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Litho-structural control, morphotectonics, and deep-seated gravitational deformations in the evolution of Alpine relief: A case study in the lower Susa Valley (Italian Western Alps)

P. Cadoppi[a,b,*], M. Giardino[a], G. Perrone[a], S. Tallone[b]

[a]Dipartimento di Scienze della Terra, Università di Torino, Via Valperga Caluso 35 10125 Torino, Italy
[b]C.N.R., Istituto di Geoscienze e Georisorse, Via Valperga Caluso 35 10125 Torino, Italy

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Abstract

An integrated study of Quaternary geology and geomorphology, structural geology, and morphotectonic lineament analysis has been performed for the Lower Susa Valley in order to evaluate the relationships between neotectonics of the central-internal side of the Italian Western Alps and the morphodynamics of the mountain relief. A regional NNE–SSW fault system, the Colle delle Finestre Fault Zone (CFFZ), separates two sectors, the Middle and the Lower Susa Valleys, characterized by different fault patterns. ENE–WSW regional faults represent the main brittle structures in the Middle Susa Valley, while E–W faults prevail in the Lower Susa Valley. Geomorphic anomalies, Plio-Quaternary deformed deposits and distribution of glacial deposits suggest differential uplift of fault-bounded sectors. Distribution of deep-seated gravitational-slope deformations and landslides depends on lithological and structural controls, suggesting a close relationship between post-glacial morphodynamic evolution and Quaternary fault activity. This activity is also indicated by instrumental data and historical earthquakes (M_s ranging from 4 to 5) that struck the Lower Susa Valley.

1. Introduction

In the geological literature, the Western Alps are described as a complete cross-section of the Alpine orogenic wedge, as the result of a complex geodynamic process due to plate convergence, characterized by prevailing "horizontal displacements" involving lithosphere oceanic subduction followed by continental collision (Polino et al., 1990). The post-collisional, "late-Alpine" (Pliocene to recent; Hunziker and Martinotti, 1987) history of the chain is mainly dominated by prevailing "vertical movements" (either uplift or subsidence), due to both active tectonics and isostatic rebound (Debelmas, 1986). Thermochronological data indicate that patterns of uplift and exhumation are different through the Western Alps (Hunziker et al., 1992; Bogdanoff et al., 2000). Subsidence data on tectonosedimentary evolution of the "Alpine realm" of the Western Po plain (Dela Pierre et al., 1995) suggest the most internal sector of the central part of the Western Alps does not show relevant differences in the vertical rates of movement with respect to the adjacent Po plain, being involved in Apenninic thrust propagation since Mio-Pliocene.

Since change in elevations and relief is a matter of balance between uplift and denudation, important contributions for a better understanding of the onset and evolution of the Alpine geomorphological landscape can be given by comparing features related to endogenic and exogenic processes. A possible approach is to examine datasets including information on distribution and characteristics of erosional/depositional landforms, superficial deposits, and their relationships with tectonic discontinuities.

Regarding the oldest information on superficial processes in the Central Western Alps, Sacco (1888) indicated incision of major Alpine valleys dating back to pre-Pliocene times. The valley mouths were filled by Pliocene marine deposits covered by "Villafranchian" regressive

*Corresponding author. Dipartimento di Scienze della Terra, Università di Torino, Via Valperga Caluso 35, 10125 Torino, Italy. Tel.: +39 011 670 5187; fax: +39 011 236 5187.
E-mail addresses: paola.cadoppi@unito.it (P. Cadoppi), marco.giardino@unito.it (M. Giardino), gianluigi.perrone@unito.it (G. Perrone), s.tallone@csg.to.cnr.it (S. Tallone).

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continental sequences. The onset of Quaternary glaciations caused erosion of Pliocene deposits and a major footprint in the Alpine landscape. In a general view of the Alpine glaciations, as shown in the historical maps (Castiglioni, 1940) and in the recent review of their extent and chronology (Ehlers and Gibbard, 2004), the ice sheets during their maximum expansions covered almost continuously the Western Alps, leaving only the highest peaks emerging. Since successive glacial phases formed progressive uplifting relief, distribution of Pleistocene glacial landforms and deposits can be seen as possible markers of uplift and denudational patterns (Carraro and Giardino, 2004; Deline et al., 2005).

The search of possible interactions between recent tectonic activity and the evolution of mountain relief led in the past to a preliminary recognition of significant ''neostructural Domains'' by means of analysis and interpretation of ''areal'' and ''linear'' Neotectonic elements. In the Neotectonic Map of Italy (Ambrosetti et al., 1987), the central part of Western Italian Alps resulted as an area affected by strong and nearly continuous uplift during Pliocene and Quaternary. The major ''linear'' Neotectonic element was indicated as a N–S ''deformation belt'' also known in literature as the ''Cenischia-Nizza'' lineament (Casati and Giovacchini, 1977); other minor NE–SW faults have been recognized, mainly showing Middle Pleistocene–Holocene activity. Evidence of a large area tilting towards E is also indicated, eastward of the ''Cenischia-Nizza deformation belt''.

In the last few years, geological studies based on structural analysis and fission-track data (Cadoppi et al., 2002; Balestrieri et al., 2004; Malusà, 2004; Perrone et al., 2005; Perrone, 2006) have been conducted in the central/internal part of the Italian Western Alps, focused on the post-metamorphic tectonic evolution of the area. These works pointed out the occurrence of a regional fault-network cross cutting and displacing the pre-existing nappe pile related to the syn-metamorphic tectonic evolution. Therefore, a detailed analysis of the ''patchwork'' of the tectono-stratigraphic units showing different geomechanical properties is useful for the interpretation of the complex interaction between exogenetic and endogenetic processes in the evolution of the Alpine relief.

As an example, besides morphoclimatic factors, the regional distribution and internal characteristic of large landslides and of deep-seated gravitational-slope deformations (DSGD) in the Western Alps has been related by Carraro et al. (1979) and Mortara and Sorzana (1987) to the litho-structural setting and neotectonic activity. Particularly, in the Middle Susa Valley, the recent activity of ENE-trending faults along the ''Susa–Chisone Shear Zone'' (SCSZ) has been indicated by Giardino and Polino (1997) as a triggering factor of large slope instabilities.

The present paper aims to get a better knowledge of the Pleistocene to post-glacial history of the regional neotectonic setting in the Lower Susa Valley. A multidisciplinary approach has been applied to investigate the relationships among different fault-systems activity and the morphodinamic processes. In particular, the role will be outlined of the major brittle structure affecting the studied area, the so-called CFFZ within the geomorphological evolution of the Lower Susa Valley located in the internal part of the Italian Western Alps (Fig. 1).

2. Susa Valley Quaternary geology and geomorphology

The Susa Valley is one of the major valley systems of the Western Alps, hosting the drainage basin of the Dora Riparia River (total area: 1231 km^2), left tributary of the Po River. As shown in Fig. 2, the valley system is segmented and composed of a major thalweg and some large tributaries. The Bardonecchia and Cesana branches (Upper Susa Valley) start near the present-day western drainage divide and join at the Oulx intermontane plain. The Middle Susa Valley crosses WSW-ENE the mountain relief, from Oulx down to the Susa Gorges. The Lower Susa Valley starts near Susa, at the Cenischia confluence: this E–W trending segment joins the Po plain at the Susa Valley mouth, in correspondence with the Rivoli-Avigliana Morainic Amphitheatre.

The studied area is located around Susa, at the lower junction between the Susa Valley segments where two Pleistocene glaciers (Middle Susa and Cenischia glaciers) merged to give rise to the main Lower Susa glacier. The valley junction is characterized by an abrupt step, the Middle Susa representing a suspended valley with respect to the Cenischia and the Lower Susa.

Similarly to the other sectors of the Western Alps, the general geomorphology of the Susa Valley is mainly characterized by Pleistocene erosional and depositional landforms of glacial origin. Still different glacial pulses are distributed along both slopes and valley bottom. Valley slopes show mainly Last Glacial Maximum (LGM) and post-LGM lodgement and ablation till; scattered pre-LGM landforms and deposits, strongly reworked and remodelled (Carraro, 1987) are still preserved in some sectors of the Lower Susa Valley, being distributed at a higher elevation than more recent glacial landforms and deposits, due to the interaction of denudational processes and orogenic uplift (Carraro and Giardino, 2004). This process is also testified at the Susa Valley mouth, where drilling and geophysical data (references cited in Carraro et al., 2005) indicate that, at different glacial stages, the valley bottoms were progressively carved into previously deposited units, starting from the top of continental Lower Pleistocene (''Villafranchian'' Auct.). In addition to glacial erosion during the different pulses, the distribution of lateral moraines, progressively younger from south to north along the right side of the Lower Susa Valley, also show that the main Susa glacier did not maintain a constant longitudinal position, as generally occurred for other southern-verging Alpine glaciers, but that it shifted along the N–S direction.

A strong influence on the geomorphological landscape of the Susa Valley is mass movement related to slope

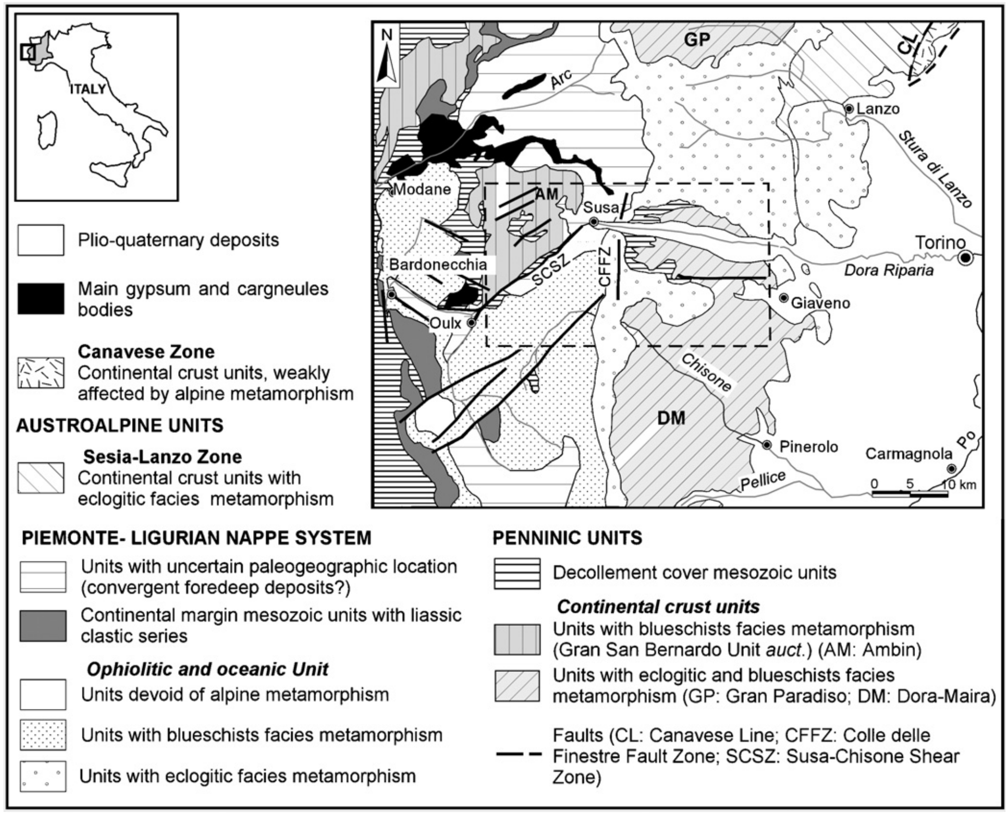

Fig. 1. Structural setting of the internal sector of the central/internal part of the Western Alps. The dashed rectangle indicates the investigated area.

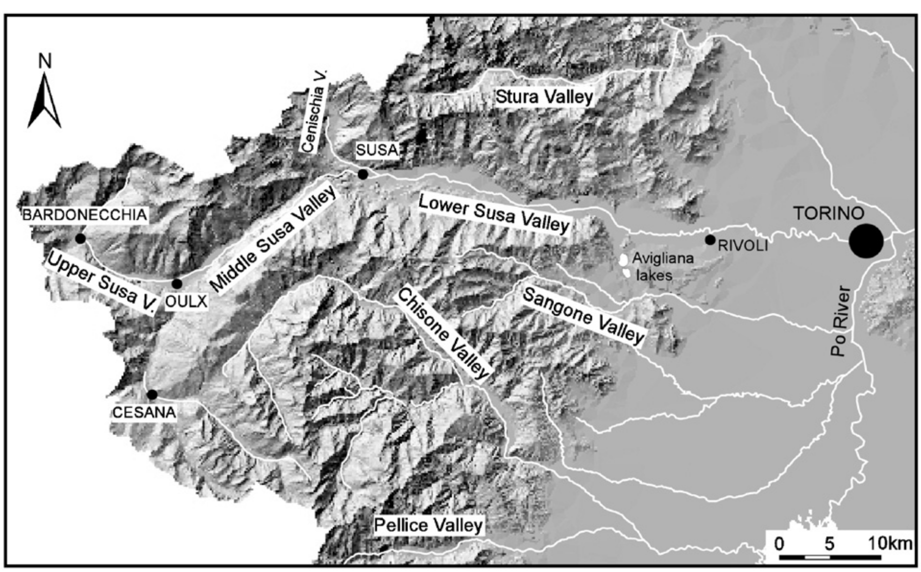

Fig. 2. Geographic setting of the Susa Valley.

instability phenomena. Large portions of valley slopes are covered by landslide deposits and/or affected by DSGD. Landslide forms, internal features and facies of related deposits account for a wide range of landslide-movement types. Post-glacial rock falls and complex slides are the most relevant and best preserved for the Middle and Lower Susa valleys. Among DSGD, the complex geometrical settings surveyed in case studies from the Susa Valley (Forno and Massazza, 1987; Mortara and Sorzana, 1987; Puma et al., 1989; Giardino and Polino, 1997) account for different deformational styles and supposed causes: typical ''gravitational spreading of ridges'' (Varnes et al., 1989) at the Susa–Chisone divide, possibly due to gravity tectonic phenomena; prevaling ''Sackung'' phenomena (Zischinsky,

1969) along the left slope of Middle and Lower Susa valleys, and large block sliding (Zaruba and Mencl, 1969) along the right slope of Lower Susa Valley, as different responses to glacial-valley stress release in different tectono-structural contexts; and large sinkholes and gravity-induced slope collapses due to deep-seated corrosion of soluble rocks at certain tectono-stratigraphic favourite settings (Alberto et al., 2004).

3. Geological and structural setting

The Susa Valley is a natural cross-section of the Western Alpine chain showing several stacked structural units of continental-margin, oceanic, and trench paleogeographic pertinence (Piemonte–Ligurian Domain) belonging to the Penninic domain, showing differences in tectono-metamorphic evolution (Fig. 1). In the study area (Lower Susa Valley) the continental crust is represented by the Dora–Maira Unit characterized by a pre-Mesozoic basement, composed mainly of orthogneiss and metapelites, covered by a Mesozoic complex made of marbles and calcschists (Fig. 3). The oceanic units are represented by metaophiolites and related metasedimentary covers. Calcschist units, probably derived from convergent foredeep deposits, diffusely outcrop.

This sector of the Alpine chain experienced a complex syn-metamorphic evolution characterized by at least four deformation phases. The first two deformation phases, coeval with HP/LT metamorphic conditions, are related to the development of a pervasive, regional transpositive foliation, which represents the axial surface of millimetric to decametric isoclinal folds. The post-transpositive structural evolution is characterized by the development of pervasive folds at a regional scale controlling the present geometrical setting. These folds, related to the greenschist facies metamorphic phase, are characterized by a general southern vergence, with subhorizontal E–W trending axis. A late metamorphic folding phase deforms the E–W trending folds and the older surface-generating open folds characterized by subvertical axial surfaces and N–S trending axes (Cadoppi and Tallone, 1992; Cadoppi et al., 1997). Starting from the Oligocene, as suggested by apatite fission-track data (Balestrieri et al., 2004), the pre-existing syn-metamorphic structural setting has been modified by the development of a complex fault network, which will be described in detail below.

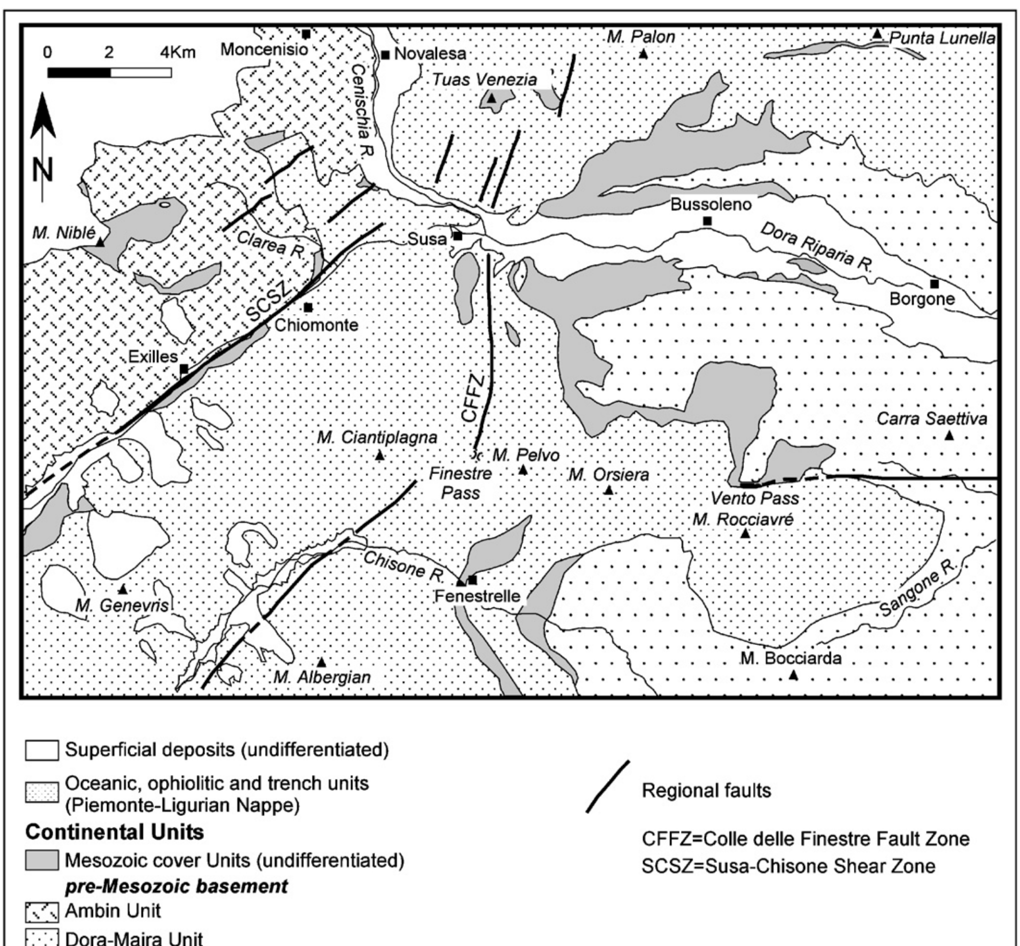

Fig. 3. Tectonic sketch map of the Susa Valley.

4. Methodology

In this work, Quaternary geology and geomorphology, structural geology and morphotectonic lineament analysis are integrated in a multidisciplinary approach to investigate the relationships between recent tectonic activity and geomorphological evolution of a mountain area characterized by a complex morphostructural setting and poor evidence of recent seismotectonic activity. Quaternary geology and geomorphological analysis have been performed using aerial photo-interpretation and field surveys. Identification and interpretation of landforms and related deposits have been carried out in the Lower Susa valley. Quaternary deposits have been interpreted in term of allostratigraphic units (NACSN (North American Commission on Stratigraphic Nomenclature), 1983; Giardino and Fioraso, 1999) according to the procedures applied for the "Susa" (Carraro et al., 2002) and "Bardonecchia" (Polino et al., 2002) sheets of the Geological Map of Italy, 1:50,000 in scale (CARG Project). Geomorphological and allostratigraphic profiles have been drawn up along the Susa Valley in order to understand patterns of erosional and depositional processes, mainly related to glacial modelling (Figs. 4–6). The cross-sections and longitudinal profiles have been created by the Spatial Analyst application (ArcGIS by ESRI) to a digital terrain model (DTM) with a spatial resolution of about 25 m.

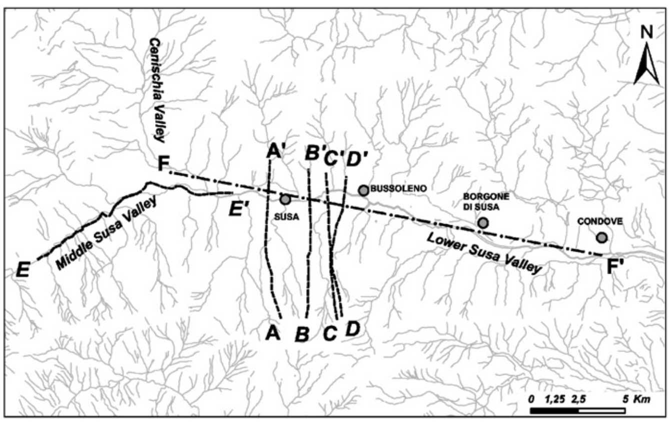

Fig. 4. Trace of morphological (dashed lines) and allostratigraphic (dashed and dotted line) profiles.

Detailed geological and geomorphological field surveys have been conducted in selected sites, aimed to detect indicators of neotectonics activity in the area: anomalous deposits distribution, superficial deformations, and landforms with possible "direct" tectonic significance or "indirectly" linked to recent tectonic processes. Such features include soft-sediment deformations, irregular patterns in erosional/depositional units, valley cross-section asymmetries, fluvial captures, occurrence of suspended valleys, and concentrations of DSGD. Standard

Fig. 5. Allostratigraphic longitudinal profile of the lower Susa valley between Susa and S. Valeriano-Condove (redrawn and integrated from Carraro et al., 2005). (A) pre LGM glacial deposits ("Bennale" Allogroup); (B) LGM glacial deposits (Frassinere Alloformation); (C) "early" cataglacial deposits (Magnoletto Alloformation); (D) "Late" cataglacial deposits (Venaus Alloformation); (E) bedrock-incised glacial landforms. 1–4: average distribution of ancient valley bottoms, related to glacial deposits (unit (A)–(D) from older to younger); 5–7: average upper limit of preserved glacial deposits related to unit (B)–(D) from older to younger.

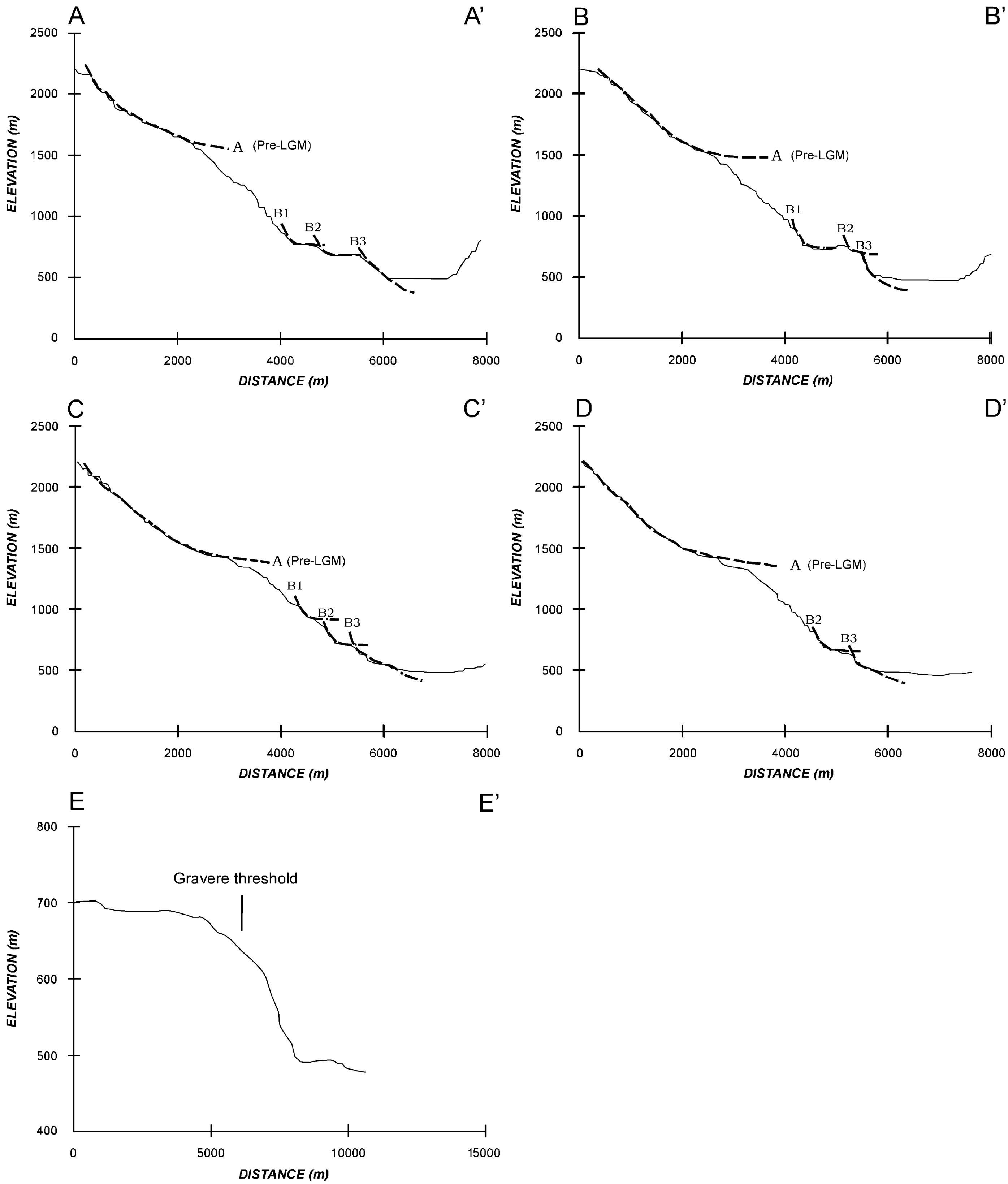

Fig. 6. Cross-sections and longitudinal morphological profile of the Susa Valley. Location in Fig. 4. Vertical exageration: 6x. (A) pre-LGM ancient valley bottom; (B1)–(B3): “cataglacial” valley bottoms.

methodology of brittle structural analysis (Hancock, 1985) was performed on bedrock units and superficial deposits in order to reconstruct the regional pattern of the post-metamorphic shear zones, their kinematic evolution and deformation environment and conditions.

The morphotectonic lineament analysis used both a 23-km-wide panchromatic scene of IRS-1D satellite, with a 5 m ground resolution, and aerial photographs, in order to recognize lineaments and to detect any possible link between structural and geomorphological features surveyed in the field. No automatic extraction of lineaments was performed and both video and printed images were used. Image analysis was performed at different scales, detecting only linear elements belonging to homogeneous, well represented, geometrical lineament families, following the methodology proposed by Morelli and Piana (2006). The first step led to major lineaments identification, corresponding to straight-lined valleys, scarps, and ridges or river and torrent with aligned channel bends. A more detailed study led to the identification of minor lineaments, geometrically similar to the longest. Lineaments have been, moreover, statistically analysed both in terms of azimuth trend and length, to minimise errors and subjective interpretation.

5. Geomorphological and Quaternary geology analysis

The study of Quaternary deposits and landforms was performed in the Lower Susa Valley from the CFFZ down to the eastern sector of Condove. The results are here presented following a ‘‘historical’’ approach, starting from the analysis of distribution and characteristics of older-to-younger superficial formations and landforms, followed by comparison to the present-day geomorphological setting. Datasets descriptions have been carried out with a spatial analysis of significant features, here supported and illustrated by the comparison of a longitudinal allostratigraphic profile (Fig. 5), some morphological cross profiles (Fig. 6) and a Quaternary geology and geomorphological sketch map (Fig. 7). Some comments have been added to highlight possible endogenic/exogenetic interactions.

The oldest glacial markers recognized in the area are the accumulations of erratic blocks (prevailing well-rounded, quartzite and augen-gneiss boulders) and the strongly remodelled lodgement tills preserved in the more elevated parts of both lower Susa valley sides around Condove. On the left-valley slope, isolated boulders distributed within an E–W elongated ridge North of S. Valeriano form the so-called ‘‘loose skeletal tills’’ (Carraro, 1987). On the right-valley side, at the same elevation interval (950–1150 m a.s.l.), deeply weathered and poorly preserved massive diamictons are interpreted as the remnants of a Pre-LGM, middle Pleistocene glaciation (‘‘Bennale Allogroup’’; Cadoppi et al., 2002).

A significant decrease in the amount of weathering of glacial deposits and in the intensity of remodelling of their original geomorphological expression differentiates the above described pre-LGM unit and more recent glacial units. By analysing weathering profiles, pedostratigraphical data, spatial distribution, internal characteristics of glacial deposits and landforms, and by comparing these evidences with those related to the glacial units of the Rivoli-Avigliana Morainic Amphitheatre, a ‘‘cataglacial sequence’’ in the Susa valley has been recognized (Cadoppi et al., 2002; Carraro et al., 2005). The outputs of these studies are essential in the definition of the geomorphological evolutionary stages of Lower Susa Valley slopes. As shown in Fig. 5, several ‘‘altitude belts’’ including different units of glacial deposits and related erosional surfaces (average distribution of ancient valley bottom) have been recognized. From top to bottom in the allostratigraphic profile, below the pre-LGM ‘‘Bennale Allogroup’’, the scattered same-colour polygons correspond to the preserved ‘‘strips’’ of the Frassinere, Magnoletto and Venaus Alloformations. They represent the markers of progressively younger and lower modelling phases, from the LGM to the last glacial-withdrawal phases. The evidence of progressive deepening of the Lower Susa Valley is also shown by the comparability of several slope breaks in the morphological cross profiles (Fig. 6). Field data indicate they are remnants of ancient glacial-erosional surfaces, the major being interpreted as a Pre-LGM one. Lower, minor glacial terraces represent the cataglacial sequence.

The record of glacial deposits in the Lower Susa Valley is completed by several units from tributary glaciers, whose geomorphological evidence is better preserved along the right Susa Valley slope (Fig. 7), reaching lower elevations (1000–1200 m a.s.l.) than the left slope (1200–1400 m a.s.l.). Along a N–S elongated area, extending from Susa to Colle delle Finestre, glacial deposits are lacking, either related to the main glacier or tributaries; here, erosional features related to the main Susa glacier also show an anomalous distribution, following an east-facing N–S step, described in detail as the ‘‘Gravere threshold’’.

The Holocene history in the Lower Susa Valley is mainly represented by Quaternary deposits and landforms related to fluvial and slope processes. The Cenischia and the Lower Susa valleys are filled by fluvioglacial and fluvial deposits related both to the main streams and the tributaries. Post-glacial torrent activity in the area is responsible for extensive aggradation of alluvial fans, mainly by debris flow deposition, and intensive degradational phenomena due to erosion and deep incision of tributary valleys. The lower altitude part of the left Susa valley slope in a long sector around Bussoleno is characterized by ravines and canyon-like features (e.g. ‘‘Orrido di Foresto’’, ‘‘Orrido di Chianocco’’), with sub-vertical faces up to 70 m in height, affecting both carbonate rocks and crystalline basement. On the opposite Susa Valley side, geomorphological anomalies affect the intermediate altitude sector of the slope. Right-tributary streams are characterized by strong geomorphological anomalies: straight N–S deep incisions, with asymmetric cross profiles and stepped longitudinal profiles (Scaglione and Gerardo Torrents); sharp changes

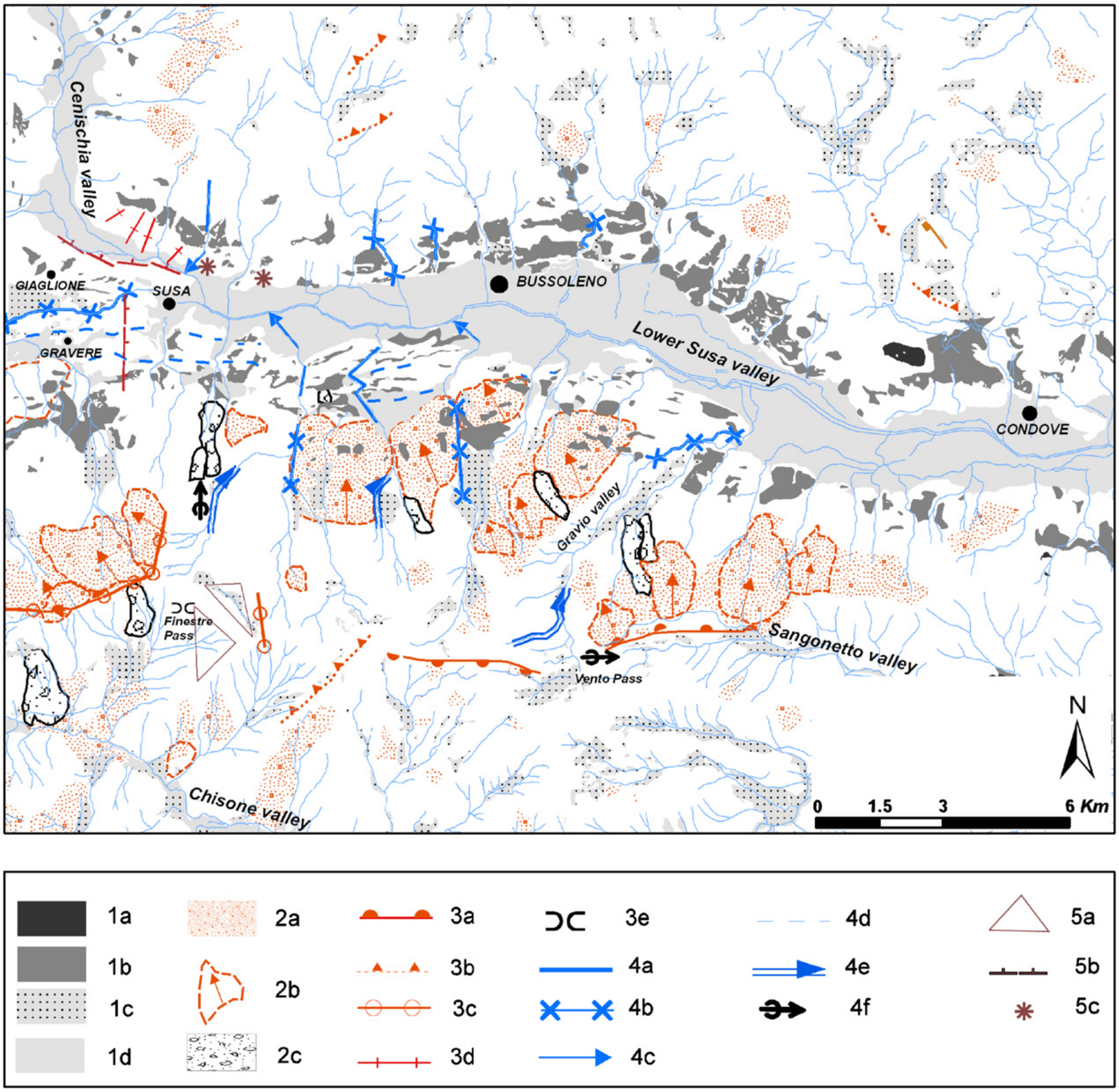

Fig. 7. Quaternary deposits distribution and geomorphologic anomalies map (modified after Carraro et al., 2002). *Quaternary deposits*: 1a = main Susa glacier Pre-LGM deposits, 1b = LGM and late glacial deposits, 1c = tributary glaciers deposits, and 1d = fluvial deposits. *Gravity-related landforms and deposits:* 2a = deep-seated gravitational deformations, 2b = deep-seated gravitational deformations homogeneous sectors (red arrow indicate the slip average direction of the DSGD), and 2c = major landslides. *Slope-related geomorphological anomalies:* 3a = double ridges, 3b = counterslopes, 3c = linear ridges, 3d = trenches, 3e = wind gap and pass. *Drainage network geomorphological anomalies:* 4a = deep fluvial incisions, 4b = straight fluvial incision, 4c = upstream confluence, 4d = spillway channels, 4e = fluvial diversion, and 4f = new-born valley head. *Other tectonic landforms and deformation:* 5a = triangular facets; 5b = major scarps and 5c = sites of deformed quaternary deposits.

of channel direction associated with wind gaps; and progressive river captures associated with headward erosion (Mortara and Tropeano, 1978). Elbow of captures suggest an extension towards the W of capturing drainage basins in the valley sector between Susa and Bussoleno (Arneirone and Corrente Torrents), from N to S in the eastern sector, at the Gravio Valley, with the exemplary "Colle del Vento" wind gap, the present-day Sangonetto Valley head (Fig. 8).

In a macro analysis from the Cenischia–Dora confluence down to Condove, the present-day Susa Valley is characterized by a relatively flat and wide, E–W trending valley bottom (up to a 2.5 km slope-to-slope distance), showing a sharp contrast with the progressively narrow N–S trending Cenischia Valley and the bedrock-incised, "suspended" thalweg of the Middle Susa Valley. From the geomorphological point of view the key features of the sector are: (1) the "Gravere threshold" ("soglia di Gravere"; Cadoppi et al., 2002; Carraro et al., 2005), a N–S morphological step between Middle and Lower Susa valleys (Fig. 6); (2) the WNW–ESE "Giaglione scarp", separating the Middle Susa valley from Cenischia valley bottom (Fig. 7); (3) the "Susa Gorge" (a deep incision carved in the bedrock by the Dora Riparia River west of

Fig. 8. Colle del Vento wind gap: (A) between Sangonetto Valley (1) and Gravio Valley (2) (photo by P. Baggio)

Fig. 9. The Susa Gorges at the junction of Middle and Lower Susa valley segments (photo by F. Carraro).

Susa; see Fig. 9) and other E–W deep river incisions, affecting the terminal sector of the Middle Susa Valley and the left slope of Lower Susa Valley. Also from the analysis of its complete cross-profile, the Lower Susa valley is strongly asymmetric with a steeper South-facing ''left'' slope characterized by transversal counterslopes and a gentler and irregularly shaped North-facing ''right'' slope, with a series of major E–W elongated steps (scarps, terraces) and several minor glacial and fluvial scours at the slope bottom.

In addition to glacial activity, this general geomorphological setting has to be related to other processes mainly characterized by widespread gravity-induced deformation along slopes. DSGDs of various type and size affect both Middle and Lower Susa Valley slopes (Fig. 10a). From up to bottom slopes, local DSGD-related geomorphological features are: segmented divides, double-crests (Fig. 10b), trenches, up- and down-facing scarps, bulging slopes, highly fractured rock walls, and wide debris-covered areas.

Distribution and size of these different types of DSGD features is not homogeneous in the study area along slopes with similary orientation and glacial history, being possibly related to litho-structural settings and neotectonic phenomena. In the Lower Susa Valley, DGSD features, with

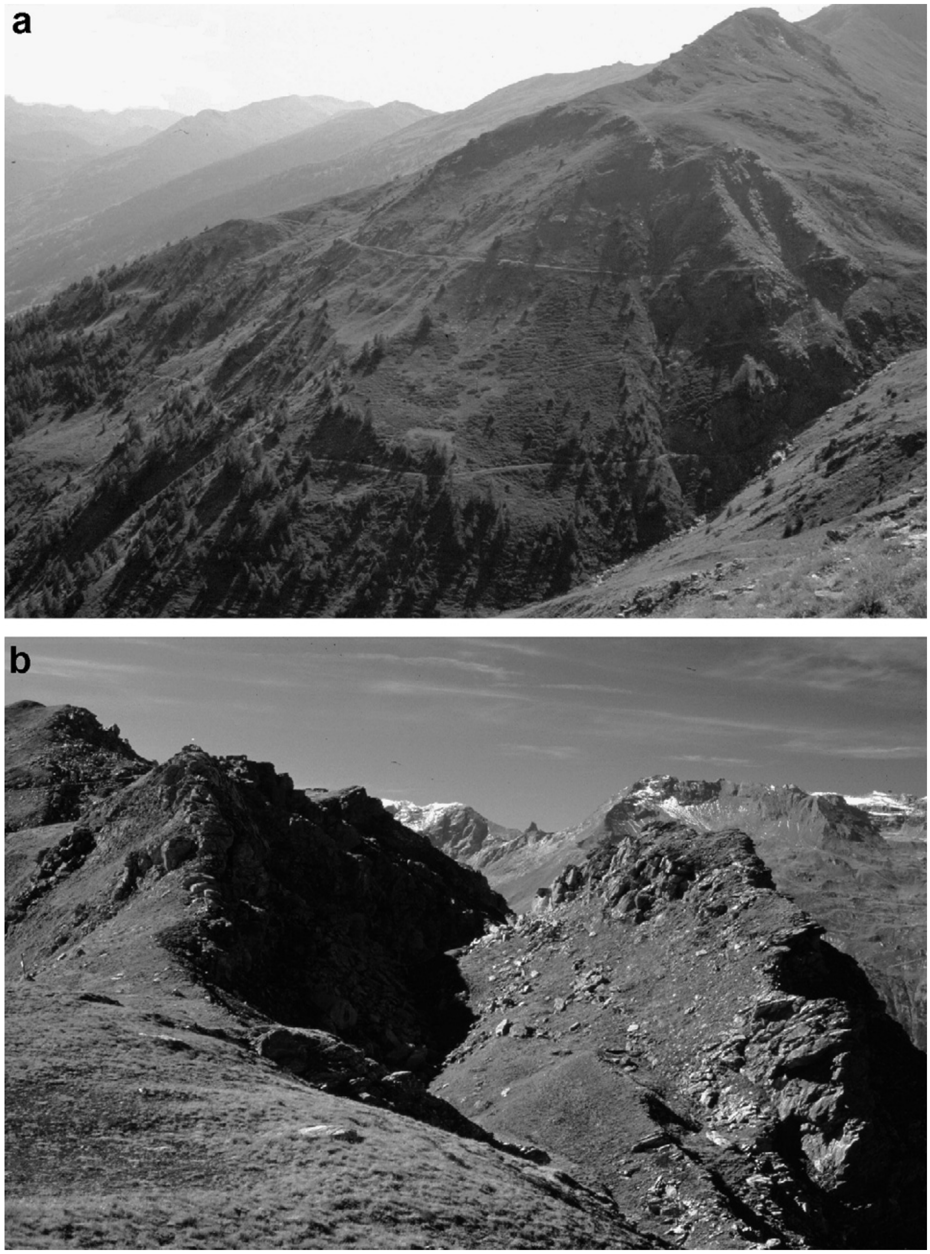

Fig. 10. DSGD characteristics in the Susa Valley. Deep-seated gravitational deformations of sackung-type: (a). Lateral expansion and double-ridge deformation at the divide between Susa and Chisone Valley: (b) (photos by M. Giardino).

various orientations, are associated in several single-deformation zones, indicating differential displacements along the slopes.

In the western part, similar NE–SW trending DSGDs are distributed along a wide area of bi-lateral expansion of top ridges at the Susa–Chisone divide. Considering the kinematic significance of superficial markers of deformation, some "homogeneous sectors" of DSGD have been recognized in the left slope of the Lower Susa Valley. They are characterized by average parallel N-dipping slip vectors in the Susa–Bussoleno sector, in the proximity of the CFFZ, by diverging NNW- and NNE-dipping slip vectors in the Bussoleno–Condove sector.

Several other active, inactive, and relict micro-scale landforms (landslide scarps and accumulations, counter-slopes) indicate a long-lasting gravitational activity concentrating in the Colle delle Finestre area. Here, the general slope forms resemble more typical tectonic landforms such as triangular facets (Fig. 11).

6. Structural analysis

The Middle–Lower Susa valley junction represents a boundary between two structural domains characterized by different fault networks. In the Middle Susa valley, a regional ENE–WSW trending fault system prevails, the

Fig. 11. Colle delle Finestre triangular facets (photo by M. Giardino).

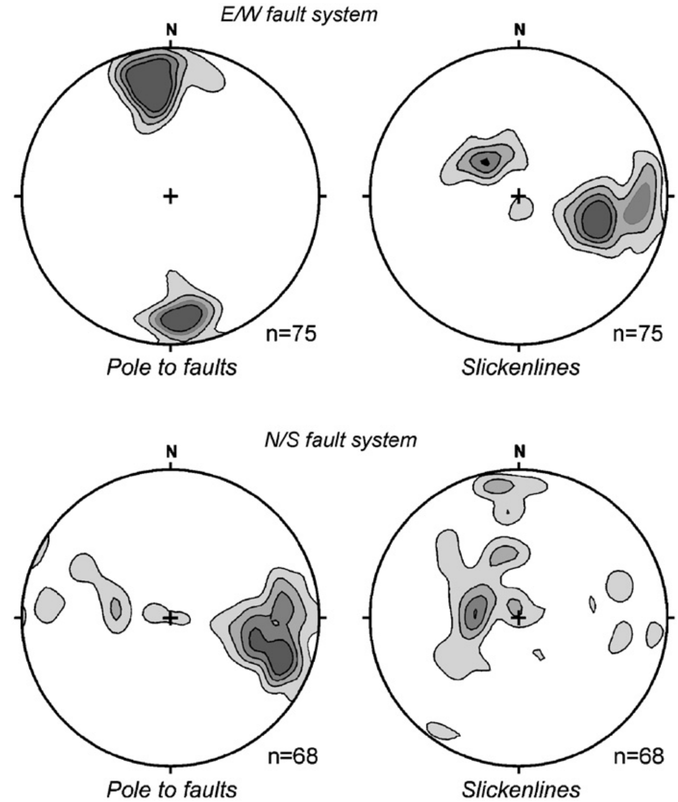

Fig. 12. Contoured stereoplots (equal-area projections, lower hemisphere) of fault plane poles and slickenlines relative to E/W and N/S fault systems. Contours at 2,4,6,8 multiples of random distribution.

Susa–Chisone Shear Zone (SCSZ), strongly controlling the main river's drainage direction, and partly affecting the tectonic contact between Ambin and Piemontese Units (Polino et al., 2002).

In the Lower Susa Valley and along its divide with the Sangone Valley, recent studies showed the occurrence of two main regional-fault system characterized by N–S and E–W trends (Tallone et al., 2002; Perrone, 2006) (Fig. 12). The kinematics of the ENE/WSW and N/S fault systems evolved progressively from right-lateral to transtensive-normal movements. The E/W fault system shows left-transtensive movements (Tallone et al., 2002; Perello et al., 2004; Malusà, 2004; Perrone et al., 2005; Perrone, 2006).

The distribution of the faults of the N–S system is prevalently concentrated in a N–S striking, subvertical deformation zone approximately 2 km in width, named CFFZ, (Cadoppi et al., 2002). The CFFZ reaches a total length of about 11 km, but morphostructural evidences suggest that this structure belongs to a N/S to NNE/SSW regional lineament system, in literature known as Cenischia–Nizza Lineament (Casati and Giovacchini, 1977). This deformation belt is also emphasized by mesostructural evidence, represented by systems of faults and damaged zones separating the Middle and Lower Susa valleys structural domains.

In the structural analysis of recently deformed areas, strong support is given by deformational data from Quaternary deposits. Along the CFFZ, on the left side of the Susa Valley, post-LGM alluvial fan deposits are highly deformed by subvertical N–S normal faults and tilted towards the WNW by N15°E mesoscale soft sediment deformation folds (Madonna dell'Ecova and Seghino sites; Fig. 13). In the same area bedrock is affected by mesoscale faults and fractures with similar orientation. The deformed superficial units were in a "protected" location with respect to the influences of Cenischia and Susa Valley glaciers, at the age of alluvial fan deposition. These features indicate a non-glacigenic origin for the deformations. Similar mesoscale faults (low angle ENE–WSW and subvertical ESE–WNW normal faults) and other associated soft-sediment deformations affect fluvial deposits along the SCSZ in the Middle Susa Valley.

Other possible markers of recent deformation in the studied area come from neotectonic landforms. As shown in the geomorphological map and profiles, the major evidence of superficial deformations comes from the CFFZ: the complex geometrical setting of their association support the interpretation of a pluri-km neotectonic N-S shear zone. The offset of glacial erosional features at the Gravere threshold suggests the relative displacement of the Middle Susa Valley with respect to the Lower Susa Valley. The concentration of tranversal ENE–WSW to NNE–SSW trenches on the left slope of Cenischia valley is coherent with a progressive rotation of major ENE–WSW joint systems at the SCSZ–CFFZ intersection. Mesoscale E–W faults and joints are widespread along the Lower Sangone Valley, affecting large portions of the left slope. Local distribution of highly fractured, disjointed and disarticulated rock masses is bounded by a sharp E–W "upper" limit corresponding to the Sangone Fault.

7. Lineament analysis

The analysis of IRS-1D satellite image (Fig. 14) and of the aerial photographs detected three main lineament systems: NNE/SSW (Ln1), ENE/WNW (Ln2), E/W (Ln3) (Fig. 15). The Ln1 system consists mainly of major

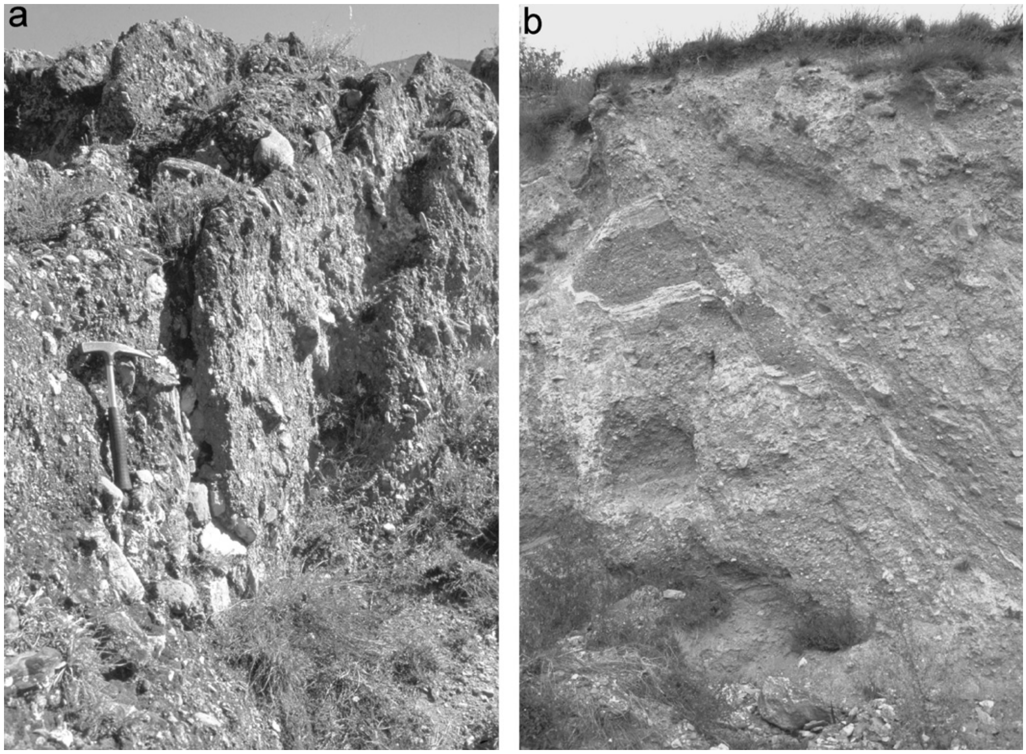

Fig. 13. Alluvial deposits steepened and displaced by N-S normal faults (Madonna dell'Ecova (a) and Seghino Village (b)) (photos by S. Tallone).

lineaments displaying moderate strike variability, forming a pluri-kilometric width belt distributed at the junction between the Lower and the Middle Susa Valley.

The Ln2 system consists mainly of sub-parallel lineaments longer than 3 km (Fig. 15b) distributed in a zone of pluri-kilometric width between the Middle Susa and Chisone valleys (Fig. 14). The lineaments of this system occur subordinately in the east sector.

The Ln3 system is particularly distributed between the right side of the Lower Susa Valley and the Chisone and Sangone valleys. It consists mainly of lineaments shorter than 3 km (Fig. 15c) forming sub-parallel bands with kilometric to pluri-kilometric spacing.

In summary, in the study area three main sectors are characterised by different lineament patterns: a western sector, where ENE–WSW major lineaments prevail, a central sector, where NNE–SSW major lineaments prevail, and a eastern sector, characterized by a complex lineament distribution, where E–W and subordinately ENE–WSW lineaments occurs. These sectors match quite well with the sectors characterized by different fault patterns, listed above.

8. Seismic data

The Susa Valley is affected by low-grade seismicity, with magnitude (Ms) less than 5 and MCS intensity (Io) less than VII (Camassi and Stucchi, 1997). In particular, instrumental seismicity is clustered both at the junction between Middle and Lower Susa Valley and at the Susa Valley mouth. Ipocentres are on the average located at a depth of about 10 km.

Relatively strong hystorical earthquakes, with magnitude (Ms) ranging from 4 to 5, struck the Lower Susa Valley near the Bussoleno, close to the CFFZ (Fig. 16). No strong historical earthquakes have been recorded in the Middle Susa valley.

As shown by geological and morphostructural data, recent tectonic activity of the CFFZ is suggested, but it is very difficult to establish a "direct" relationship of this structure with the seismicity of the area. Based on the Wells and Coppersmith (1994) relations, however, the length of the CCFZ in the area, reaching about 15 km, fits well with the magnitude of the above-mentioned earthquakes.

Though this sector of the Western Alps is poorly constrained by available data, focal mechanisms show transtensive and extensional solutions (Eva and Solarino, 1998; Perrone et al., 2005; Perrone, 2006). These data are in agreement with the structural evidence, as indicated by Plio-Quaternary deposits displaced by N–S normal faults.

9. Discussion

Analysis of the geological maps and the allostratigraphic profile shows a general W to E progressively lower inclination of basal discontinuities of glacial deposits in the Middle to Lower Susa. This confirms, not only the importance of glacial erosion in the evolution of the Alpine

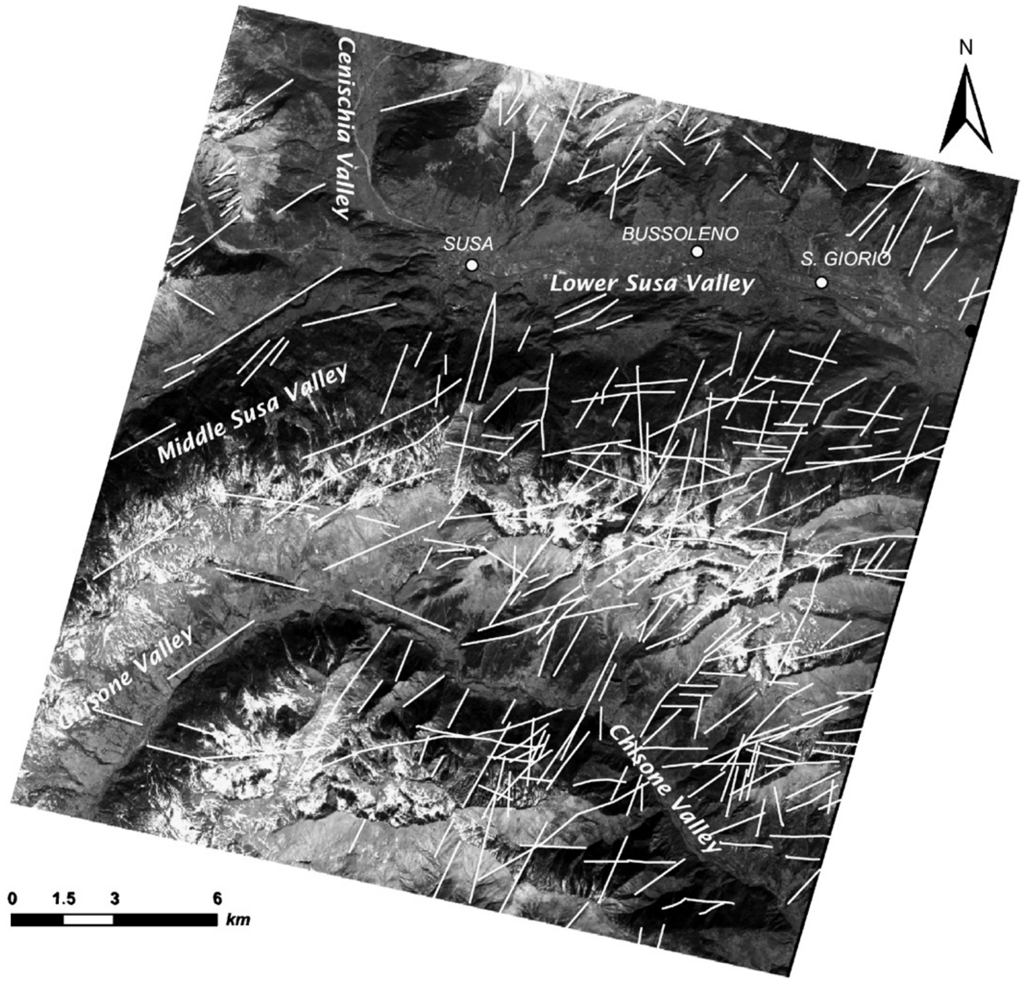

Fig. 14. Lineaments distribution along Susa and Chisone Valleys as shown on the panchromatic image of IRS-1D satellite.

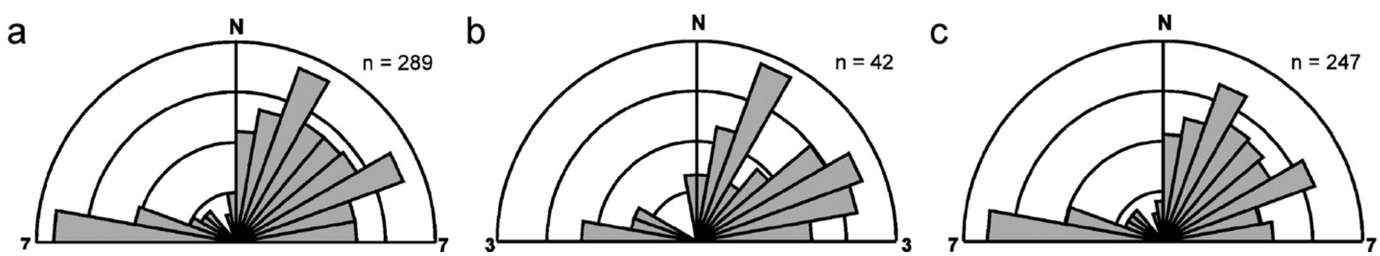

Fig. 15. Rose diagrams of azimuthal frequencies of lineaments. (a) all lineaments; (b) lineaments longer than 3 km, and (c) lineaments shorter than 3 km. The radius is proportional to the square root of frequency. Interval: 10°.

relief and the progressive reduction of glacial masses since the LGM, but also a progressive long-term interaction between uplift and erosional processes, as indicated by apatite fission-track data (Balestrieri et al., 2004).

Other outputs come from the interpretation of the slope breaks in the longitudinal profiles. The steepest thalwegs in the upper sector are limited to more recent allostratigraphic units, due to the position of glacial divides after the LGM. The increase of valley gradients around Condove since pre-LGM times is notable, as also testified by deep infillings of surficial deposits in the present-day valley bottom, suggesting possible morphotectonic activity in this sector of the Lower Susa Valley.

In other sectors of the same area, even if Quaternary fault activity is not well constrained by strong ''unequivocal'' morphostructural evidence, the occurrence of Pleistocene–Holocene deposits displaced both by ENE–WSW and N–S faults, suggest possible ''impulsive'' interactions among stress field and relief development (seismic events?). Quaternary faults show mainly normal movement, in agreement with the kinematic evolution of the regional fault systems.

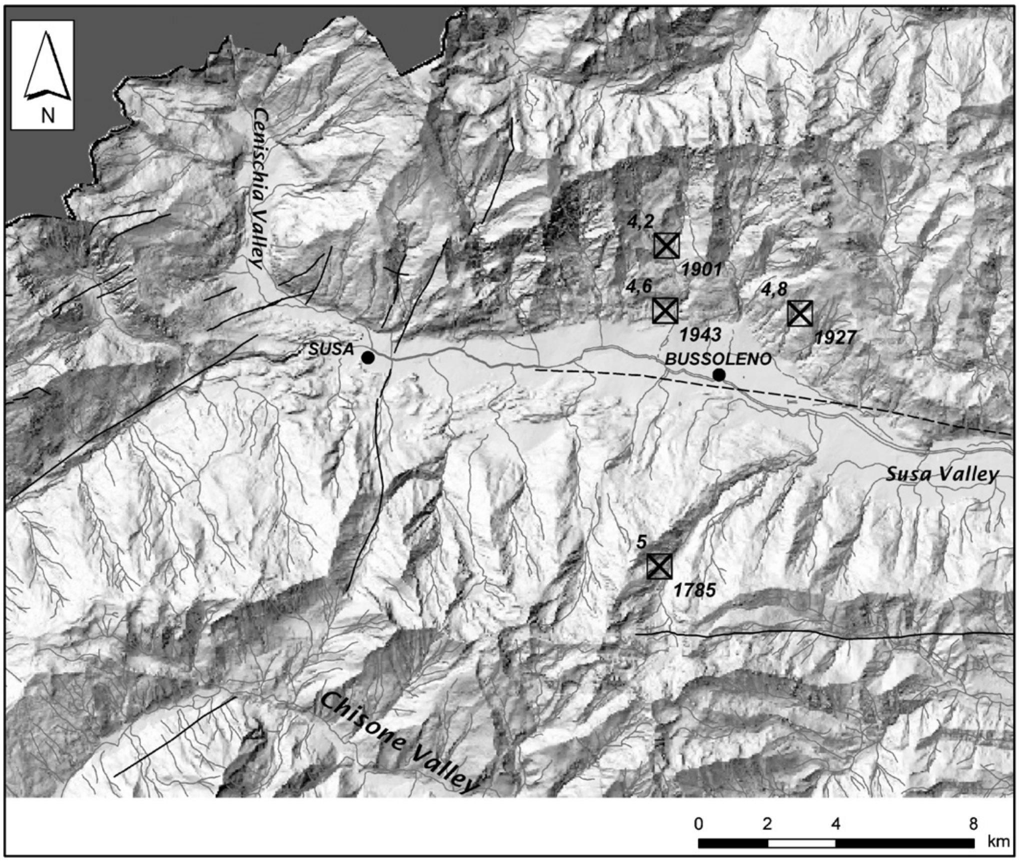

Fig. 16. Distribution of faults and strong hystorical earthquakes occurred in the Susa Valley. Crossed squares indicate earthquake epicentres; the number on the top-left and on the bottom-right of the square indicate the estimated magnitudo (Ms) and the date of the earthquake respectively. Black lines indicates the regional fault systems trace.

Integrating geomorphological and structural data, it is possible to divide the study area in sectors, corresponding to blocks bounded by regional fault systems, characterized by different uplift. From the Upper Oligocene, as indicated by apatite fission-track data, kinematic data of the three main fault systems (SCSZ, CFFZ and the E/W faults) show a gradual change, from a strike-slip regime to a transtensive/extensional one. The persistence of the extensional regime in recent/present times is suggested by the occurrence of mesoscale normal faults displacing both Plio-Quaternary glacial and fluvial deposits and landforms. Earthquake focal mechanisms also show, in the internal sector of Western Alps, extensional/transtensive solutions (Eva et al., 1997, Eva and Solarino, 1998; Perrone, 2006). These data suggest that the present-day stress-field results from isostatic readjustments of a fractionating lithosphere in pluri-kilometric blocks, characterized by different uplift rates.

In Fig. 17 a neotectonic map of the studied area is presented. The interpretation of relative movements of different sectors is derived from the integration of structural and seismic data, with evidence of long-term geomorphological evolution. The CFFZ is the most important neotectonic structure in the area. It separates two sectors (corresponding to the Middle and Lower Susa valleys) with different fault geometry, lineament distribution and uplift rate.

Morphostructural evidence (the alignment of DSGDs along the right side of Lower Susa Valley, the capture elbow of the Sangonetto Valley by the Gravio Stream, the occurrence of subvertical fault scarps, and double ridges along the Susa–Sangonetto divide and landforms related to the lateral migration of Pleistocene Susa glacier) suggests the lowering of the right side of the lower Susa Valley with respect to the opposite valley side. This lowering was driven both by the activity of the Sangone Fault system to the south and, probably, by a buried fault below the Plio-Quaternary deposits of the Susa valley bottom, to the north. This hypothesis is supported by the asymmetrical geomorphologic cross-section of the Susa Valley between Susa and Chianocco, with a steeper northern slope and with left-tributary valley characterized by deep fluvial incisions. This evidence is in agreement with the apatite fission-track data, showing younger ages on the left side of the Lower Susa Valley and older ages on the right side of the valley.

In the Middle Susa Valley (Giardino and Polino, 1997; Polino et al., 2002), the occurrence on the left side of suspended-tributary valleys and of several deep fluvial incisions suggests that this sector is uplifting with respect to

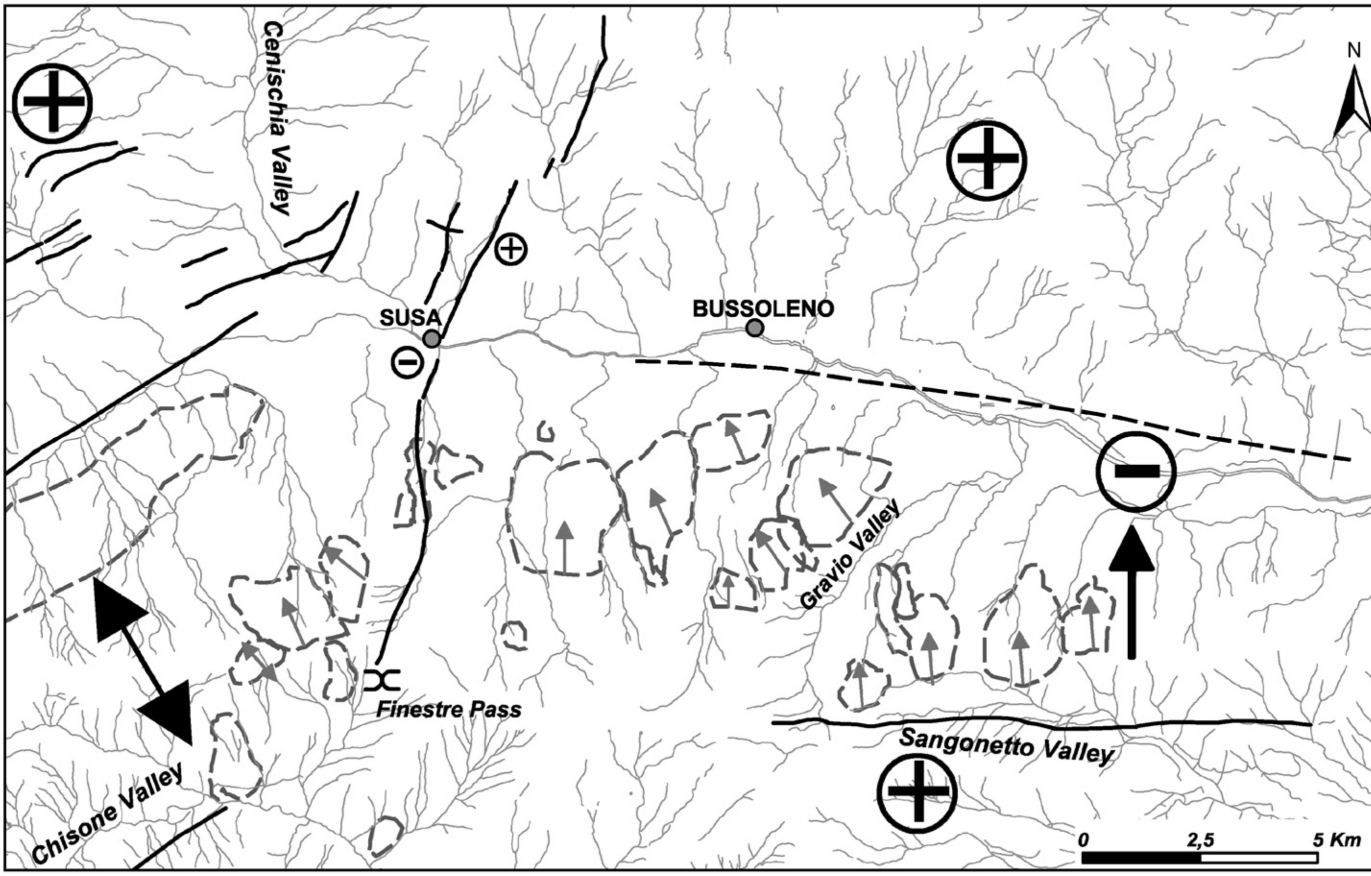

Fig. 17. Neotectonic map of the studied area. Double black arrows indicates bilateral extension, single black arrow indicates the slip direction of the DSGD; + indicates uplifting sectors;—indicates lowering sectors; dashed thick grey lines with related grey arrows indicates DSGD homogeneous sectors.

the right side of the valley, where several landslides and very huge DSGSs, double ridges along the Susa–Chisone divide and ridge-valley are concentrated. According to Giardino and Polino (1997) this morphostructural evidence suggests a bilateral extension of the sector between the Susa and Chisone valleys, triggered by the ENE–WSW fault-system activity. The Gravere threshold, elevating the Middle Susa Valley bottom about 200 m with respect to the Lower Susa Valley bottom, could be the result of the long-term effect of the CFFZ activity, as suggested by the morphostructural evidence and historical and instrumental seismicity around Susa.

10. Conclusions

The integrated approach, including Quaternary geology and geomorphology, structural geology and morphotectonic lineament analysis, verified the existence of a tight relationship between recent (Plio-Quaternary) tectonic activity and morphodinamic evolution of the mountain relief. In particular, the control of seismotectonic activity over the distribution and characteristics of DSGDs appears evident. Different types of DSGD are also related to peculiar litho-structural contexts. Lateral expansion is concentrated in the Middle Susa Valley, at the Susa–Chisone divide, bounded by a ENE–WSW transtensive fault zone (SCSZ), where calcschists units of the Piemonte–Ligurian nappe system outcrop. Sackung-type DSGD are mainly aligned along the right side of the Lower Susa Valley bounded by E/W faults and where basement rocks of the Dora–Maira Unit outcrop, with the regional foliation dipping towards the north.

Glacial and fluvial modelling responded dynamically to the different uplift of the blocks bounded by regional faults, changing their erosional paths. In the Middle–Lower Susa Valley sectors, three fault systems drive such uplift: ENE–WSW (SCSZ), N–S (CFFZ), and the E–W (affecting the Sangonetto and the Lower Susa valleys) fault systems.

A better knowledge in the spatial distribution of sectors with different seismotectonic and morphotectonic behaviour is of strategic value in a densely, populated area, such as the Lower Susa Valley. Here, besides town planning activities related to urban expansion, regional and international infrastructure is present along the valley bottom and slopes. Long tunnels are planned, which will cross rock units and fault zones characterized by poor geomechanical properties and possible relative movements.

In conclusion, in metamorphic chain areas characterized by low seismicity, the evidence of neotectonic activity is generally very poor. However, direct evidence of neotectonic activity is reported here. The integrated approach among different methodologies used in this work may constitute a valuable tool for the better understanding of the present tectonic regime affecting these areas.

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References

Alberto, W., Carraro, F., Giardino, M., Martinotti, G., Sassone, P., Tiranti, D., 2004. Segnalazione di sinkholes a vari stadi di evoluzione nelle Alpi occidentali. Atti 1 Seminario Nazionale "Stato dell'arte sullo studio dei fenomeni di sinkholes", L'Agenzia per la protezione dell'ambiente e per i servizi tecnici (APAT), Roma, pp. 37–52.

Ambrosetti, P., Bosi, C., Carraro, F., Ciaranfi, N., Panizza, M., Papani, G., Vezzani, L., Zanferrari, A., 1987. Neotectonic map of Italy; scale 1:500.000. Quaderni de La Ricerca. Scientifica 114 (4).

Balestrieri, M. L., Bigazzi, G., Cadoppi, P., Sacchi, R., 2004. Studio preliminare di alcuni campioni di ortoderivati provenienti dalla Val di Susa mediante il metodo delle tracce di fissione su apatite. In: Sacchi, R., Balestro, G., Cadoppi, P., Carraro, F., Delle Piane, L., Di Martino, L., Enrietti, M., Gallara', F., Gattiglio, M., Martinotti, G., Perello, P. (Eds.), Studi geologici in Val di Susa finalizzati ad un nuovo collegamento ferroviario Torino-Lione. Museo Regionale di Scienze Naturali (Torino), monografie, Vol. 41, pp. 103–115.

Bogdanoff, S., Michard, A., Mansour, M., Pouoeau, G., 2000. Apatite fission tracks analysis in the Argentera massif: evidence of contrasting denudation rates in the external crystalline massifs of the Western Alps. Terra Nova 12, 117–125.

Cadoppi, P., Tallone, S., 1992. Structural and lithostratigraphic heterogeneity of northern part of the Dora–Maira Massif (Western Alps). Atti Ticinensi di Scienze della Terra 35, 9–18.

Cadoppi, P., Riccio, I., Tallone, S., 1997. Revised tectonostratigraphic setting of the outer envelope of the Dora Maira Nappe (in the middle Susa Valley). Third Workshop on Alpine Geological Studies, Oropa-Biella, 29/9–1/10/97. Quaderni di Geodinamica Alpina e Quaternaria 4, 166.

Cadoppi, P., Castelletto, M., Sacchi, R., Baggio, P., Carraro, F., Giraud, V., 2002. Note illustrative della Carta Geologica d'Italia alla scala 1:50000. Foglio 154, Servizio Geologico d'Italia, Susa, 123pp.

Camassi, R , Stucchi, M., 1997. NT4.1.1, un catalogo parametrico di terremoti di area italiana al di sopra della soglia del danno. Gruppo Nazionale per la Difesa dai Terremoti (GNDT,) Milano, 95pp.

Carraro, F., 1987. Remodelling and reworking as causes of error in distinguishing between glacial and non-glacial deposits and landforms. Geological Survey of Finland Special Paper 3, 39–48.

Carraro, F., Dramis, F., Pieruccini, U., 1979. Large-scale landslides connected with neotectonic activity in the Alpine and Apennine ranges. In: Proceedings, 15th Meeting, Geomorphological Surveying and Mapping, Modena, Institute of Geology, University of Modena, pp. 213–230.

Carraro, F., Cadoppi, P., Baggio, P., Bellino, L., Castelletto, M., Giraud, V., Mensio, L., 2002. Foglio 154—Susa—Carta Geologica d'Italia, scala 1:50.000. Servizio Geologico d'Italia, Roma.

Carraro, F., Giardino, M., 2004. Quaternary glaciations in the western Italian Alps—a review. In: Ehlers, J., Gibbard, P.L. (Eds.), Quaternary Glaciations–Extent and Chronology, Part I. Europe. Elsevier, Amstedam, pp. 201–209.

Carraro, F., Forno, M.G., Giardino, M., Paro, L., 2005. Guidebook of the 14th meeting of the Association of European Geological Societies. Il Quaternario—Italian Journal of Quaternary Sciences 18-2, 3–55.

Casati, C., Giovacchini, A., 1977. L'utilizzo delle immagini Landsat per indagini di neotettonica. Bolletino di Geodesia e Scienze Affini 36, 399–410.

Castiglioni, B., 1940. Le Alpi nel glaciale. In: Atlante fisico—economico d'Italia. Milano.

Debelmas, J., 1986. Intracontinental subduction and mountain uplift: the example of Western Alps. Géologie Alpine 62, 1–10.

Dela Pierre, F., Mikhailov, V., Polino, R., 1995. The tectonosedimentary evolution of the tertiary basins in the Western Po plain: kinematics inferred from subsidence curves. In: Polino, R., Sacchi, R. (Eds.), Rapporti Alpi-Appennino e guide alle escursioni. Accademia Nazionale dei Lincei, Vol. 14, pp. 129–146.

Deline, P., Giardino, M., Nicoud, G., 2005. Le Quaternarie des vallees Alpines. Front glaciaires, mouvements de versants et comblements alluviaux dans les vallées de l'Arve, d'Aoste et de Suse. Collection EDYTEM—Cahiers de Géographie, Vo. 3, 195pp.

Ehlers, J., Gibbard, P., L., 2004. Quaternary Glaciations—Extent and Chronology. INQUA Special Pubblication, Amsterdam, Elsevier (Netherlands) 475pp.

Eva, E., Solarino, S., Eva, C., Neri, G., 1997. Stress tensor orientation derived from fault plane solution in the southwestern Alps. Journal of Geophysical Research 102, 8171–8185.

Eva, E., Solarino, S., 1998. Variation of stress directions in the western Alpine arc. Geophysical Journal International 135, 438–448.

Forno, M.G., Massazza, G., 1987. Movimenti gravitativi diffusi e ripetuti nel versante sinistro della Val Cenischia (Alpi Graie) e loro relazione con il sistema di fratture Cenischia-Nizza. Geografia Fisica e Dinamica Quaternaria 10, 277–306.

Giardino, M., Polino, R., 1997. Le deformazioni di versante nell'alta Valle di Susa: risposta pellicolare dell'evoluzione tettonica recente. Il Quaternario 10 (2), 31–38.

Giardino, M., Fioraso, G., 1999. Cartografia Geologica delle formazioni superficiali in aree di catena montuosa: il rilevamento del Foglio "Bardonecchia" nell'ambito del progetto CARG. Memorie di Scienze Geologiche 50, 133–153.

Hancock, P.L., 1985. Brittle microtectonics: principles and practice. Journal of Structural Geology 7, 437–457.

Hunziker, J.C., Martinotti, G., 1987. Geochronology and evolution of Western Alps: a review. Memorie della Società Geologica Italiana 29, 43–56.

Hunziker, J.C., Desmons, J., Hurford, A.J., 1992. Thirty-two years of geochronological work in the Central and Western Alps: a review on seven maps. Mémoires Géologique Lausanne 13, 1–59.

Malusà, M., 2004. Post-metamorphic evolution of the Western Alps: kinematics contraints from a multidisciplinary approach (geological mapping, mesostructural analysis, fission track dating, fluid inclusions analysis). Ph.D. thesis, University of Turin, Turin, Italy, 320pp.

Morelli, M., Piana, F., 2006. Comparison between remotely sensed lineaments and geological structures in intensively cultivated hills (Monferrato and Langhe domains, NW Italy). International Journal of Remote Sensing in press.

Mortara, G., Tropeano, D., 1978. Eventi di piena nei bacini dei rii Gerardo e Perilleux in Val di Susa (1972–1973). In: CNR-IRPI (1983). Eventi alluvionali e frane nell'Italia settentrionale, periodo 1972–1974, Bollettino della Associazione Mineraria Subalpina (Torino), raccolta, pp. 181–202.

Mortara, G., Sorzana, F., 1987. Fenomeni di deformazione gravitativa profonda nell'arco alpino occidentale italiano. Considerazioni lito-strutturali e morfologiche. Bolletino della Società Geologica Italiana 106, 303–314.

NACSN (North American Commission on Stratigraphic Nomenclature), 1983. North American Stratigraphic code. American Association of Petroleum Geologists Bulletin, 67, 841–875.

Perello, P., Delle Piane, L., Piana, F., Morelli, M., Damiano, A., Venturini, G., Bianchi, G. W., Spanò, M., Cadoppi, P., Gattiglio, M., Tallone, S., 2004. New constraints on late to post-Oligocene deformation history of the Western Alps: data from middle Susa valley and High Maurienne valley. Abstract, 32° International Geological Congress, Florence, p. 247.

Perrone, G., Cadoppi, P., Morelli, M., Tallone, S., Eva, E., Solarino, S., 2005. Relationships between fault network and seismicity in the internal sector of the Cottian Alps (italian western Alps). Geophysical Research Abstracts 7, 3211, European Geological Union 05, Vienna (AU), 24–29/4/2005.

Perrone, G., 2006. Evoluzione tettonica post-metamorfica e recente del Distretto Sismico del Pinerolese. Ph.D. thesis, University of Turin, Turin, Italy, 205pp.

Polino, R., Dal Piaz, G.V., Gosso, G., 1990. Tectonic erosion at the Adria margin and accretionary processes for the Cretaceous orogeny of the Alps. Mémoires, Societe Géologique France 156, 345–367.

Polino, R., Dela Pierre, F., Fioraso, G., Giardino, M., Gattiglio, M., 2002. Foglio 132–152–153—Bardonecchia–Carta Geologica d'Italia, scala 1:50.000. Servizio Geologico d'Italia.

Puma, F., Ramasco, M., Stoppa, T., Susella, G., 1989. Movimenti di massa nelle alti valli di Susa e Chisone. Bolletino della Società Geologica Italiana 108, 391–399.

Sacco, F., 1888. I terreni terziari e quaternari del Biellese. C.A.I. Torino, Sezione Biellese, 16, Guadagnini, Condellero, Torino.

Tallone, S., Cadoppi, P., Balestro, G., Delle Piane, L., Perello, P., Riccio, I., 2002. Ductile-to-brittle tectonic evolution at the structural knot between the lower and middle Susa Valley (province of Turin). In: Cinematiche collisionale: tra esumazione e sedimentazione- Riassunti dell'81a Riunione estiva della Società Geologica Italiana, Torino 10–12 Settembre 2002, pp. 310–311.

Varnes, D. J., Radbruch-Hall, D., Savage, W. Z., 1989. Topographic and structural conditions in area of gravitational spreading ridges in the Western United States. Unites States Geological Survey Professional Paper 1496, Washington, pp. 1–28.

Wells, D.L., Coppersmith, K.J., 1994. New empirical relationships among magnitude, rupture length, rupture width, rupture area and surface displacement. Bulletin, Seismological Society of America 84, 974–1002.

Zaruba, Q., Mencl, V., 1969. Landslides and their control. Elsevier, Amsterdam, Academia-Praha, 1969.

Zischinsky, U., 1969. Uber Bergzerreißung und Talzuschub. Geologische Rundschau 58 (3), 974–983.