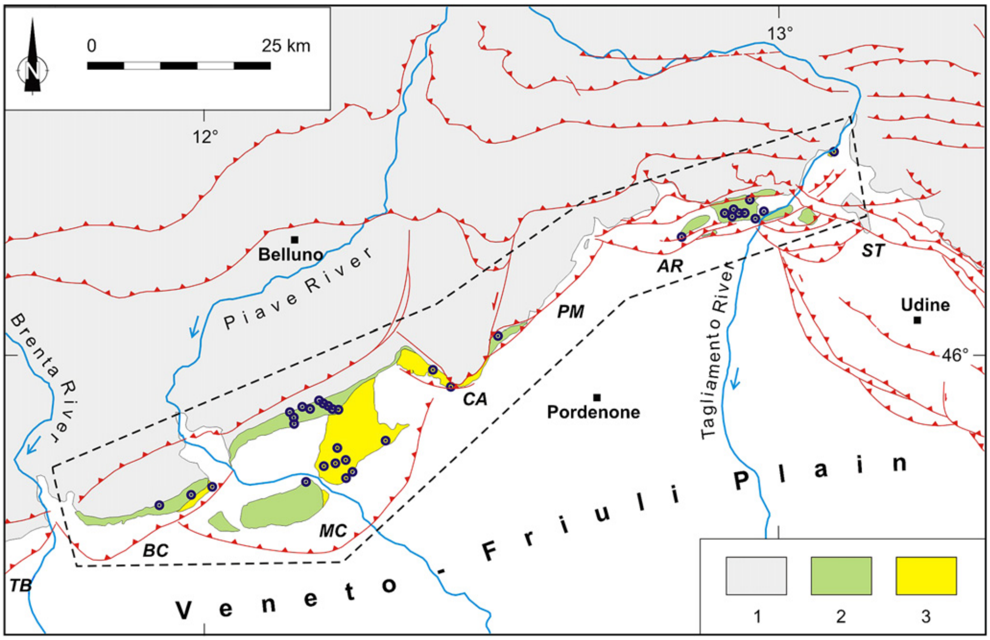

Fig. 2. Geological map of the investigated area (dashed line). 1: pre-Tortonian successions; 2: Tortonian-Messinian sedimentary units; 3: Pliocene-Pleistocene sedimentary units. Dots represent the sites of mesostructural investigations. Thrust labels as in Fig. 1.

we eventually discuss the eastern Southern Alps orogenic event in the frame of the Late Tertiary geodynamic evolution of the broader Central Mediterranean region.

The eastern Southern Alps is one of the most seismically active zones of the Central Mediterranean region as documented by both historical and instrumental seismicity (Slejko et al., 1989, 1999; Bressan et al., 2003; Working Group CPTI, 2004; Galadini et al., 2005; Burrato et al., 2008). In particular during historical times it has been struck by numerous earthquakes with magnitude between 6 and 7, as indicated in the catalogue by Working Group CPTI (2004) among which are the 1117 (Verona area), 1348 (Carnia region), 1695 (Asolo area), 1873 (Belluno area), 1936 (Cansiglio area) and 1976 (Friuli) events. Accordingly, a better understanding of the recent tectonic and geodynamic evolution of the broader investigated area could also contribute to improve the seismic hazard assessment of the region locally characterised by high vulnerability values.

As a second principal aim of this research, we would like to show the potential benefit in analyzing and using pitted pebbles in conglomerates as palaeostress indicators when performing mesostructural investigations.

As a final goal, we analyse and discuss the problem of separating different deformational events when performing mesoscopic and macroscopic structural analyses in broad regions. In particular, the main issue is how to distinguish between a major regional tectonic 'phase' from a second-order tectonic 'pulse' when investigating complex structural frameworks at the regional scale. Indeed, the question on the meaning of the space and time distribution of deformational events affecting wide areas is posed.

2. Regional tectonic framework

The development of the eastern Southern Alps as a well distinct orogen with respect to the Alps *s.s.* occurred during the Neogene–Quaternary time interval (Doglioni and Bosellini, 1987; Doglioni, 1990a; Castellarin et al., 1992; Fantoni et al., 2002). As commonly observed during the orogenic processes within the peri-Tethyan realm, deformation of the sedimentary cover and uppermost crust was not homogeneous in terms of involved rock volumes and stress-strain field, therefore inducing the researchers to distinguish and separate some major tectonic events or sub-events (Massari, 1990; Castellarin et al., 1992, 2006a; Caputo, 1996; Caputo et al., 1999).

2.1. First event

The first well defined tectonic event probably started in late Chattian (Mancin et al., 2007), but mainly developed in Early Miocene (Aquitanian–Burdigalian). In the literature, it is commonly referred to as the "Insubric" (Massari, 1990; Castellarin et al., 2006a) or "Chattian–Burdigalian" event (Caputo, 1996; Castellarin and Cantelli, 2000). Based on systematic mesoscopic structural analyses, the mean orientation of the maximum compressional axis (σ_1) associated with this event was N20°–30°, while the σ_3 axis was sub-vertical thus implying a purely compressional Andersonian regime (Castellarin et al., 1992; Caputo, 1996).

The affected area was mainly restricted to the northern sector of the eastern Southern Alps mountain chain. According to Fantoni et al. (2002), during this period and up to Langhian time, the present-day central and southern Veneto and Friuli areas represented a distal foreland-basin characterised by a regional monocline dipping roughly northwards by less than 1° and filled by the terrigenous-carbonate Cavanella Group deposits. Accordingly, the overall gentle dip and the lithological information suggest that the tectonic-topographic load of the new orogene was limited and still in its initial growing stage. Monegato et al. (2010) have also recently argued on the progressive uplift occurred during Early Miocene and the consequent erosion of the northern sector of the Southalpine fold-and-thrust belt, which at that time represented an external tectonic setting though at present it is in a more internal position. Based on the results of fission-track analyses, these authors indeed document a cluster of exhumation ages between 21.7 ± 3.4 Ma and 16.5 ± 1.0 Ma.

2.2. Second event

The second major tectonic phase contributing to the development of the eastern Southern Alps began in Serravallian time. In the literature, it is variably referred to as "Valsugana" (Castellarin et al., 2006a), "Giudicarie" (Laubscher, 1985; Massari, 1990), "Serravallian-Tortonian" (Castellarin et al., 1992; Caputo, 1996) or "Serravallian-Messinian" event (Massari et al., 1986a; Zanferrari et al., 2008a). This tectonic event formed new structures (such as the Valsugana and Belluno Thrust Systems in Fig. 1b) that progressively propagated southwards, thus cumulating large amounts of shortening (Largaiolli and Semenza, 1966; Doglioni, 1987, 1990a, 1992; Massari et al., 1993; Carulli and Ponton, 1993; Caputo, 1997; Castellarin et al., 1992, 1998, 2006a; Selli, 1998; Schönborn, 1999; Neri et al., 2007). These contractional structures are generally characterized by ramp-flat geometries, frontal splays, an average ENE-WSW strike and primarily by SSE-directed slip-vectors. Detailed and systematic mesoscopic structural analyses based on stress-inversion methods allowed to estimate the direction of maximum compression showing a mean N160°−170° orientation (Castellarin et al., 1992; Caputo, 1996).

Detrital apatite fission-track analyses (Dunkl et al., 1996; Zattin et al., 2003, 2006; Monegato et al., 2010) show a second cluster of ages that confirms a strong regional uplift and exhumation during Tortonian, likely due to the rapid growth and migration of the Southalpine fold-and-thrust belt. As a consequence, the now important tectonic load induced a pronounced flexural folding of the Adria lithosphere and the development of a real foredeep basin characterized by a strong subsidence (Massari et al., 1986a,b; Fantoni et al., 2002; Barbieri et al., 2004; Zanferrari et al., 2008b). The depocenter occupied the actual prealpine area, and the northern Veneto-Friuli Plain and the corresponding peripheral bulge was roughly located along the present-day Adriatic coastline (Fig. 1b). The reconstructed clastic wedge, more than 2500 m thick in Friuli and about 3000 m in Veneto, gradually thins atop an NNW-dipping basement monocline (Fantoni et al., 2002; Barbieri et al., 2004). The infilling material is particularly rich in carbonate clasts (Massari et al., 1986a,b; Stefani, 1987; Stefani et al., 2007), thus suggesting a proximal source area characterised by progressively eroded and dismantled carbonate massifs (mainly from Dolomites, Carnian and Julian Alps). With the deposition of the Montello Conglomerate (Upper Tortonian-Lower Messinian) this foredeep was almost completely filled up.

2.3. Third event

Notwithstanding the apparent continuity of the foredeep evolution up to Messianian time (Fantoni et al., 2002; Barbieri et al., 2004), since late Tortonian time onwards the eastern Southern Alps were affected by a new tectonic regime. This third major deformational event is referred to in the literature as "Messinian-Pliocene" (Castellarin et al., 1992) or "Adriatic" event (Castellarin et al., 2006a). According to several macro- and mesoscopic structural investigations, this deformation phase is characterized by an NW-SE-directed maximum horizontal compression (Castellarin et al., 1992, 2006a; Cantelli and Castellarin, 1994; Caputo, 1996; Caputo et al., 1999; Castellarin and Cantelli, 2000). In the Dolomites, which at that time already represented a structurally internal sector of the Southalpine fold-and-thrust belt, the reconstructed stress field is essentially of transcurrent type (*viz.* vertical σ_2) generating and activating mainly meridian sub-vertical strike-slip faults that systematically disrupt the older low-angle, nearly E-W trending contractional features (Caputo, 1997; Caputo et al., 1999; Neri et al., 2007). In turn, within the more external sectors of the chain (*viz.* southern), the tectonic regime remained purely compressional (*i.e.* vertical σ_3) and determined a complex contractional pattern mainly represented by the Bassano-Valdobbiadene and Cansiglio-Maniago thrusts (Fig. 1b). These major tectonic features are (E)NE-(W)SW striking and generally characterized by a large-scale well-developed fault-propagation anticline, locally affected by a cut-through emergent ramp-fault or by a lower-angle (*i.e.* flat) frontal blind segment (Doglioni, 1990a, 1992; Carulli and Ponton, 1993; Caputo, 1994; Castellarin et al., 1998, 2006b; Schönborn, 1999; Zanferrari et al., 2008b). Mainly due to the activity of these structures, the Serravallian-Messinian foredeep stratigraphic succession widely crops out along the Veneto-Friuli prealpine area (Figs. 1 and 2).

2.4. Fourth event

Finally, during the late Pliocene-Pleistocene time interval, a generic N-S compression has been suggested by Castellarin et al. (1992) as the fourth, still active, tectonic phase, though Caputo et al. (2003) document the occurrence of distinct stress fields affecting the region in chronological succession. The Pliocene-Quaternary tectonic evolution is characterised by the activation and propagation of new major segments and fault splays (Thiene-Bassano, Bassano-Cornuda, Montello and Arba-Ragogna thrusts) as well as the segmentation and partial reactivation of inherited structures (Cansiglio and Polcenigo-Maniago thrusts) caused by lateral variations in geometry and mechanical behaviour and/or the occurrence of transfer faults (*e.g.* Galadini et al., 2005; Burrato et al., 2008; Zanferrari et al., 2008a, b). We refer to all these younger tectonic features as the Frontal Thrust System (Figs. 1 and 2).

These deformational structures generally affect the entire clastic succession (up to Quaternary) of the Veneto-Friuli foothills and the contiguous alluvial plain (*e.g.* Zanferrari et al., 2008a, b). The recent activity of some of the major segments is well documented by geological and morphotectonic evidence, like river diversions and uplifted-tilted fluvial terraces (Galadini et al., 2005; Zanferrari et al., 2008a; Poli et al., 2009). These features are generally caused by an incipient folding at shallow depth, which in places is associated with a blind thrust with stepped (*i.e.* ramp-flat) geometry, a fault-propagation structure or a combination of the two classes of structures (Benedetti et al., 2000; Burrato et al., 2008).

Since late Messinian-to-Present, no foredeep can be recognised in the area that becomes a foreland-basin characterised by a Pliocene low subsidence rate, slightly increasing only during Quaternary (Fantoni et al., 2002). It is noteworthy that no differential subsidence nor lithospheric flexure associated with the Southalpine mountain chain seem to occur during Pliocene-Quaternary and the lack of any statistically significant fission-track ages for this period (Monegato et al., 2010) confirm that the regional uplift of the Southalpine mountain chain has decreased.

In the following sections of the paper, we will focus on the third and fourth tectonic events (as listed above), presenting new structural data from the prealpine area and discussing the overall Tortonian-Quaternary tectonic evolution.

3. Neogene−Quaternary sedimentary succession

In the frame of this research and in order to achieve the above mentioned goals, we focus on the Tortonian-Quaternary deposits outcropping along the foothill belt facing the Veneto-Friuli plain between the Brenta River, to the west, and the Tagliamento River, to the east (Fig. 2). As a whole, the investigated stratigraphic units show a typically clastic shallowing upwards sequence representing the infill of the eastern Southalpine foredeep-foreland basins, which developed from Late Oligocene to Pleistocene (Massari et al., 1986a; Monegato, 2006; Stefani et al., 2007). The stratigraphic succession starts with a proximal marine facies (deltaic front), passing upwards to a transitional one associated with a deltaic plain and closes up with a typical continental alluvial plain facies.

The different stratigraphic units are locally separated by angular unconformities, providing a crucial evidence for synsedimentary activity of the major tectonic structures.

A brief description of the investigated sedimentary units, spanning from Tortonian *p.p.* up to Early Pleistocene, is reported in this chapter (Fig. 3), while more exhaustive information can be found in Zanferrari et al. (2008a, 2008b), which performed a new detailed mapping of the Friuli sector in the frame of the Italian Geological Mapping Project at the 1:50,000 scale (CARG-FVG Project). For the Venetian area see also Massari et al. (1986b). The acronyms associated with each stratigraphic unit directly reflect the results of the CARG-FVG Project and they will be used throughout the text when referring to the different sedimentary units.

3.1. Vittorio Veneto Sandstone (VVE; Tortonian p.p.)

It consists of a coarsening upwards clastic succession, where the lower portion is mainly arenaceous, while it is prevailingly conglomeratic upwards (Massari et al., 1986a, 1986b; Zanferrari et al., 2008a). Pebbles are mostly carbonate, from rounded to sub-rounded in shape. The unit is about 300 m thick and the age is based on its stratigraphic relationships (Zanferrari et al., 2008a; Fig. 3).

3.2. Montello Conglomerate (MON; upper Tortonian-lower Messinian)

It consists of a thick succession widely outcropping within the investigated foothill belt. In the Friuli area it was completely revised, both stratigraphically and sedimentologically. Based on new palynological and radiometric ($^{87}Sr-^{86}Sr$) datings a late Tortonian-early Messinian depositional age (Fig. 3) was established (Grandesso et al., 2000; Zanferrari et al., 2008a). The formation is subdivided into three members recognized in both eastern Veneto and Friuli sectors:

MON_1: conglomerate-sandstone member (upper Tortonian *p.p.*) consisting of relatively well-sorted conglomerates with sub-rounded pebbles, very thickly bedded, alternating with yellowish sandstone and grey siltstone layers.

MON_2: sandstone-mudstone member (uppermost Tortonian-lowermost Messinian) characterised by weakly cemented light-grey sandstone and grey mudstone, with few, but thick, conglomerate beds containing rounded to sub-rounded pebbles. The Tortonian-Messinian boundary has been located in the middle of this member (Grandesso et al., 2000).

MON_3: conglomerate member (lower Messinian) consisting of poorly sorted conglomerates with sub-angular to sub-rounded mostly carbonate pebbles, thickly to very thickly bedded, alternating with thin yellowish sandstones and grey to greenish mudstones.

For what concerns the conglomerates outcropping in the Montello Hill, they have been correlated with an Upper Pliocene-Pleistocene unit which has been identified in the subsurface of the nearby Veneto Plain and inferred from seismic profiles, lithological-geoelectrical logs and some boreholes for hydrocarbon exploration (Fantoni et al., 2002). However, because the Montello Thrust (Fig. 2; Pieri and Groppi, 1981; Scrocca et al., 2003; Burrato et al., 2008) separates the sedimentary succession outcropping in the Montello Hill from that recognized underneath the Veneto Plain, a straightforward seismostratigraphic correlation is at least doubtful. In contrast, based on bio-stratigraphic determinations (Dal Piaz, 1942) and especially on new palynological and lithostratigraphic

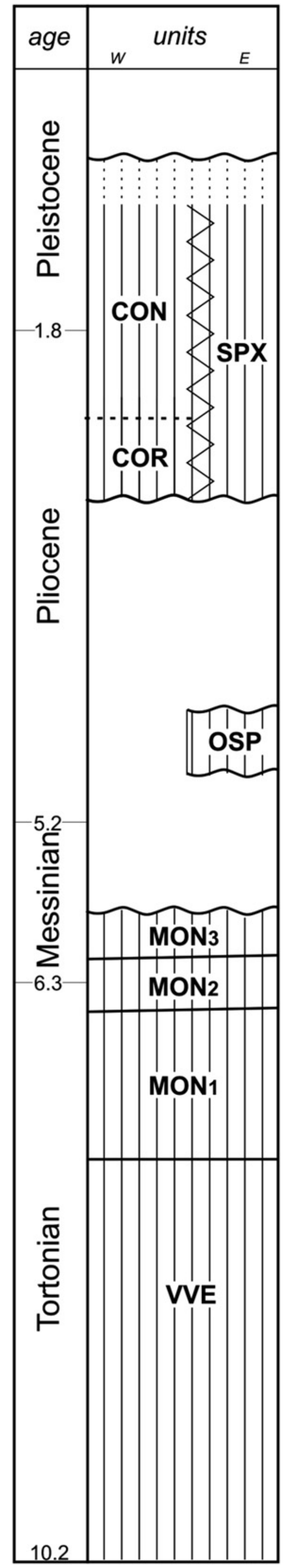

Fig. 3. Tortonian *p.p.*-Pleistocene sedimentary succession outcropping within the investigated area (Fig. 2). Stratigraphic units are from Zanferrari et al. (2008a,b) and correspond to Conegliano Unit (CON); Cornuda Member (COR); San Pietro di Ragogna Conglomerate (SPX); Pliocene Osoppo Conglomerate (CON); Montello Conglomerate (MON; −1: lower, −2: middle, −3: upper members) and Vittorio Veneto Sandstone (VVE).

Table 1
Sites of mesostructural analysis showing the NW-SE late Tortonian compression (Fig. 8). *Lat.*, *Lon.* = geographical coordinates; *formation* = affected stratigraphic unit [VVE: Vittorio Veneto Sandstone (Tortonian *p.p.*); MON_1: Montello Conglomerate lower member (upper Tortonian *p.p.*); MON_2: Montello Conglomerate middle member (uppermost Tortonian-lowermost Messinian); MON_3: Montello Conglomerate upper member (lower Messinian); OSP: Osoppo Conglomerate (Lower Pliocene); CON: Conegliano Unit (Upper Pliocene-Lower Pleistocene); COR: Cornuda Conglomerate (base of Upper Pliocene)] *N* = number of collected data; S_0 = attitude of the layering (dip direction and dip angle), an asterisk indicates overturned beds; *axis/α* = azimut of the rotation axis and angle of rotation used for the palinspstic restoration (back-tilting) of the data; S_0* = attitude of the layering (dip direction and dip angle) after the palinspastic restoration (only when performed); σ_1 = orientation of the maximum compressional axis.

Site	Lat. (N)	Lon. (E)	formation	N	S_0	axis/α	S_0*	σ_1
Collagu__	45° 55.0′	12° 07.6′	MON_1 (upper)	14	147/80	57/80	subhor.	316/02
Pedeguarda__	45° 55.9′	12° 09.0′	MON_1 (lower)	24	160/65	70/65	subhor.	135/04
Bresolin__	45° 55.9′	12° 10.1′	MON_1 (lower)	6	165/70	75/70	subhor.	305/02
Lierza1__	45° 56.4′	12° 11.9′	VVE (upper)	7	155/65	65/30	155/30	313/06
Paludea____	46° 11.9′	12° 53.3′	MON_2	17	336/75*	66/105	subhor.	139/00
mean value								313/00

researches (Ravazzi and Pini, 2002), it is more likely that most of the Montello Hill consists of Tortonian-Messinian conglomerates (MON Unit). Only along the eastern flank of the Montello Hill, the Upper Pliocene-Pleistocene Conegliano Unit (see below) probably crops out and disconformably lies on the Montello Conglomerate (MON Unit).

3.3. *Osoppo Conglomerate (OSP; Lower Pliocene)*

This sedimentary unit represents a conglomerate succession deposited in a Gilbert-type fan delta developed within the Messinian palaeovalley of the Tagliamento River (Fig. 2; Venturini, 1991; Monegato, 2006). Based on recent palynological analyses (Monegato, 2006), this unit is Early Pliocene in age (Fig. 3). The clasts are sub-rounded to sub-angular, mainly carbonate but also include a considerable amount of sedimentary Palaeozoic rocks and metamorphic rocks of the Variscan basement that presently crop out in the Carnic Alps.

3.4. *Conegliano Unit (CON; Upper Pliocene-Lower Pleistocene)*

The strong drop of the sea level during Late Messinian time produced also in the study area a diffused sub-aerial erosion and the formation of deeply entrenched valleys (Fantoni et al., 2002; Barbieri et al., 2004; Zanferrari et al., 2008a, 2008b). On top of this unconformity, the Conegliano Unit consists of prevailing sandy-clay layers alternating with clays (locally coal levels) and carbonate sands. Conglomerate bodies with variable thickness and lateral extension are also frequent in this continental succession. Pebbles are mainly carbonate, even if metamorphic and magmatic clasts originating from the eastern Southalpine Variscan basement are locally abundant.

New palynological analyses (C. Ravazzi and R. Pini, unpublished data) allow to refer the base of the Conegliano Unit to the Upper Pliocene. According to Fantoni et al. (2002), the upper part of the CON Unit includes at least the Lower Pleistocene, while a Middle Pleistocene age is uncertain.

It is noteworthy that the late Messinian-Early Pliocene tectonic activity along the Southalpine thrust front (see next chapter), deformed and locally tilted the MON clastic succession. As a consequence, in the Veneto area the CON Unit lies onto its substratum, from which is separated by an erosional surface. In particular, near Cornuda the basal conglomerates of the Conegliano Unit (COR Unit in Fig. 3) show an angular unconformity of about 35° on top of the Lower Pliocene mainly pelitic succession (Venzo, 1977).

In the literature, the CON Unit coincides with the "*ps*" (Upper Pontian) and "*pls*" (Upper Pliocene) units mapped in the "Conegliano" geological sheet (AA.VV., 1963). In Venzo (1977), the same units form the "Ma" unit, which at the time was tentatively assigned to the Upper Messinian.

3.5. *San Pietro di Ragogna Conglomerate (SPX; Upper Pliocene-Lower Pleistocene)*

In the eastern investigated area (Friuli), a lithological unit similar to the Conegliano Unit has been recently mapped (Zanferrari et al., 2008a). Although new palynological analyses provide the same Upper Pliocene age for the stratigraphic base, the San Pietro di Ragogna Conglomerate (SPX Unit in Fig. 3) has been cartographically and stratigraphically distinguished due to the lack of lateral continuity with the CON Unit (Monegato, 2006; Zanferrari et al., 2008a). Similar to the western Veneto sector and due to the late Messinian-Early Pliocene tectonic activity, in the hills facing the Friuli plain, the SPX Unit lies onto its substratum, from which is separated by an erosional surface with an angular unconformity up to 45° on top of the tilted MON_3 Conglomerate (Poli et al., 2009). Because of their higher degree of cementation and karst-related phenomena, the conglomerates of the SPX Unit are not suitable for our mesoscopic structural analysis.

Table 2
Sites of mesostructural analysis showing the NNW-SSE Late Messinian-Early Pliocene compression (Fig. 9). Symbols as in Table 1.

Site	Lat. (N)	Lon. (E)	formation	N	S_0	axis/α	S_0*	σ_1
Casa Nardi__	45° 54.8′	12° 07.6′	MON_3	8	155/85	65/85	subhor.	146/00
Pedeguarda__	45° 55.9′	12° 09.0′	MON_1 (lower)	9	160/65	70/35	160/30	152/02
Lierza2__	45° 56.3′	12° 11.0′	VVE (upper)	37	155/65	65/65	subhor.	160/14
Lierza1__	45° 56.4′	12° 11.9′	VVE (upper)	40	155/65	–/–		347/09
Visinale__	46° 11.4′	12° 54.2′	MON_1 (lower)	24	340/70	250/70	subhor.	330/13
Rez__	46° 11.8′	12° 54.5′	MON_3 (lower)	20	330/65	240/65	150/25	149/02
Romagnoi1__	46° 11.6′	12° 54.6′	MON_1 (middle)	16	340/80	250/80	subhor.	341/09
Romagnoi2__	46° 11.6′	12° 54.7′	MON_1 (upper)	25	003/50	273/50	183/40	001/33
Manazzons__	46° 12.5′	12° 55.3′	MON_1	22	345/88*	75/70	165/22	354/12
Beorchia__	46° 11.2′	12° 56.1′	MON_1 (lower)	13	340/30	250/30	subhor.	149/11
Pinzano____	46° 11.2′	12° 56.8′	MON_3	14	155/86	65/86	subhor.	155/03
mean value								338/04

Table 3
Sites of mesostructural analysis showing the NW-SE Late Pliocene compression (Fig. 10). Symbols as in Table 1.

Site	Lat. (N)	Lon. (E)	formation	N	S_0	axis/α	S_0*	σ_1
Cornuda_	45° 49.6′	11° 59.9′	con	54	143/65	53/27	143/39	140/00
S. Salvatore2	45° 51.1′	12° 14.1′	con	17	130/20	–/–		318/09
S. Salvatore1	45° 51.0′	12° 14.5′	con	26	subhor.	–/–		147/05
Case Porchera	45° 54.6′	12° 07.8′	mon_3	16	150/88	–/–		121/05
Vallotai2	45° 56.0′	12° 11.3′	mon_1	43	153/60	–/–		138/02
Molinetto_	45° 55.9′	12° 11.4′	mon_2 (lower)	23	130/53	–/–		309/05
Osoppo_NW	46° 15.7′	13° 04.8′	osp	14	subhor.	–/–		307/22
mean value								314/03

4. Tectonic stratigraphy

4.1. Methodological approach

In the frame of the present investigation, we performed a detailed structural mapping aimed at identifying and selecting as many sites as possible, within the above described Tortonian to Pleistocene deposits, affected by mesoscopic deformation structures. In particular, due to the relatively large distribution of conglomerate bodies within the considered stratigraphic interval, we focused our attention on, and carefully analysed, numerous deformed pebbles characterised by pitted surfaces. These structural features are classically related to small-scale pressure-solution processes (*e.g.* Trurnit, 1968; Alvarez et al., 1976) mainly occurring along those particle contacts that are roughly oriented perpendicular to the direction of maximum compression and usually associated with similarly oriented chains of forces (*e.g.* Socolar, 1998; Clement, 1999; Ouadfeld and Rothenburg, 2001). Pressure-solution phenomena can occur on pebble contacts where effective stresses are as low as 10 MPa (*e.g.* McEwen, 1978; Sanz de Galdeano and Estévez, 1981), while in loose-to-fairly cemented conglomerates with a clast-supported texture these pressure values can be easily reached even at some tens of meters of burial depth. Accordingly, the clustering in orientation of such mesoscopic structural features as obtained from numerical and analogical modelling and observed in natural case studies (McEwen, 1981; Hippolyte, 2001; Marella, 2005), allows to document the occurrence of a similarly oriented σ_1 axis. Based on careful analysis of the shape and orientation of the indented features on the pebbles' surface and following a statistical approach based on as many as possible measurements for each site, the mean orientation of the maximum compressive stress axis (σ_1) is obtained by contouring the data on a stereonet and calculating the density peak. For this purpose, we used the StereoNett shareware (Duyster, 2001). Formally speaking, the above mentioned 'mean orientation' represents a principal strain axis, but reasonably assuming that stress and strain ellipsoids are coaxial, in the following both a stress-related terminology (compression) and a strain-related one (contraction or shortening) will be used.

Although potential stress conditions for triggering the pressure-solution process are relatively common in a subsiding foredeep basin, other physical and chemical conditions must be fulfilled for the process to be widespread within the rock volume. For example, if the silty-sandy component is too abundant, compression could be entirely or largely accommodated within the matrix by both inter-clasts sliding and intra-clasts deformation (*e.g.* Bjørkum, 1996; Gratier et al., 1999). Also, if the strain-rate is too high or mainly dry conditions occur (*e.g.* Renard et al., 1997, 1999), the pressure-solution process cannot develop. Moreover, throughout the burial history, pebbles could be imprinted only during a limited period of time because if diagenetic cementation is too rapid and pervasive, the conglomerate is instead deformed brittlely by generating mesoscopic to macroscopic fault surfaces.

4.2. Collection and data processing

Following the above described methodological approach, numerous sites have been investigated and analysed in detail. In Tables 1–4 the location (*site*) and the coordinates (*Lat.* and *Lon.*) of each site of measurements are reported as well as the affected sedimentary unit (*formation*). The number of measurements (*N*) and the local setting of the layering (S_0) are also indicated. According to the stratigraphic succession of the area, the maximum burial depth of the outcropping deposits we investigated was at most of thousand metres and generally of some hundreds of metres. As a consequence, the observed deformational features were formed in structurally shallow conditions and therefore we

Table 4
Sites of mesostructural analysis showing the NNW-SSE Early-Middle Pleistocene compression (Fig. 11). Symbols as in Table 1.

Site	Lat. (N)	Lon. (E)	formation	N	S_0	axis/α	S_0*	σ_1
Asolo1	45° 48.1′	11° 54.0′	mon_3	17	143/28	–/–		163/03
Asolo2	45° 50.3′	11° 57.2′	mon_3	14	145/45	–/–		148/06
Montello1	45° 51.2′	12° 10.0′	mon_3	21	190/20.	–/–		341/01
Col di Guarda	45° 52.2′	12° 12.9′	con	14	subhor.	–/–		336/01
M. Cucco2	45° 52.3′	12° 13.3′	con	33	subhor.	–/–		163/02
M. Cucco1	45° 52.2′	12° 13.6′	con	40	subhor.	–/–		179/01
Sandago	45° 53.3′	12° 12.9′	con	60	subhor.	–/–		161/02
Conegliano	45° 53.2′	12° 18.0′	con	27	subhor.	–/–		159/02
Casa Nardi	45° 54.8′	12° 07.6′	mon_3	23	155/85	–/–		146/06
Collagu	45° 55.0′	12° 07.6′	mon_1 (upper)	13	147/80	–/–		156/05
Bresolin	45° 55.9′	12° 10.1′	mon_1 (lower)	9	165/70	–/–		156/11
Vallotai1	45° 56.2′	12° 11.0′	mon_1	31	150/65	–/–		347/05
Torre	45° 59.9′	12° 21.6′	con	41	subhor.	–/–		159/04
Caneva	45° 58.0′	12° 24.7′	con	46	170/60	–/–		173/06
Polcenigo	46° 01.7′	12° 29.8′	mon_1	16	180/80	–/–		179/14
Colle (Meduna)	46° 09.9′	12° 48.6′	mon_3	15	307/21	–/–		328/11
Romagnoi1_	46° 11.6′	12° 54.6′	mon_1 (middle)	12	340/80	–/–		157/07
mean value								160/03

Fig. 4. Examples of pitted pebbles observed in the field.

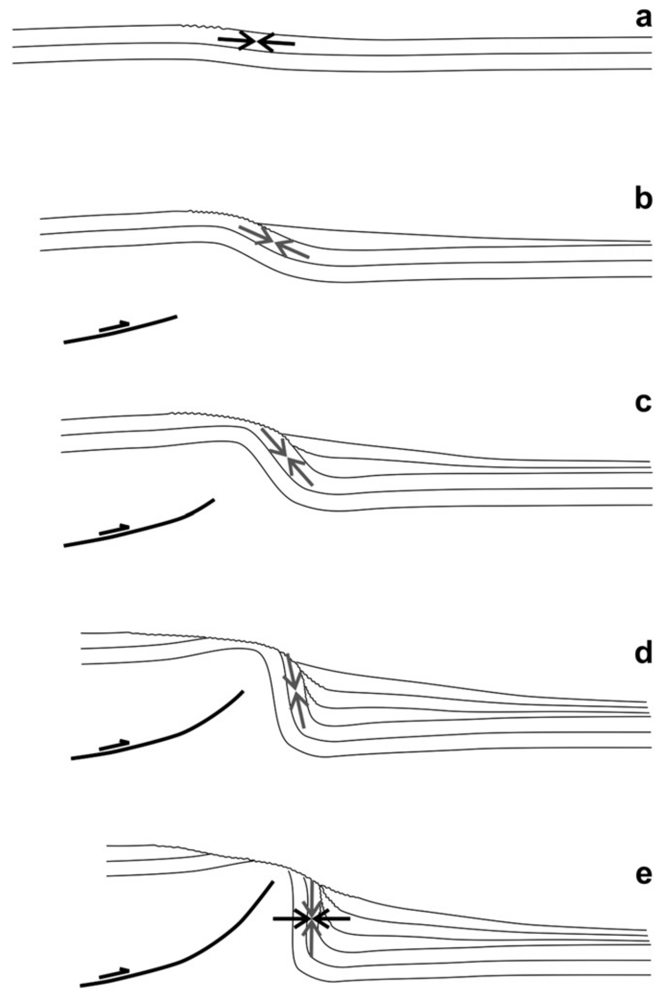

Fig. 5. Relation between compressional events as inferred from pitted pebbles and the large-scale thrust-propagation folding affecting the investigated area. In the five-steps figure, black arrows indicate phases of active compression, while grey ones represent the shortening directions as recorded by pitted pebbles and passively rotating during fault-propagation folding.

can assume that the associated stress regime was roughly Andersonian (*i.e.* with a sub-vertical principal stress axis). Accordingly and due to the Neogene–Quaternary geodynamic setting of the area, it is also evident that throughout the considered time window the σ_3 and σ_1 axes were always sub-vertical and sub-horizontal, respectively, thus defining a purely compressional regime.

Many sites of measurements have been studied in sub-horizontal conglomerates and the observed cluster of pitted features (Fig. 4) show a mean sub-horizontal attitude. Most of the younger sites mainly located in external (*viz.* southern) structural sectors display this geological setting.

However, in many localities geometrical and structural relationships are relatively more complex mainly because layering is no longer horizontal and strata show strong dips and up to overturned attitudes. When this is observed, two end-member situations generally occur: i) the mean σ_1 axis is sub-horizontal or ii) it is highly plunging to sub-vertical. In the first case and following the above premise of a persisting compressional Andersonian regime, it is likely that the observed deformational pitted features have been recorded in the rock mass only after a major tilting event has occurred associated with, and caused by, large-scale tectonic structures, like folding induced by the propagation of an underlying major blind thrust (Fig. 5e), imbricate thrusting and/or duplexing (Zanferrari et al., 2008a, 2008b). Conversely, in the stations of measurements where both conglomerates are dipping and the mean σ_1 is plunging, the latter is generally parallel or subparallel to layering (Fig. 5b–d). In line with the above argument, we thus assume that the analysed rock volume has been subject to tilting only subsequently to the deformational imprinting event (Fig. 5a). In this case, the original mean σ_1 orientation can be easily obtained by conventional tilt-correction procedure. Two examples are shown in Fig. 6, while the application of this procedure is emphasised in Tables 1–3 for the specific sites of measurements by reporting the applied horizontal rotation axis and rotation angle (*axis*/α).

The palinspastic operation commonly restores the density peak of the pitted features to a horizontal setting or within their $\pm 5^\circ$ of natural variability and measurement uncertainty. In this case, it is clear that the observed contractional structures were fully generated prior to tilting of the stratigraphic unit. However, in few cases some compressional datasets are not parallel to layering and show a different plunge. When this occurs, the palinspastic back-rotation is halted when the mean value of the density peak is restored to a sub-horizontal setting. Therefore, a still dipping layering (S_0^* in Tables 1–3) implies that the observed deformation mesoscopic structures were generated during the long-term tilting process and they consequently recorded the compressional direction affecting the area when the large-scale thrust-propagation folding or the imbricate thrusting were active. For example, based on this evolutionary model, it is possible to interpret two key sites (see also Discussion) showing a peculiar scatter of measured compressional

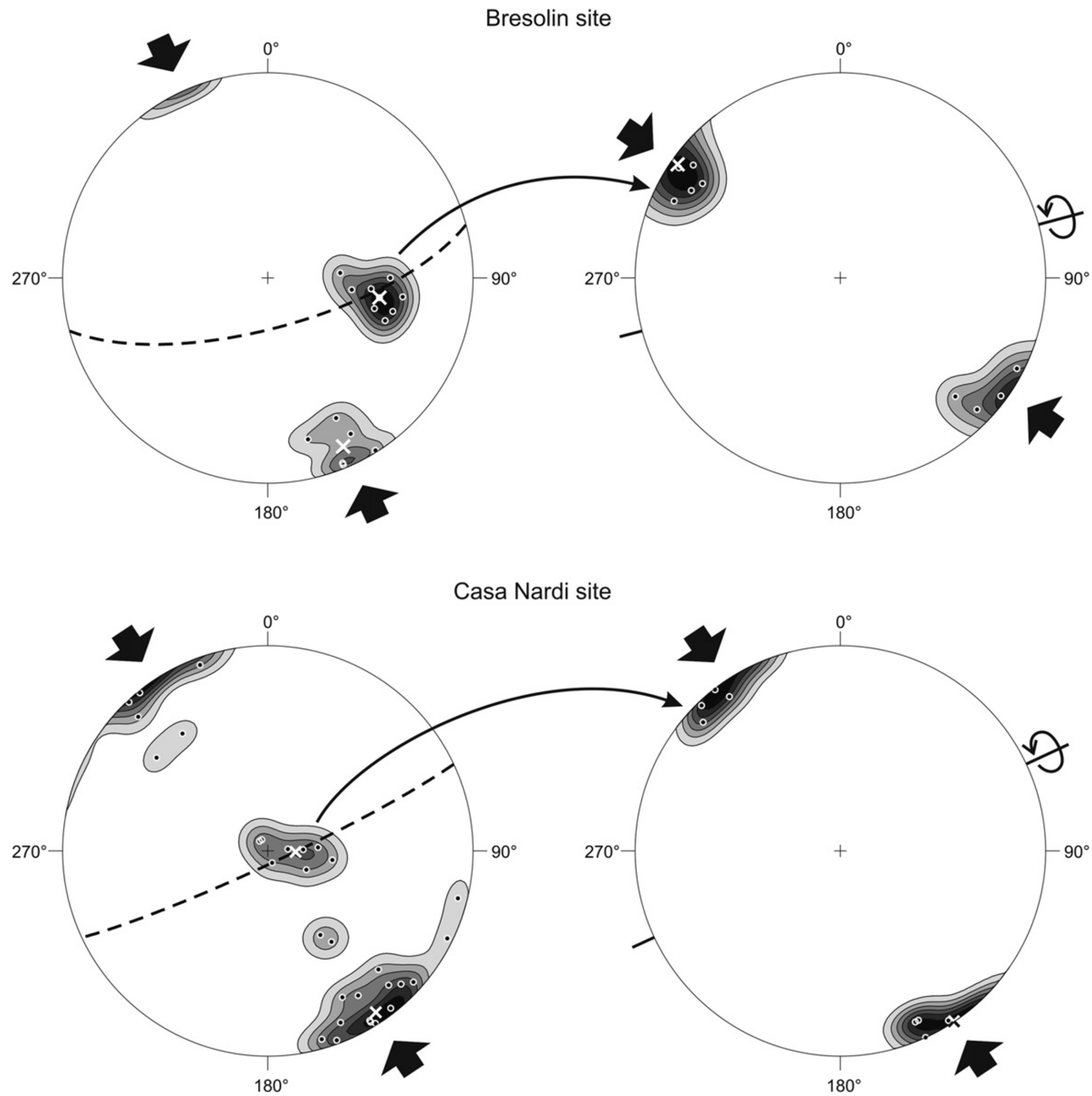

Fig. 6. Examples of investigated sites in late Tortonian (Bresolin site) and early Messinian (Casa Nardi site) conglomerates. Black dots represent the directions of compression directly measured in the field from pitted pebbles. Density distributions are also represented. On the left-side stereonets, all measurements are represented together with the attitude of the layering (dashed cyclographic trace). Two clusters can be clearly observed where the first one documents an NNW-SSE post-tilting (horizontal) compression, while the other cluster is characterised by high plunge values being subparallel to the layering. In both cases, the latter set of data has been palinspastically back-tilted assuming an originally horizontal setting (right-side stereonets), thus showing pre-tilting NW-SE (Bresolin site) and NNW-SSE (Casa Nardi site) directions of compression. Crosses (×) represent maximum densities.

directions. Indeed, in sites Lierza1 and Pedeguarda the measured σ_1 axes vary progressively from highly plunging to sub-horizontal, thus outlining a girdle pattern in the stereographic projection (Fig. 7).

In conclusion, the occurrence of pre-, syn- and post-tilting compressional density peaks together with the stratigraphic age of the affected deposits provide crucial information and essential chronological constraints for the reconstruction of the tectonic evolution of the area. Using the above methodological approach, a grouping of the results is clear, therefore suggesting the occurrence of distinct deformation events. In Tables 1–4, we have separated the four main groups and in the following section we discuss each group separately. The mean orientation of these clusters is also reported in Tables 1–4 (σ_1 axis) and corresponding Figs. 8–11.

4.3. Late Tortonian event

Five localities where the Montello Conglomerate and particularly its lower and middle members (mon$_1$ and mon$_2$, respectively), or the Vittorio Veneto Sandstone (vve Unit) crop out, represent a first group of sites showing a cluster of mean compressional axes which are all parallel to the strongly dipping layers (Table 1). Following the palinspastic restorations as described in the previous section, the pre-tilting sub-horizontal σ_1 axes trend NW-SE with an average orientation of 313°/00° (Table 1 and Fig. 8). The lower chronological constraint for this deformational event is provided by the age of the youngest deformed deposits (latest Tortonian; see Figs. 3 and 12), while the imprinting process certainly occurred before the inception of the large-scale fault-propagation-folding, and the consequent tilting, associated with the propagation of Bassano-Valdobbiadene and Cansiglio-Maniago thrusts (Fig. 2), whose paroxistic activity started in early Messinian (Castellarin et al., 1992; Castellarin and Cantelli, 2000; Zanferrari et al., 2008a; Fig. 12). More exhaustive information about site location, deformed sedimentary units, number of measurements per site and σ_1 orientation is reported in Table 1 and Fig. 8.

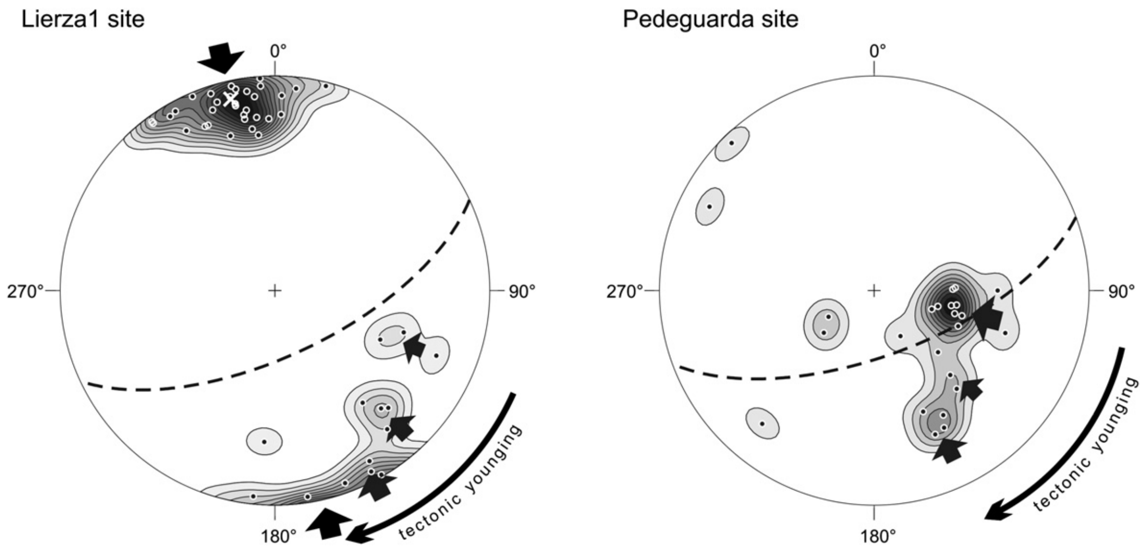

Fig. 7. Lierza1 (a) and Pedeguarda (b) sites of measurements showing a distribution of the compressional data from subparallel to layering (dashed cyclographic trace) to sub-horizontal therefore suggesting that pebbles' deformation occurred during the whole tilting process caused by the large-scale fault-propagation folding. If a palinspastic restoration is gradually performed, it is worth mentioning that the direction of compression progressively changed from NW-SE to NNW-SSE.

4.4. Late Messinian-Early Pliocene event

Eleven sites within the Vittorio Veneto Sandstone (vve) and both lower (MON_1) and upper (MON_3) members of the Montello Conglomerate represent a second group of measurements (Table 2). In most sites the observed compressional features are parallel to layering or form a low intersecting angle. Accordingly, they have been likely recorded before the large-scale tilting or, most important, during its initial stages. The palinspastic restoration provides an NNW-SSE trending compression with an average orientation of 338°/04° (Table 2 and Fig. 9). The two above mentioned key sites of Lierza1 and Pedeguarda (Fig. 7) belong to this group of data, and they document the progressive rotation of the compressional features during tilting, therefore allowing to clearly separate the two, mainly pre-tilting, deformation events. For what concerns the timing, this is constrained i) by the age of the youngest affected rocks (MON_3, early Messinian) and ii) by the full development of the Bassano-Valdobbiadene and Cansiglio-Maniago thrusts (Fig. 2; Castellarin et al., 1992; Castellarin and Cantelli, 2000; Zanferrari et al., 2008a), as lower and upper chronological boundaries, respectively (Fig. 12). The slightly variable timing among the different sites, which in turn are characterised by a common NNW-SSE σ_1 direction, is likely due to the diachronous effects of thrusting during its propagation and growth, whose typical duration is in the order of 10^5–10^6 years (Calamita et al., 1991, 1994; Cavinato and De Celles, 1999; Tozer et al., 2006; Basili and Barba, 2007).

4.5. Late Pliocene event

Seven sites have been included in this group, which is again characterised by a mean NW-SE direction of compression (314°/03°; Table 3 and Fig. 10). This value is similar and statistically equivalent to that of the Late Tortonian event (Table 1 and Fig. 8), but there are two main reasons for separating the two datasets and inferring a distinct, though coaxial, deformation event. Firstly, in four out of seven sites the youngest affected conglomerates belong to the Early Pliocene Osoppo Conglomerate (CON) or even to the Late Pliocene-Early Pleistocene Conegliano Unit (con), therefore constraining the lower chronological boundary (Table 3 and Fig. 12). Secondly, in the three remaining sites affecting the older Montello Conglomerate (MON_1 and MON_3), the layering is steeply dipping while the measured mesoscopic contractional features are horizontal. This observation suggests that they have been imprinted after the occurrence of the macroscopic tilting process associated with the fault-propagation folding of the Bassano-Valdobbiadene and Cansiglio-Maniago thrusts (Fig. 2). As previously discussed, the inferred age of these major tectonic structures is Messinian to Early Pliocene (Castellarin et al., 1992; Castellarin and Cantelli, 2000; Zanferrari et al., 2008a; Fig. 12), thus confirming the timing of this deformation event, which is Late Pliocene at the oldest. Only in one site of measurements (Cornuda site, con Unit), some amount of tilting has occurred either before or after the formation of the pitted pebbles, likely documenting the preliminary surface effects of the large-scale folding–thrusting activity of the crustal structures that will generate, mainly during Quaternary, the Frontal Thrust System (Figs. 2 and 12).

4.6. Early-Middle Pleistocene event

The largest dataset obtained from the investigated area consists of seventeen sites forming a last group of mesoscopic structural measurements (Table 4). They are characterised by a renewed NNW-SSE-trending direction of maximum compression with an average orientation of 160°/03° (Table 4 and Fig. 11). Notwithstanding a perfectly matching mean σ_1 direction with that of the Messinian event (338°/04°; Table 2 and Fig. 9), the striking difference among the two deformational events and groups of data is due to the fact that irrespective of the structural setting of the affected conglomerate layers, in this case the measured compressional directions are all horizontal to sub-horizontal, therefore lacking any significant post-deformation tilting. In particular, seven out of seventeen sites have been carried out in the conglomerates of the Conegliano Unit (con) and they are consequently younger than the above mentioned Messinian deformational event (Table 1 and Fig. 12). In the remaining ten sites, which are in Tortonian and Lower Messinian deposits (vve, MON_1 and MON_3), the layering is generally strongly dipping thus implying that this NNW-SSE compression has occurred only after the macro-scale tilting process (Fig. 5e) associated with the Frontal Thrust System. In conclusion, we feel confident in stating that this last dataset represents a distinct, younger deformation event, which likely started in Early Pleistocene time. Taking into account the elapsed time, say 1–1.5

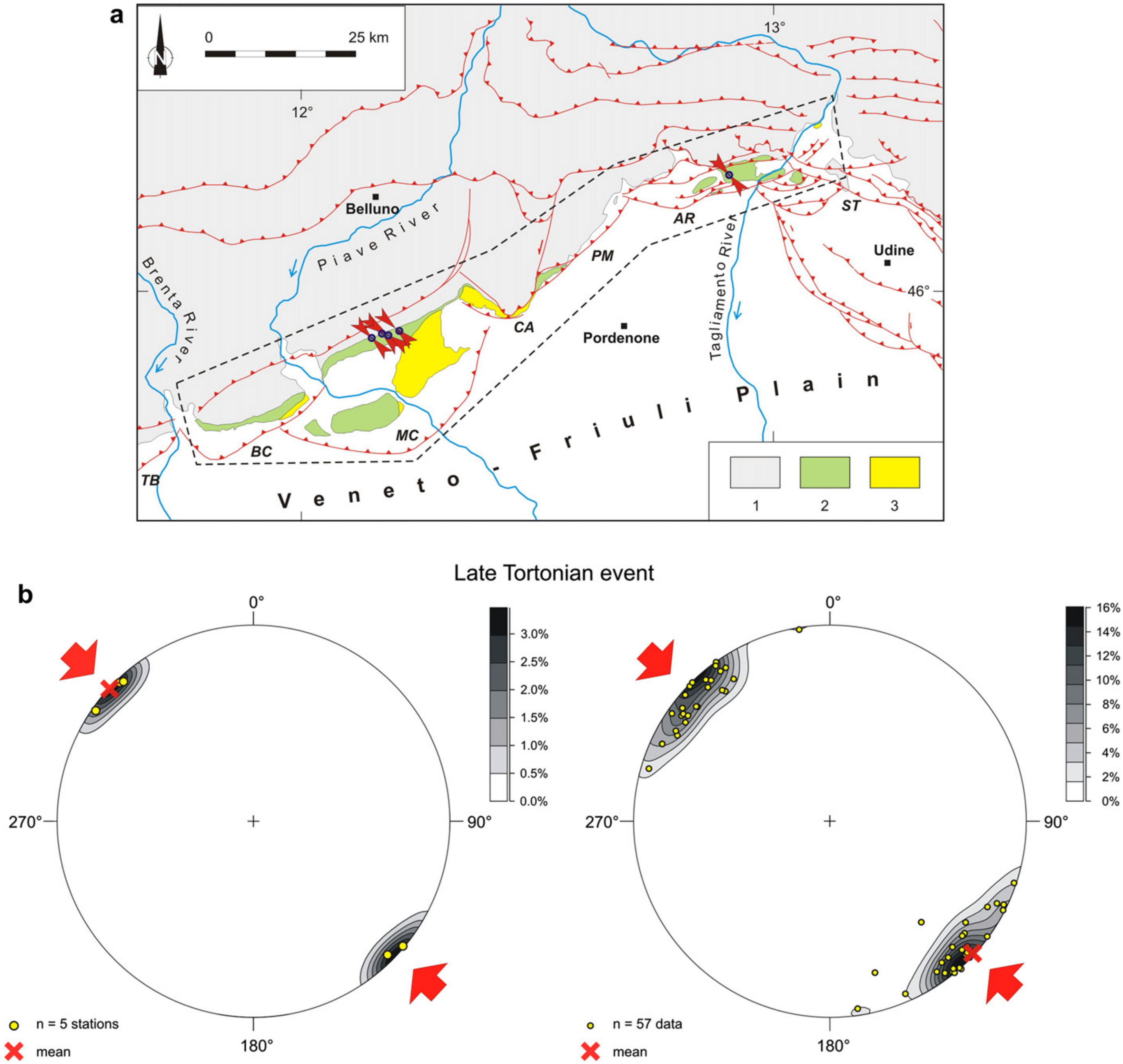

Fig. 8. a) Map representing the location of the sites documenting a pre-tilting NW-SE direction of compression occurred during Late Tortonian. Double arrows represent the mean σ_1 direction obtained from each station of measurements. The same results are represented in stereographic view b) as stations of measurements (left stereonet) or all data together (right). See Table 1 for detailed information.

Ma (Fig. 12), and comparing the average compressional direction obtained from the mesoscopic structural analyses with that inferred from the seismicity of the area (Slejko et al., 1989, 1999; Bressan et al., 1998, 2003, Pondrelli et al., 2001; Poli et al., 2002; Bressan and Bragato, 2009), it is likely that this tectonic regime is still active (*e.g.* compare the stereographic projection in Fig. 11 with that of Fig. 13, which represents the P-axes inferred from focal mechanisms obtained for the 1977–1999 events occurred within the investigated area; Poli et al., 2002).

5. Discussion

The principal results obtained from the mesoscopic structural analysis are now correlated with the large-scale tectonic setting of the investigated area. In the following section, we discuss and fit the eastern Southern Alps orogenic event in the frame of the Late Tertiary geodynamic evolution of the broader Central Mediterranean region.

First of all, our reconstruction of the late Tortonian-Quaternary Tectonic Stratigraphy in the eastern Southern Alps has emphasized the occurrence of four distinct deformation events. It is noteworthy that these events do not represent 'simple' local variations of the stress field because for all datasets the corresponding sites of measurements (Tables 1–4) are spread along the entire 120 km-long investigated area (Figs. 8–11) and in many cases, the same localities and sedimentary units are affected by more than one dataset (*viz.* stress field). In particular, the four events could be recognized and distinguished based on i) a different mean direction of compression and ii) their timing of activity.

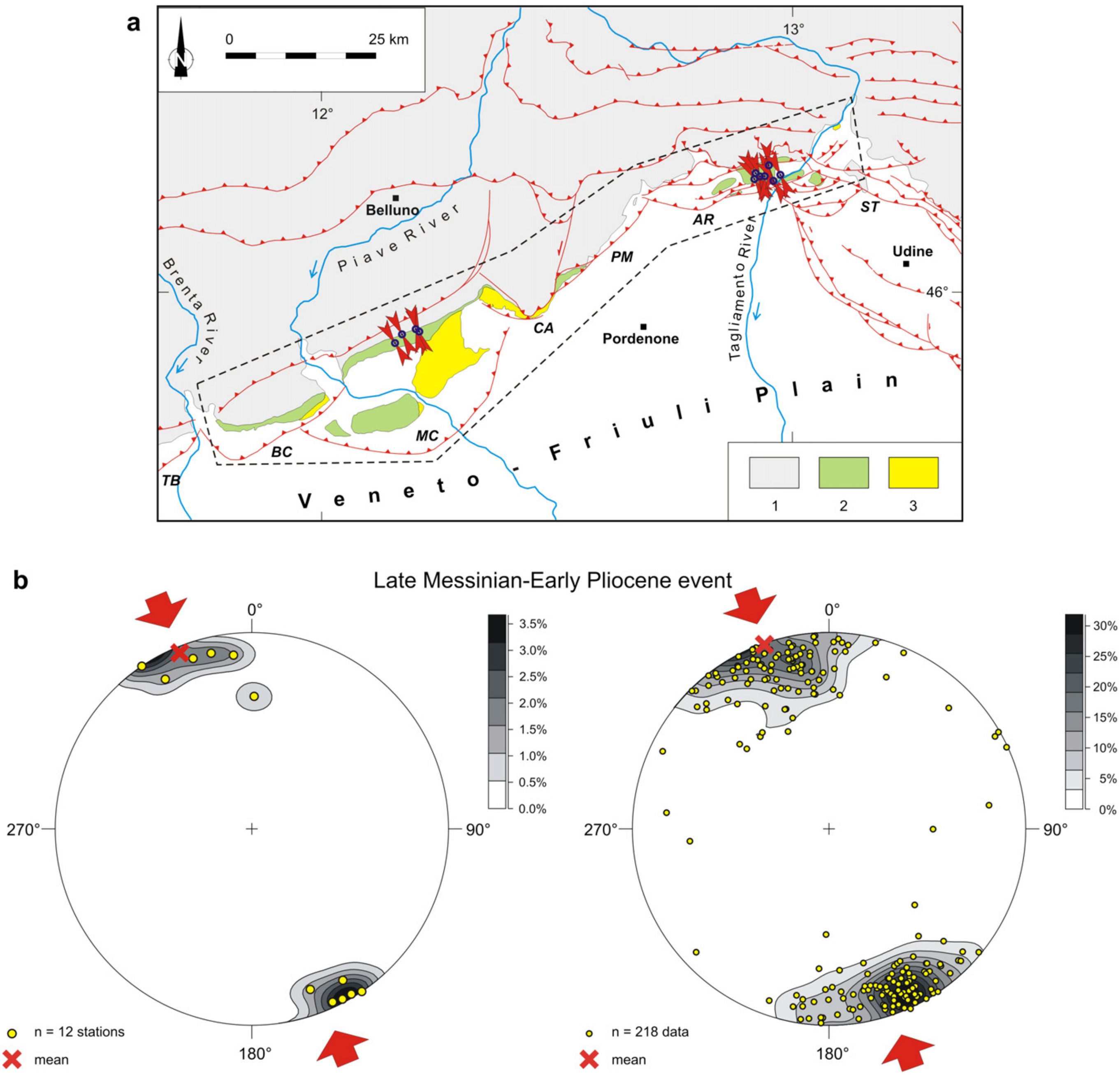

Fig. 9. a) Map representing the location of the sites documenting a pre-tilting NNW-SSE direction of compression occurred during the Late Messinian-Early Pliocene. Double arrows represent the mean σ_1 direction obtained from each station of measurements. The same results are represented in stereographic view b) as stations of measurements (left stereonet) or all data together (right). See Table 2 for detailed information.

If we also take into account the well-documented "Serravallian-Tortonian" tectonic phase and the fact that it was also characterized by an NNW-SSE trending compression (*e.g.* Castellarin et al., 1992, 2006a; Caputo, 1996), during the last ca. 10 Ma we observe repeated variations of the σ_1 axis (maximum compression) from a mean NNW-SSE to a mean NW-SE direction and *viceversa*. Accordingly, during Late Neogene–Quaternary the stress trajectories of the eastern Southern Alps were affected by repeated rotations with rapid permutations of the principal horizontal stresses. As already proposed in the literature, we refer to this behaviour as Twist Tectonics (Caputo et al., 2003; Caputo, 2005).

At this regard, two sites (Pedeguarda and Lierza1) are of particular interest for highlighting the rotation process of the stress trajectories. Indeed in these two localities, the measured compressional directions smoothly varies from subparallel to layering, which is now steeply dipping, to a sub-horizontal setting (Fig. 7). Accordingly, this data distribution indicates that the contractional features on the pebbles were produced right through the tilting process, while a gradual palinspastic restoration also documents that the mean direction of compression progressively changed in time from NW-SE to NNW-SSE.

For what concerns the timing of deformation, it is important to emphasize that only the availability of a very detailed litho- and chrono-stratigraphic record of the sedimentary units cropping out in the area (Zanferrari et al., 2008a; and references therein) allowed to separate four distinct tectonic events within the last few million

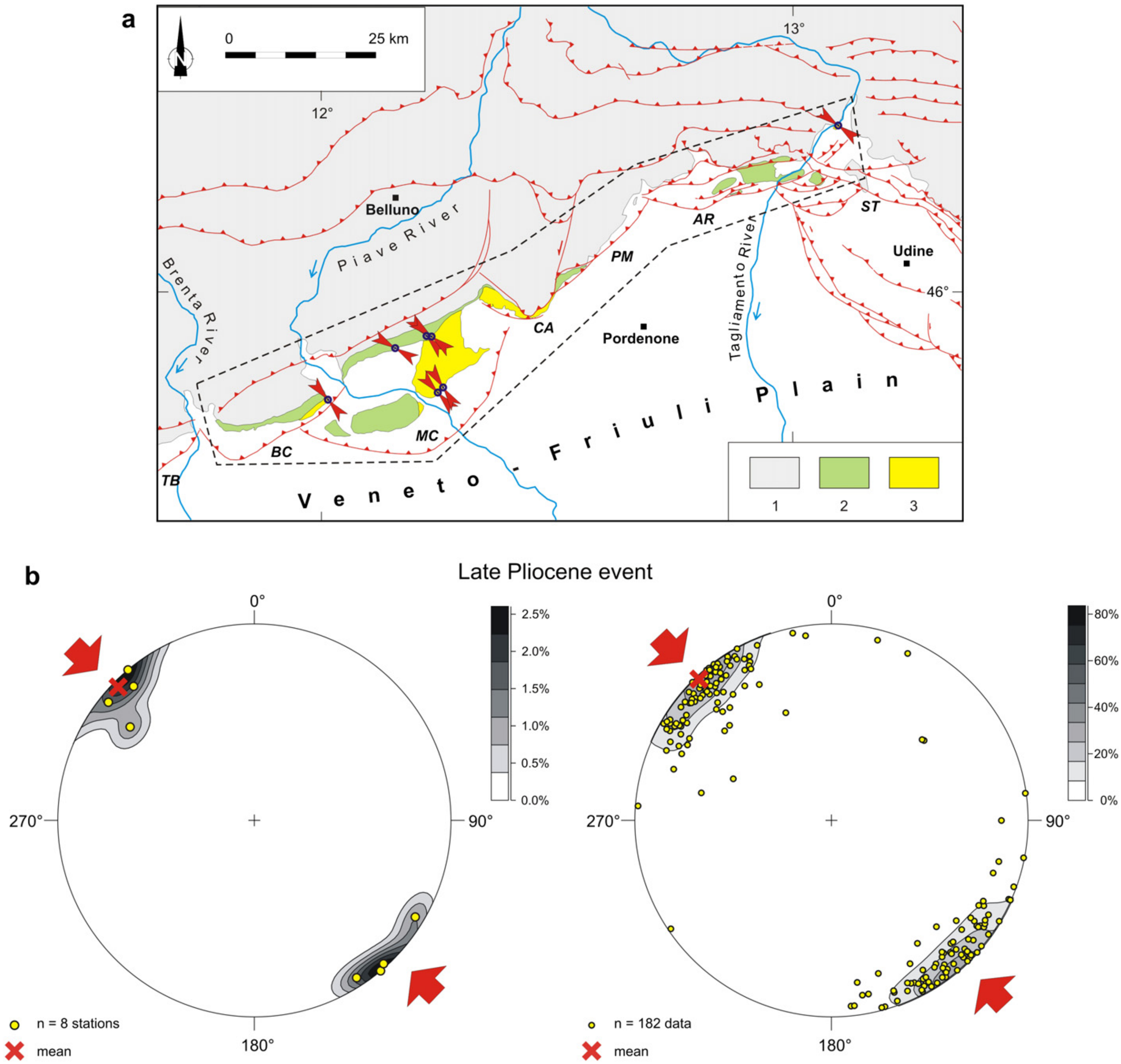

Fig. 10. a) Map representing the location of the sites documenting a pre-tilting NW-SE direction of compression occurred during the Late Pliocene. Double arrows represent the mean σ_1 direction obtained from each station of measurements. The same results are represented in stereographic view b) as stations of measurements (left stereonet) or all data together (right). See Table 3 for detailed information.

years (Tables 1–4; Fig. 12). Lacking these data, the results would have been largely overlapping thus probably providing a clumsy final picture of the overall tectonic evolution occurred in the investigated area. A similar procedural approach based on the relationships between deformation structures and unconformity-bounded sedimentary packages has been followed by Tavarnelli and Holdsworth (1999) leading to methodologically comparable conclusions. In contrast, it has been possible to chronologically constrain each of the four events within 1–2 Ma-long time intervals (Fig. 12).

By integrating the results of the mesoscopic structural analyses with geological and tectonic macroscopic observations, and taking into account the reciprocal geometrical relationships, the timing of activity for the major deformation structures (Fig. 12) represented by, and associated with, the Valsugana and Belluno thrusts, the Bassano-Valdobbiadene and Cansiglio-Maniago thrusts as well as the Frontal Thrust System seems confirmed. Accordingly, the Neogene to Present evolution of the eastern Southern Alps shows a typical spasmodic migration of thrusting and deformation towards the external (*viz.* southern) sectors of the fold-and-thrust belt. For example, based on the sites Pedeguarda and Lierza1 (Figs. 8 and 9 and Tables 1 and 2) it is possible to constrain the period of activity of the Bassano-Valdobbiadene Thrust, in the time interval between late Tortonian and Pliocene, with a likely paroxism during Messinian-Early Pliocene time (Fig. 12). The period of primary activity of this major tectonic structure is few millions of years. A similar conclusion can be reached for the Frontal Thrust System whose activation age is broadly coeval with the Conegliano Unit (con Unit) and hence not older than 2–2.5 Ma (Fig. 12). Comparable time values of thrust activity have been

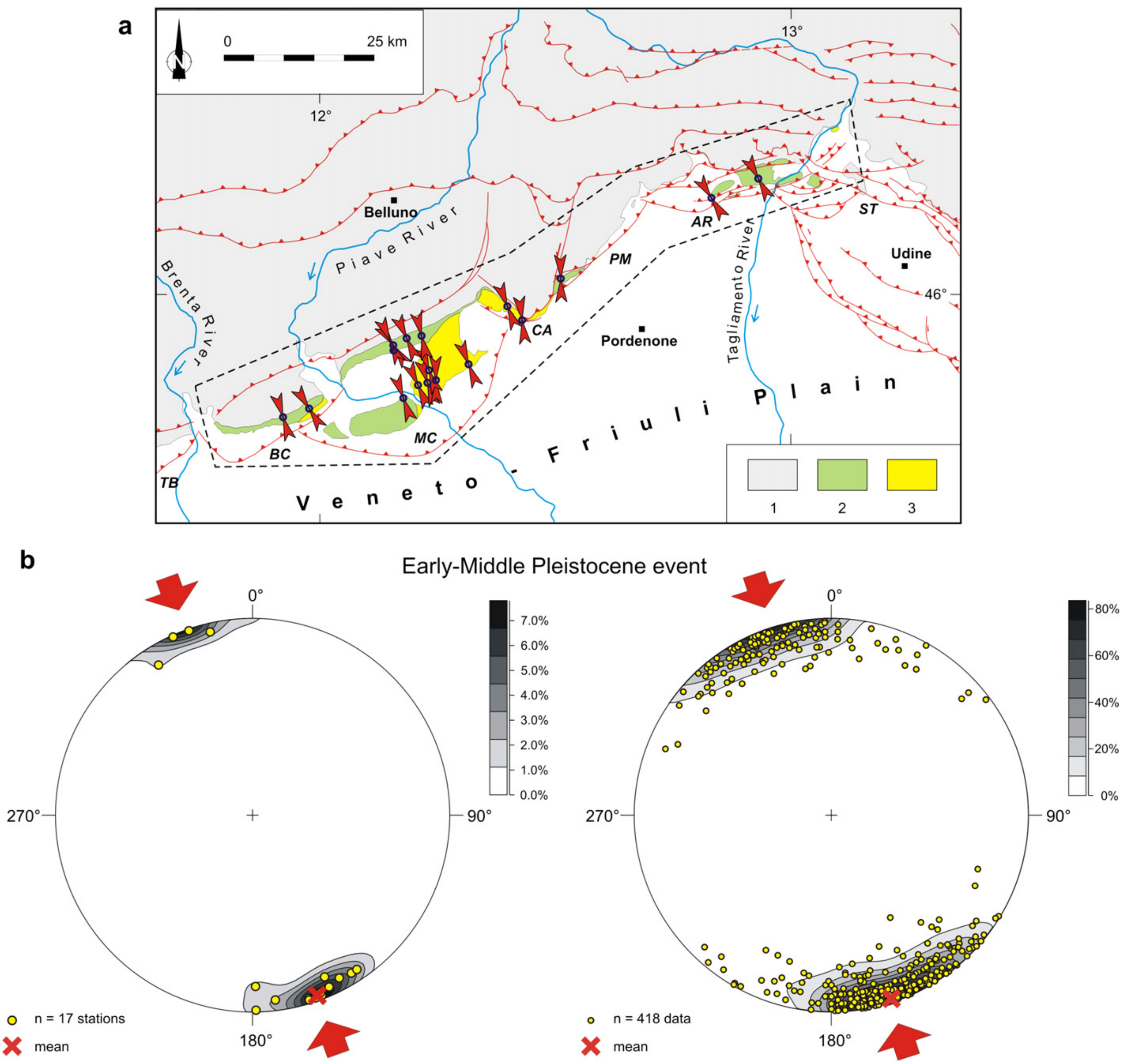

Fig. 11. a) Map representing the location of the sites documenting a pre-tilting NNW-SSE direction of compression occurred during the Early-Middle Pleistocene. Double arrows represent the mean σ_1 direction obtained from each station of measurements. The same results are represented in stereographic view b) as stations of measurements (left stereonet) or all data together (right). See Table 4 for detailed information.

documented for several crustal structures in the Northern and Central Apennines (Calamita et al., 1991, 1994; Cavinato and De Celles, 1999; Tozer et al., 2006; Basili and Barba, 2007), which are in geologic and tectonic settings similar to those investigated in this paper.

In order to fit our results within the evolution of the eastern Southern Alps and the Late Tertiary geodynamic framework of the broader Central Mediterranean realm, it is worth mentioning that both assumed timing and documented shortening orientation of the Chattian–Burdigalian phase (Castellarin et al., 1992; Caputo, 1996; Castellarin and Cantelli, 2000) are in agreement with the relative motion of Africa with respect to Europe, the latter as inferred from the analysis of magnetic anomalies for this period (Mazzoli and Helman, 1994; Rosenbaum et al., 2004; Fig. 14). A similar statement is also appropriate for the second major tectonic phase (Serravallian-Tortonian) affecting the eastern Southern Alps. Indeed, notwithstanding the abrupt change in direction of relative motion between Africa and Europe about 15 Ma ago (Fig. 14), the new NNW-SSE orientation of crustal shortening, as largely documented in the broader Southern Alps and surroundings (Castellarin et al., 1992, 2006a; Cantelli and Castellarin, 1994; Caputo, 1996; Caputo et al., 1999; Castellarin and Cantelli, 2000), nicely parallels the direction of convergence between the two plates during Langhian and early Tortonian (Figs. 12 and 14).

Taking into account the late Oligocene-Middle Miocene geodynamics of the Central Mediterranean and considering that the Adria lithospheric block likely behaved consistently with the major Africa plate at that time (Dewey et al., 1989; Robertson and Grasso,

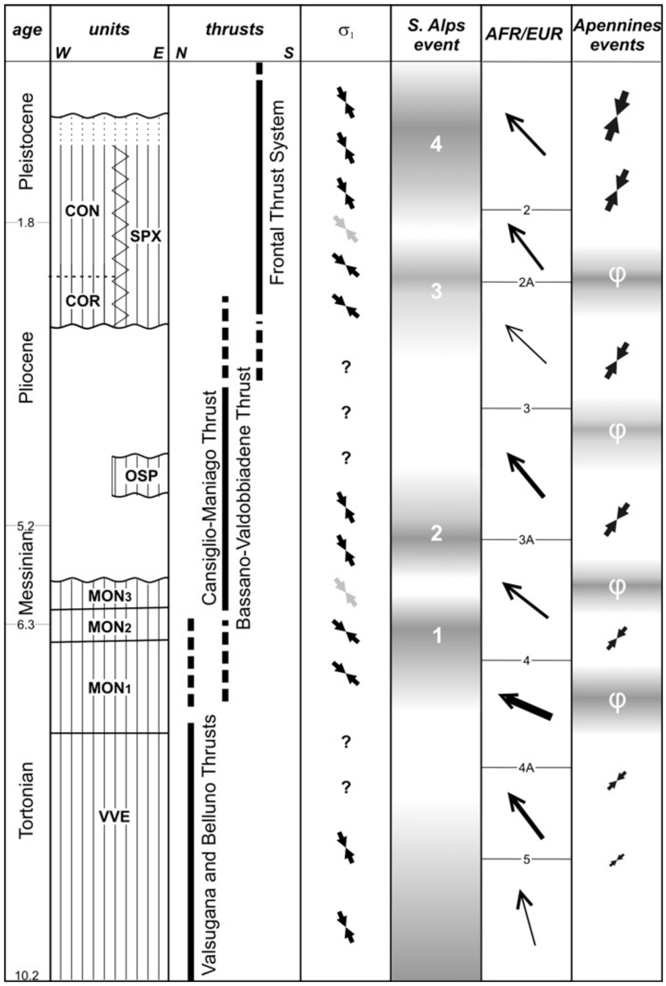

Fig. 12. Synthetic diagram showing the Tortonian *p.p.*-Pleistocene sedimentary stratigraphy (*units*), the period of activity for the major tectonic structures (*thrusts*), the direction of maximum compression estimated from the mesostructural analyses (σ_1), the tectonic stratigraphy of the eastern Southern Alps with the principal deformational events (darker sectors) and the corresponding table including all datasets (*S. Alps event*), the direction of relative motion of Africa with respect to Europe (*AFR/EUR*) and the major periods of coupling-decoupling along the basal detachment of the Northern Apennines (*Apennines events*). Stratigraphic units as in Fig. 3. In column *AFR/EUR*, numbers refer to normal magnetic anomalies as specified in Fig. 14, while arrows thickness is proportional to the amount of relative convergence (Mazzoli and Helman, 1994). In the last column, darker sectors represent periods of frontal thrust propagation (*i.e.* decoupling) as inferred from large-scale unconformities in the Apennines foredeep (Ghielmi et al., 2009) alternating to periods of possible coupling and transmission of compressional stresses to the Southern Alps. The size of the arrows is tentatively proportional to the stress contribution of the Apennines within the investigated area.

1995; Mantovani et al., 1997, 2001; Muttoni et al., 2001; Carminati et al., 2004; Rosenbaum et al., 2004; Fig. 15), it is likely that the two above discussed geological phenomena (*e.g.* relative plate motion and stress field at the Africa-Europe plate boundary along the Southern Alps) are directly linked by a cause-effect relationship. As a consequence, along the boundary with Europe (*i.e.* northern Adria), the pervading stress field was fully controlled by the relative plate motion of Africa with respect to Europe. In this geodynamic context, the remotely applied forces were responsible for the ‘tectonic genetic component’ of the stress field (*sensu* Caputo, 2005), which ultimately governed the deformation within the investigated area (see σ_1 trajectories in the box of Fig. 15a and b). The first two tectonic phases of the eastern Southern Alps orogenesis, the so-called Chattian–Burdigalian and Serravallian-

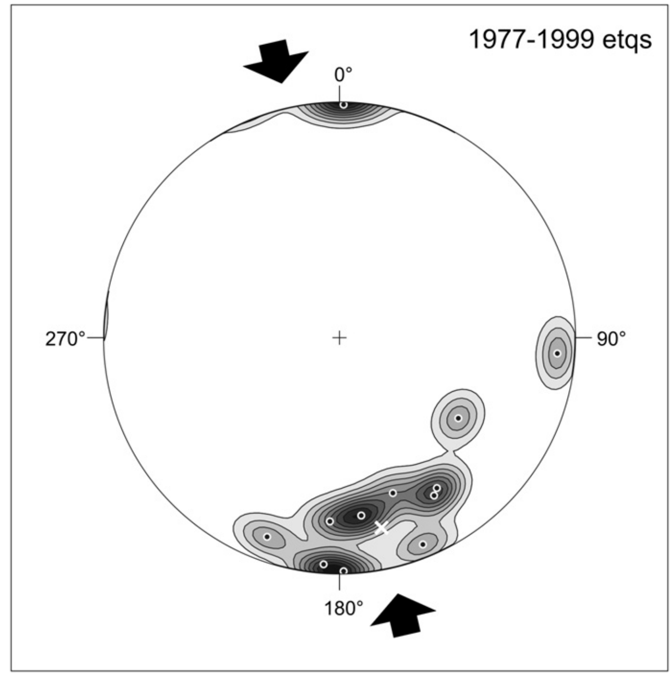

Fig. 13. Stereonet showing the distribution of the P-axes associated with the focal mechanisms available for the investigated area in the period 1977–1999 (data from Poli et al., 2002).

Tortonian events, could be thus considered as direct effects of the plate convergence between Africa and Europe (Fig. 15a and b).

Analysis of the magnetic anomalies suggests, for late Tortonian time, the occurrence of a new abrupt variation in relative plate motion. Indeed, Africa started moving towards NW and this direction basically persisted up to Recent (Dewey et al., 1989; De

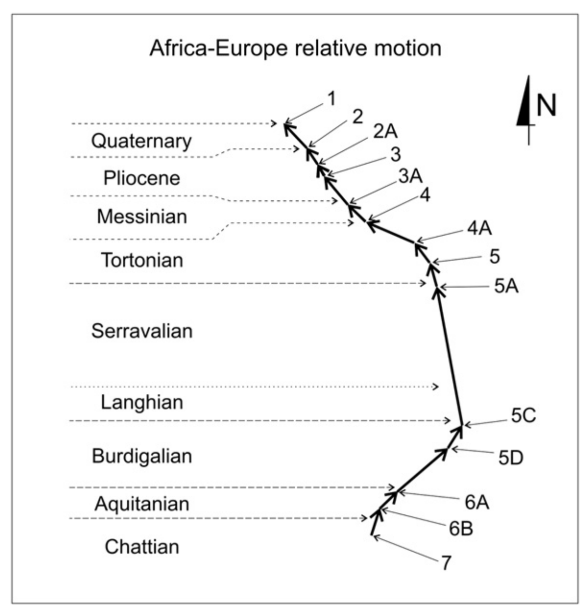

Fig. 14. Relative motion of Africa with respect to Europe from Late Oligocene (anomaly 7, 24.72 Ma) to Present (from Mazzoli and Helman, 1994). Represented stages are relative to anomalies 7 (24.72 Ma), 6B (22.60 Ma), 6A (20.55 Ma), 5D (17.31 Ma), 5C (16.04 Ma), 5A (11.85 Ma), 5 (9.59 Ma), 4A (8.53 Ma), 4 (7.25 Ma), 3A (5.71 Ma), 3 (4.03 Ma), 2A (2.60 Ma) and 2 (1.76 Ma). Ages of normal polarities from Cande and Kent (1992). The chronological scale on the left is not linear and stages' boundaries are purely indicative.

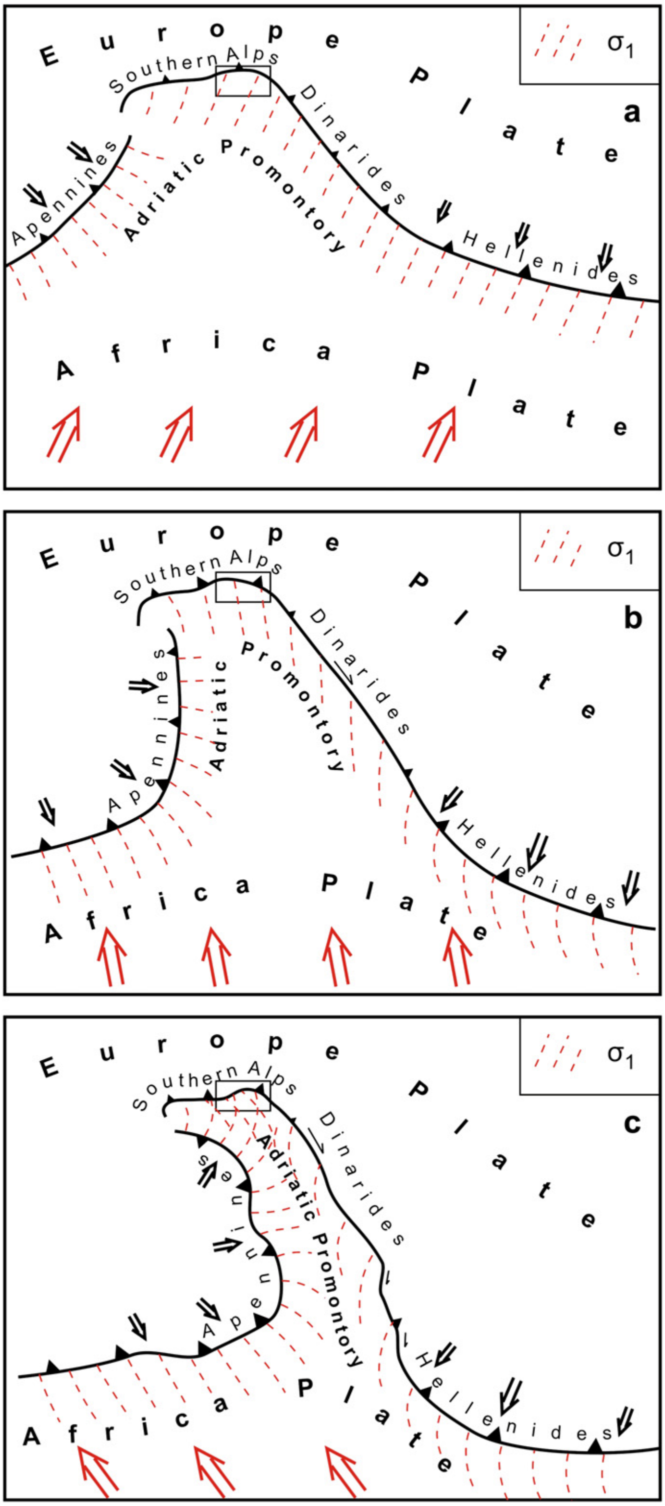

Fig. 15. Sketch maps of the Central Mediterranean realm suggesting how and why the maximum horizontal stress trajectories varied in time within the eastern Southern Alps. The box indicates the investigated area. The three frames roughly correspond to the Chattian-Early Miocene (a), Langhian-Serravallian (b) and late Tortonian-Messinian (c) geodynamic reconstructions (Dewey et al., 1989; Robertson and Grasso, 1995; Mantovani et al., 1997, 2001; Muttoni et al., 2001; Carminati et al., 2004; Rosenbaum et al., 2004). The major 'tectonic genetic components' (*sensu* Caputo, 2005) governing the stress field within the investigated area are associated with the relative plate motion of Africa with respect to Europe (large arrows) and after Tortonian also with the propagating accretionary wedge of the Apennines (smaller arrows). The thin dashed lines depict the inferred direction of the σ_1 axis within the growing orogenic prisms. In the youngest frame, the crossing stress trajectories schematically indicate the two principal stress fields, which possibly alternate in time due to the prevailing Apennines *versus* Africa remote forces. See text for discussion.

Mets et al., 1994; Mazzoli and Helman, 1994; Calais et al., 2003; McClusky et al., 2003; Heidbach et al., 2008; Fig. 14). Indeed, numerous literature data (Castellarin et al., 1992; Caputo, 1996; Caputo et al., 1999; Castellarin and Cantelli, 2000) as well as the results of our mesoscopic structural investigation document the occurrence of a younger (late Tortonian-Early Messinian) deformation event characterized by an NW-SE oriented maximum compression (Table 1; Figs. 8 and 12), which is once more in good agreement with the stress field caused by the remotely applied African forces (see NW-SE trending σ_1 trajectories in the box of Fig. 15c). Although since Messinian the progressively advancing and rotating Apennines front strongly narrowed the superficial expression of the Adriatic Promontory (Fig. 15c), an unceasing mechanical continuity between Adria and Africa is confirmed by the efficient propagation of S_n waves (Mele, 2001), therefore supporting the continuous transmission of Africa-related forces as far as to the investigated area.

Notwithstanding a stable direction of plate convergence since Messinian (Fig. 14) and the assumed parallelism between the relative plate motion and the mean stress trajectories at the plate boundary, our results clearly show that in late Messinian-Early Pliocene time (Fig. 12) the tectonic regime was characterized by a rotation of the σ_1 axis that flips horizontally from NW-SE to NNW-SSE (compare Figs. 8 and 9). This phenomenon (Twist Tectonics) was inverted and repeated during the Pliocene-Quaternary time interval.

In order to understand this change in tectonic behaviour, it is worth of note to consider the fastly approaching front of the Apennines during Miocene time. The Messinian accretionary wedge of the Northern Apennines probably reached a critical distance, therefore starting to heavily influence the tectonic evolution of the eastern Southern Alps (Fig. 15c). From a geodynamic point of view, several were the effects and the consequences for the Southalpine chain due to the arrival of a new tectonic 'player'.

Firstly and probably as a consequence of the synergic role of i) the counteracting mantle flow and ii) the Apennines slab roll-back (Doglioni, 1990b, 1991), the lithospheric flexural process caused by the Apennines subduction and the associated peripheral bulging progressively prevailed on the subsidence caused by the propagation of the Southern Alps orogenic wedge, therefore inhibiting the development of further accommodation space within the Veneto-Friuli basin. Assuming typical values for flexural rigidity and differential density, it is possible to estimate the distance between the Apennines load and the area of maximum uplift due to lithospheric bulge (*e.g.* Turcotte and Schubert, 1982). Including all uncertainties, this value ranges between 150 and 300 km, which nicely coincides with the (late Messinian-) Pliocene-Quaternary distance of the Northern Apennines orogenic wedge from the Southalpine foredeep. Following this geodynamic model, we can also explain the two-phase evolution of the Southalpine foredeep, which was fully established in Serravallian and strongly subsiding up to early Messinian (2.5–3 km; Massari et al., 1986a, 1986b; Fantoni et al., 2002; Barbieri et al., 2004; Zanferrari et al., 2008a,b), while during (late Messinian-) Pliocene-Quaternary only few hundred meters of clastic sediments have been accummulated (Fantoni et al., 2002; Barbieri et al., 2004; Zanferrari et al., 2008a,b). The drastic subsidence decrease observed and the almost complete infill of the foredeep basin by the Montello Conglomerate (early Messinian) could be interpreted as a consequence of the modified regional boundary conditions induced by the approaching Apennines wedge (Fig. 15c).

As a second major effect, the closer distance of the Northern Apennines accretionary complex with respect to the eastern Southern Alps probably modified the regional stress field within the interposed crustal volume (see box in Fig. 15c). For example, periods of coupling (*versus* decoupling) along the basal detachment of the Apennines critical taper could have caused an increase (*versus* decrease) of an NNE-SSW-oriented 'tectonic genetic component' (*sensu* Caputo, 2005) within the northern Adria sector. This stress component temporarily summed up with that induced by the persisting northwestwards pushing force caused by the relative motion of Africa with respect to Europe (Fig. 14). As a result, we suggest that the variability of the stress field observed within the investigated region during the late Messinian-to-Present time interval was associated with the variation in magnitude of one or both remotely applied forces (Apennines-related *versus* Africa-related) and the ensuing principal stresses that have been 'locally' produced (*viz.* tectonic genetic component).

The main phases of frontal propagation along the Northern Apennines (*i.e.* decoupling periods; φ in Fig. 12, last column) strongly governed the foredeep evolution by generating large-scale unconformities which separate the major sedimentary allogroups (Ghielmi et al., 2009). In contrast, during periods of strong coupling on the basal Apennines detachment (arrows in Fig. 12, last column), compressional stresses are either transmitted far away or accommodated by out-of-sequence faults and/or internal deformation (Castellarin et al., 1992; Cerrina Feroni et al., 2004). In the former case, along the external sector of the eastern Southern Alps (box in Fig. 15c) the Africa-related σ_1 trajectories were probably distorted and partially rotated clockwise in an NNW-SSE direction. The role played by the Apennines in determining the 'local' stress trajectories along the Southern Alps was possibly growing in time as tentatively indicated by the increasing size of the arrows in Fig. 12 (last column).

6. Concluding remarks

We recall here the three are the principal goals of this research. First of all, it is the reconstruction of the Tortonian-Quaternary Tectonic Stratigraphy of the eastern Southern Alps; secondly, to emphasize and confirm the high information potential from the analysis of pitted pebbles for unravelling the evolution of the palaeostress field; thirdly, to provide a contribution on the tectonic and geodynamic problem of hierarchically classifying and hence correctly naming different deformational events.

We feel confident in stating that the first goal has been fully achieved. Indeed, based on the fact that the available chronostratigraphy of the Tortonian-Quaternary sedimentary succession within the investigated area is very detailed thanks to the recent investigations and the new geological mapping (Zanferrari et al., 2008a,b; and references therein), we were able to reconstruct a similarly detailed Tectonic Stratigraphy for the region. For this time period, we can recognise and characterize four distinct tectonic events. From a structural point of view and considering the overall dimension of the affected crustal volume (Figs. 1 and 2), it is clear that the observed deformations are not simple local effects associated, for example, with the deviation of the stress trajectories caused by a fault-bend or the occurrence of inherited structures misoriented with respect to the stress field. These latter hypotheses should also be neglected because fault geometry and fault setting cannot change so rapidly within an orogenic wedge and especially so frequently in order to generate the observed "Twist Tectonics" pattern. In summary, we could say that the Tortonian-Quaternary tectonic evolution of the eastern Southern Alps is reasonably well reconstructed (Figs. 8–12 and Tables 1–4).

Regarding the second goal of this paper, our results clearly show that the systematic use of mesoscopic structural features associated with pitted pebbles in conglomerates that underwent deformation in shallow conditions could be a valuable tool for reconstructing the tectonic evolution of a region. All these kinds of structural analyses obviously need a statistical approach based on as many as possible sites of measurements and a large amount of data. Although the distribution of the conglomeratic bodies and their lithology governed the distribution of our sites of measurements, the obtained results are certainly encouraging for applying such analyses to other regions.

For what concerns the third aim of the research, the problem is manyfold. On one hand, the results of our investigation show that the availability of a detailed chrono-stratigraphic sedimentary succession potentially allows to obtain a similarly detailed reconstruction of the deformational history. At this regard, we suspect that more simple reconstructions of the Tectonic Stratigraphy suggested in the literature for older periods of the eastern Southern Alps, or other regions with a comparable tectonic setting, have been in fact forcedly simplified by the lack of data and hence of analytical resolution of the applied methodology. As previously discussed, the lack of a detailed sedimentary chrono-stratigraphy for the investigated area would have probably caused the recognition of a 'unique' stress field characterized by a mean σ_1 axis oriented somewhere between NW-SE and NNW-SSE. This would have also implied an obvious larger scatter of the results, but most likely there would have been no way to separate different subsets of data (*e.g.* Tavarnelli and Holdsworth, 1999).

On the other hand, according to the reconstructed Tectonic Stratigraphy it is possible to recognize deformation events lasting for few million years (Fig. 12). Notwithstanding the documented regional-scale dimensions of the affected area, is it reasonable to consider these relatively short-lived events (1–2 Ma) as major tectonic phases in the frame of the eastern Southern Alps orogene? Alternatively, and consistently with the fact that the discussed deformation events differ in essence only in terms of σ_1 orientation (ca. 25°), is it not more practical and realistic to regard them as minor tectonic 'pulses' within a more or less continuous, regional NNW-SSE to NW-SE trending convergence? Although we prefer the latter hypothesis, the issue is obviously still open and it will certainly deserve more attention in future mesoscopic structural researches in orogenic belts.

The above problem is certainly universal and it is not restricted to the Tortonian-Quaternary evolution of the eastern Southern Alps. Indeed, during a previous time period of the same orogene, or within different accretionary wedges, similar 1–2 Ma-long tectonic pulses could have occurred, but with the basic difference to be characterized by coaxial stress fields. With these tensorial conditions, even the availability of a very detailed chrono-stratigraphic succession would not help too much in unravelling the tectonic evolution and particularly in distinguishing and separating the sequence of deformation events. Also in this case, the problem of hierarchically classifying the different tectonic events would remain unsolved.

In order to further contribute on this issue, we should be aware that in multifractured and polyphased crustal volumes as well as, at a larger scale, in angular plate boundaries the stress field could be similarly complex and likely characterised by relatively high stress gradients and puzzling principal stress trajectories (Zoback, 1992; Caputo, 2005). For example, immediately east of the investigated area, the Adria margin shows an abrupt change in orientation (from a mean WSW-ENE trend to NW-SE, Fig. 1), while the present-day stress field inferred from the focal mechanism rotates in this sector to an N(NE)-S(SW) direction (*e.g.* Slejko et al., 1999; Bressan et al., 2003; Heidbach et al., 2008; Bressan and Bragato, 2009). It is likely that also during Neogene and Quaternary this eastern area suffered a complex tectonic evolution, but only future mesoscopic structural investigations similar to those here presented for the nearby sector, will possibly confirm a tectonic history comparable to the one outlined in this paper.

As a final comment, it is worth of note to take into account the hypothesis that the "Twist Tectonics" pattern that we documented for the last ca. 10 Ma could also work at a shorter time-scale comparable to the seismic cycle, say hundreds of years or few thousands of years. Moreover, as suggested by our results, the tectonic evolution of the eastern Southern Alps is strongly influenced by the tectonic activity of the nearby Northern Apennines. Due to these interacting stress conditions inducing both local (space) and rapid (time) variations of the stress field, tectonic structures apparently not ideally oriented with a regionally mean trend of the stress trajectories, could be reactivated. If this is the case, the seismic hazard assessment of the region should be revised accordingly.

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