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The effects of late Alpine tectonics in the morphology of the Argentera Massif (Western Alps, Italy–France)

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Abstract

Several swath profiles, drainage morphometric parameters, slope and drainage density maps were obtained by DTM analysis of the Argentera Massif (Western Alps). The spatial distribution of the analysed parameters indicates that the central-southern sector is characterized by orographic and drainage characteristics very different from the rest of the Massif. Two main systems of NW- and WNW-trending faults, the Orgials Fault and Valletta Fault, bound this area. Both faults belong to large-scale fault zones: the dextral strike-slip Bersezio Fault and the south-facing Colle del Sabbione thrust. The orientations and kinematics of both faults indicate a late Alpine (Pliocene to recent) SW-verging thrusting coupled with a dextral strike-slip movement. The central-southern sector of the Massif corresponds to the hanging wall of a SW-verging late Alpine thrust zone, and underwent the highest post Pliocene tectonic uplift in the Argentera Massif. The uplift occurred in a transpressive setting with an N–S shortening direction, which is consistent with the post-Pliocene tectonics in the southern portion of the Western Alps.

1. Introduction

The Cenozoic uplift and exhumation of the Argentera Massif is due to both active tectonics and isostatic release, which characterized the late Alpine (Pliocene to recent) evolution of the Western Alps chain (Debelmas, 1986). The exhumation history of the Argentera Massif, reconstructed for the last 8 Ma on the basis of apatite and zircon fission tracks, is characterized by mean denudation rates of 0.25 mm yr^{-1} in the late Miocene–Pliocene (8–3 Ma) and 0.8–1 mm yr^{-1} for the Pliocene–present (3–0 Ma) (Bigot-Cormier et al., 2000; Bogdanoff et al., 2000).

In the Argentera Massif, the denudation processes mostly correspond to the glacier and fluvial erosion (Federici et al., 2001a; Julian, 1980), which, since the late Miocene, have affected the Variscan basement (Iaworsky and Curti, 1960). However, even though these processes involved the whole Massif, there is a big difference in the landscape between the Italian and the French sides, northeast and southwest of the main watershed, respectively. Deeply incised steep slopes on the Italian side strongly contrast with the smoother landscape of the French side. These regional morphologic differences (Ribolini, 2000) and the fission track thermochronology (Bigot-Cormier et al., 2000) indicate a spatial variation in the late Alpine exhumation processes throughout the Massif. It is likely that this is related to differential vertical motions of the crystalline blocks within the Massif.

The aim of this work is to investigate, through integrated geomorphic and structural analysis, the relationships between topography and active tectonics in the Argentera Massif. A long wavelength geomorphic analysis was carried out using a 50 m digital elevation model (DEM). Five serial swath profiles, nearly perpendicular to the Alpine structures, were traced in order to analyse: (i) the maximum, minimum and mean elevation; (ii) the local relief; and (iii) the depth of landscape incision. The drainage network, automatically extracted by the DEM, was processed to obtain a drainage density map and several geomorphic related parameters. In key areas, a structural analysis was performed in order to investigate the main tectonic structures responsible for the recent vertical movements. A model which explains the Pliocene to the recent morphotectonic evolution of the Argentera Massif is presented.

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2. Geomorphological and geological outline

The Argentera Massif is the southernmost part of the External Crystalline Massif in the Western Alps (Fig. 1), with the Italy–France border running along the main watershed. In this Massif, where the maximum elevations exceed 3000 m a.s.l., the landscape is the product of glacial, periglacial, hillslope and fluvial processes. The valleys were deeply shaped by Quaternary glaciers that abandoned large frontal and lateral moraines from 700 to 2600 m a.s.l. (Federici and Pappalardo, 1991). Six small glaciers are still present in the area and the present-day Equilibrium Line Altitude has been estimated at about 2800 m a.s.l. (Federici et al., 2001b; Pappalardo and Rapetti, 2001). The Argentera Massif is drained by four main rivers, the Gesso and the Vesubie rivers in the south, and the Stura di Demonte and the Tinèe rivers in the north.

From a geological point of view, the Argentera Massif corresponds to a wide outcrop of the European Variscan basement in the outer Delfinese Zone (Fig. 1). The basement consists of high-grade metamorphic and intrusive rocks, the latter of late Carboniferous (290 Ma) age (Ferrara and Malaroda, 1969), unconformably covered by a marine sedimentary succession of late Carboniferous–Cenozoic age, partly detached at the level of the Triassic evaporites (Malaroda et al., 1970). The area analysed in this paper only includes the crystalline basement outcrops and consequently can be considered uniform from a lithological point of view.

The main tectonic lineaments in the basement are the NW-trending Ferriere-Molliéres Line and the WNW-trending Fremamorta-Colle del Sabbione Line. Both represent late Variscan shear zones characterized by steeply dipping mylonitic rocks. The Alpine tectonic history of the Variscan basement and marine sedimentary cover is characterized by two deformational phases (Bogdanoff, 1986). The D_1 phase (Oligocene) led to fold and thrust development, the latter being responsible for the cover detachment at the level of the Triassic evaporites level. During the D_2 phase (Upper Miocene–Pliocene), some slices of basement were thrust over the overlying cover. These structures correspond to the Tortisse, Sespoul, and Colle del Sabbione thrust zones (Fig. 1). Coeval reverse and strike-slip fault systems (e.g. Bersezio Fault; Fig. 1; Labaume et al., 1989), reactivated the older Variscan tectonic lines with the development of cataclastic rocks along narrow bands nearly parallel to the late Variscan mylonites. Most of these structures were activated at different times along the same tectonic lines with SW vergent and right lateral

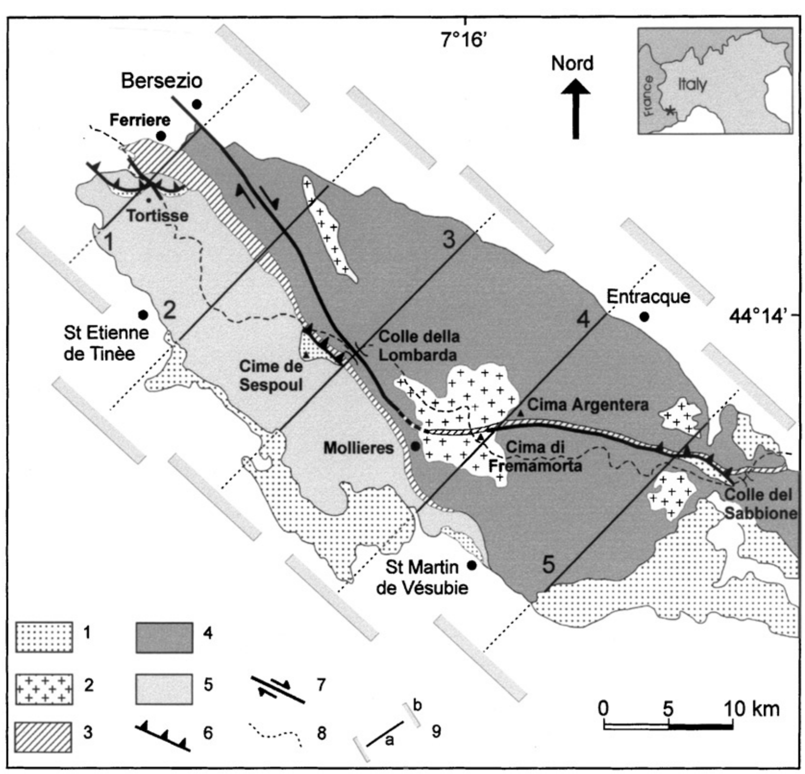


Fig. 1. Geological sketch map of the Argentera Massif (simplified from Bogdanoff et al., 2000). (1) Permian–Triassic sedimentary cover; (2) Malinvern Granite; (3) late Variscan mylonites; (4) Malinvern Complex; (5) Tinèe Complex; (6) Alpine thrust; (7) Alpine strike-slip fault; (8) Italy France border; (9) Trace (a) and computing area (b) of swath profile.

compressive movements (Bogdanoff, 1986; Labaume et al., 1989).

According to Frechet (1978), this sector of the western Alps was characterized by a NE–SW shortening direction in the Oligocene–Miocene, which turns to a NS direction in the Upper Miocene–Pliocene. Recently, Madeddu et al. (1996), on the basis of seismotectonic and microstructural data, stated that active tectonics in the southern portion of the Western Alps is dominated by N–S and NE–SW shortening directions. Within this context the Argentera Massif has been interpreted as a *pop-up* structure in a compressional NE–SW late Neogenic tectonics (Fry, 1989).

3. Orographic features

3.1. Swath profiles

Five swath profiles, following the Burbank (1992) and Fielding et al. (1994) methods, were traced transversally to the current axis of the Massif (Fig. 1), in order to provide a quantitative assessment of the morphological differences between the Italian and the French sides of the Argentera Massif. The swath profiles, between 24 and 35 km long, were first drawn on the DEM. Along each profile, five parameters were automatically calculated every 1 km and were averaged on a surrounding area ($8 \times 1\,km^2$) using specific GIS functions. The computing area ($8\,km^2$) was chosen to be large enough to avoid problems related to the influence of different river orientations within the two sides of the Massif, always averaging more than just one valley. The parameters taken into account are: (i) minimum, mean and maximum elevation ($E_{min}, E_{mean}, E_{max}$); (ii) local relief ($r = E_{max} - E_{min}$); and (iii) depth of landscape incision ($d = E_{max} - E_{mean}$) (Fig. 2).

In profiles 1 and 2 (Fig. 2), the different extension of the crystalline basement makes comparison between the opposite sides of the chain difficult. Nevertheless, considering the first 5 km NE and SW far from the chain axis, the general trend is asymmetric and the elevation parameters ($E_{max}, E_{mean}, E_{min}$) are higher on the Italian side (NE) than on the French side (SW). Even though in the northernmost swath profile (profile 1) the asymmetry is less evident (Fig. 2), the Italian side is still characterized by a higher altitudinal landscape than the French one.

Profiles 3–5 show a relatively common trend of the different analysed parameters. In these profiles, the Italian side is characterized by mean elevation and r values usually higher than those of the French side. E_{mean} and r relative maximums are located on the Italian side, at a distance of 4–8 km from the main watershed, in correspondence of the Gesso Valley and

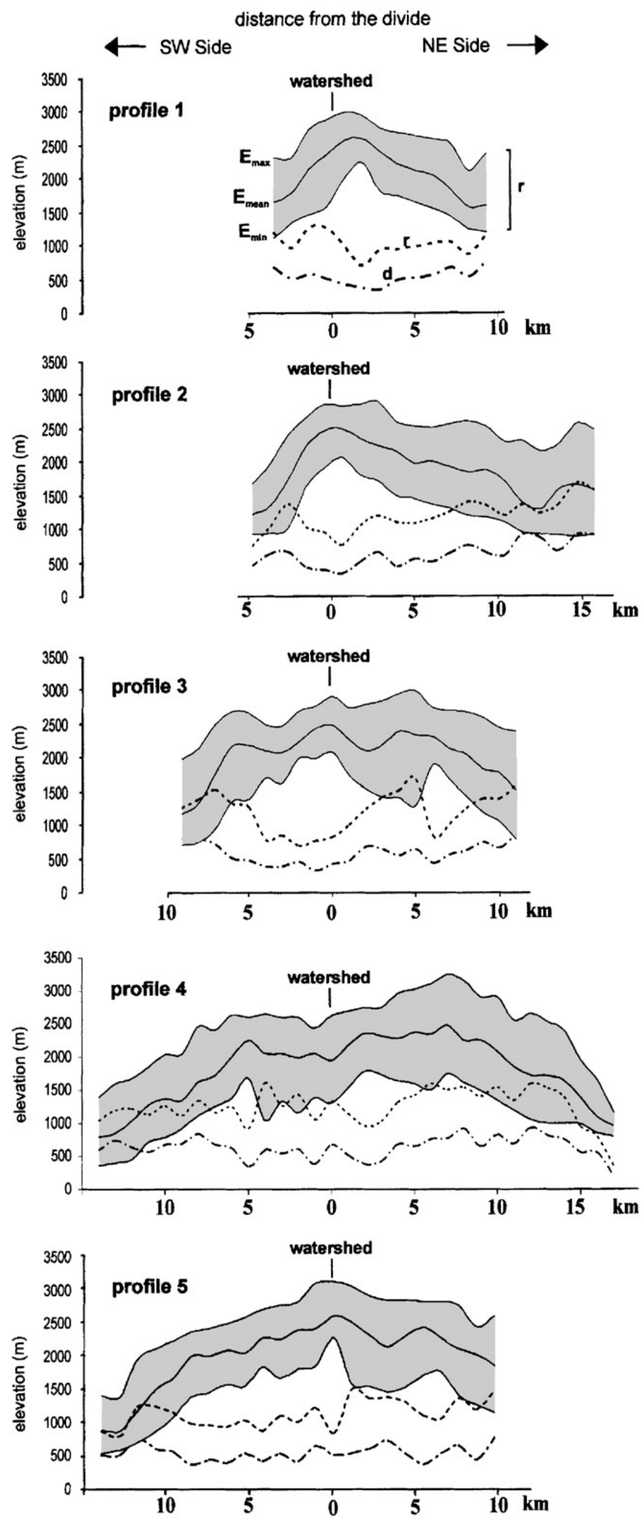


Fig. 2. Swath profiles showing E_{min}, E_{mean}, E_{max}, r and d. Location in Fig. 1.

Vallone d'Orgials-Colle della Lombarda sector. Moreover, low d values are characteristic of the French side, while the maximum values are reached again on the Italian side at a distance of 6–8 km from the main watershed.

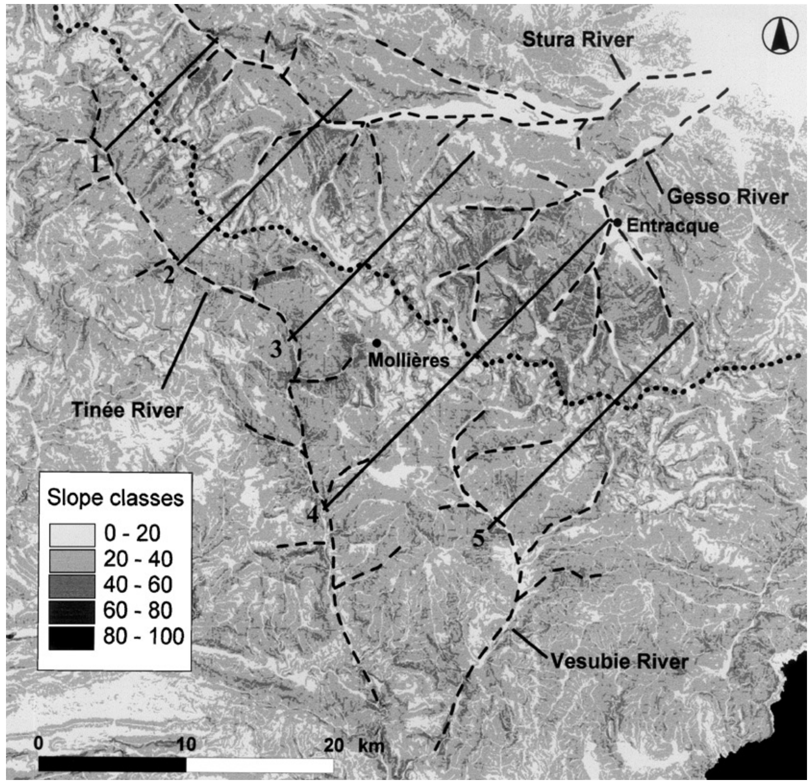


Fig. 3. Slope map (values in degrees). Dotted line: Italy–France border, dashed line: main river, solid line: trace of swath profile.

3.2. Slope map

The DEM was processed in order to obtain a slope map of the area (Fig. 3). The analysis was carried out at a 50 m resolution. Similar to the swath profiles, the slope map clearly shows an evident difference between the Italian and French sides, especially in the southern portion of the Massif. Steep slopes (mean value 31°, max 70°, high frequency of the highest slope classes) deeply incised by water channels characterize the Italian side, while the French side is shaped more regularly with gentle and smooth slopes (mean 28°, max 65°, high frequency of the middle slope classes). In particular, the Gesso Basin has a mean slope of 30° with a maximum slope of 71° and a very high frequency of the highest slope classes (dark tones in Fig. 3).

4. Morphometric properties of the Italian side drainage network

Due to the different orographic assessment, we focused on the drainage density and morphometry of the Italian side of the Massif.

4.1. Drainage density

The drainage density was automatically extracted from the DEM of the area (Fig. 4). First, the flow directions and accumulated area matrixes were calculated in order to obtain a new grid with cell values correspondent to the upstream drainage area. Following the most common method (Mark and O'Callaghan, 1984) of identifying channels on a DEM as all points with a certain upstream contributing area above them ("flow-accumulation" or "contributing-area" method), four different contributing area thresholds (20–25–30–35 pixels, correspondent to 0.05–0.0625–0.075–0.0875 km^2) were tested. For a sub-sample area the networks obtained from the DEM were compared with the one drawn on high-resolution topographic maps. Even though some errors were encountered in the low gradient areas (eventually removed), the network obtained from the DEM with a 25-pixels threshold (0.0625 km^2 of minimum accumulated flow area) was found as the closest approximation to the topographic one. Once the drainage network had been derived, specific GIS functions allowed the automatic evaluation of the drainage density for a unit cell of defined area (1 km^2). The result was expressed by a drainage density grid map (Fig. 4), where the attribute value of each cell is the cumulative length of the channels within the cell (km) divided by the area of the cell itself (km^2).

The drainage density varies from 0.5 to 6.5 km/km^2, with low values along the main river stems, especially in the upper Tinèe valley (French side). A high value of drainage density ($>4.5\,km/km^2$) belt, roughly parallel to the main watershed divide, can be observed on the

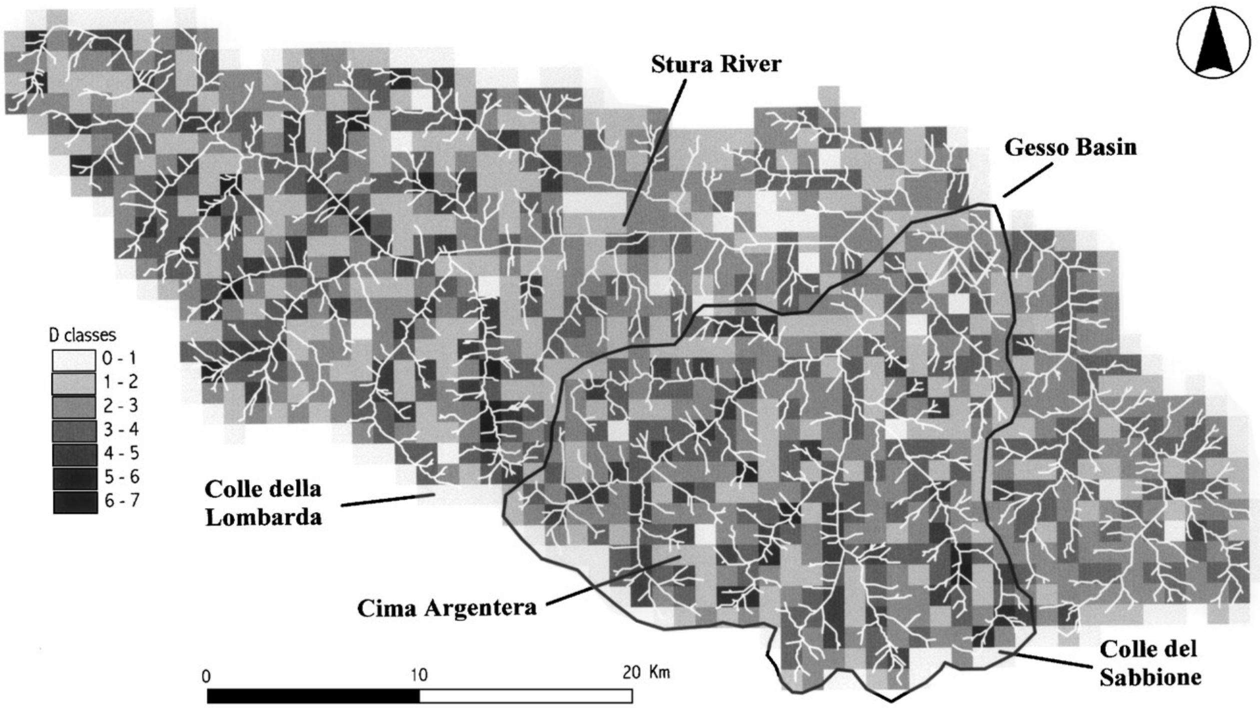


Fig. 4. Drainage density map of the Italian side (values in km/km^2).

Table 1
Comparison of the morphometric indexes

Channel gradient (%)	1st order	2nd order	3rd order	4th order	5th order	6th order	7th order
(a) *Morphometric indexes of the whole Italian side*							
Min	0	0	0	0	2	2	1
Max	144	100	67	46	14	7	2
Mean	46	37	27	13	7	4	2
(b) *Morphometric indexes of the Gesso basin*							
Min	0	0	0	0	5		
Max	44	94	67	46	14		
Mean	53	45	34	13	9		

Italian side, with the highest values corresponding to the head valleys of the Gesso Basin (Fig. 4). This belt of higher drainage density is spatially coherent with the maximum values of the $E_{\max}, d$ and r, as shown in the swath profiles 3–5 (Fig. 2).

4.2. Stream order analysis

Specific morphometric parameters of the drainage network, generally investigated in active tectonic areas, were evaluated (Tables 1 and 2). The drainage network was first ordered following the Horton–Strahler method. Specific GIS functions were used to evaluate the channel gradients (Table 2), the bifurcation ratio R_b (Strahler, 1957), the direct bifurcation ratio R_{bd}, the bifurcation index R (Avena et al., 1967), being $R_b = N_u/N_{u+1}$, $R_{bd} = N_{du}/(N_{u+1})$ and $R = R_b - R_{bd}$ (where N = number of channels, u = order and N_{du} = number of streams of order u that flow directly into streams of order $u+1$) (Table 1). According to Avena et al. (1967), the hierarchical organization is better highlighted by the bifurcation index more than any other parameters, weighting both the bifurcation and direct bifurcation ratios. In particular, the morphometric parameters referred to the I–III order streams are very useful in order to find areas with different tectonic activity by comparing the spatial variation of their values.

The parameters referring to the Gesso Basin (Table 2) were extracted and compared to those of the whole study area. The Gesso Basin channel gradients show mean values higher than those for the whole area, with the highest difference in the second order (45 vs. 37).

Also, the other morphometric parameters of the basin are generally higher that those of the whole area, especially the bifurcation index.

5. Structural analysis

Mesoscopic scale structural analysis was performed within the Vallone D'Orgials-Colle della Lombarda and Valle della Valletta areas in the central and southern sectors of the Argentera Massif, respectively, corresponding to the swath profiles 3 and 4. In both areas, selected on the basis of their geomorphic parameters, two fault zones, named Orgials Fault and Valletta Fault, were recognized in the field. These faults, cross-cutting the Variscan metamorphic and intrusive rocks, are nearly parallel or make a low angle with both metamorphic and mylonitic structures in the Variscan basement.

Table 2
Comparison of the channel gradients

u	N	R_b	N_d	R_{bd}	$R(R_b - R_{bd})$
(a) *Channel gradients of the whole Italian side*					
I	**3649**		**1859**		
		4.16		**2.12**	**2.039**
II	**878**		**593**		
		3.55		**2.40**	**1.154**
III	**247**		**150**		
		4.41		2.68	1.732
IV	56		29		
		4.31		2.23	2.077
V	13		13		
		3.25		3.25	0
VI	4		5		
		2		2	0
VII	2				
(b) *Channel gradients of the Gesso basin*					
I	**1164**		**528**		
		4.56		**2.07**	**2.49**
II	**255**		**142**		
		4.11		**2.29**	**1.82**
III	**62**		**13**		
		3.65		0.76	2.88
IV	17		4		
		4.25		1	3.25
V	4				

5.1. *Orgials Fault*

Along the northeastern flank of the Vallone d'Orgials, a narrow band of intensely faulted and fractured rocks at a height of 2250 m a.s.l. defines the Orgials Fault. On the surface, this fault corresponds to a series of parallel NW-trending morphologic culminations that terminate at the Colle della Lombarda (Fig. 5). Other minor systems of steeply dipping faults also occur along the eastern flank of the valley at an elevation lower than 2150 m a.s.l. (Fig. 5).

The fault planes strike NW–SE and moderately to steeply dip towards NE (Figs. 6a and 7a). Slickenside striae on the fault planes plunge toward NE or NW. The former correspond to down-dip lineations while the latter are moderately to gently plunging oblique lineations (Fig. 7a). The attitude of slickenside lineations and the kinematic indicators are consistent with a top to southwest reverse movement on the fault planes with a minor right lateral slip component. Some centimeter wide brittle shear bands, with cataclastic deformation locally occur in association with fault planes in the Colle della Lombarda area. These structures show S–C fabric

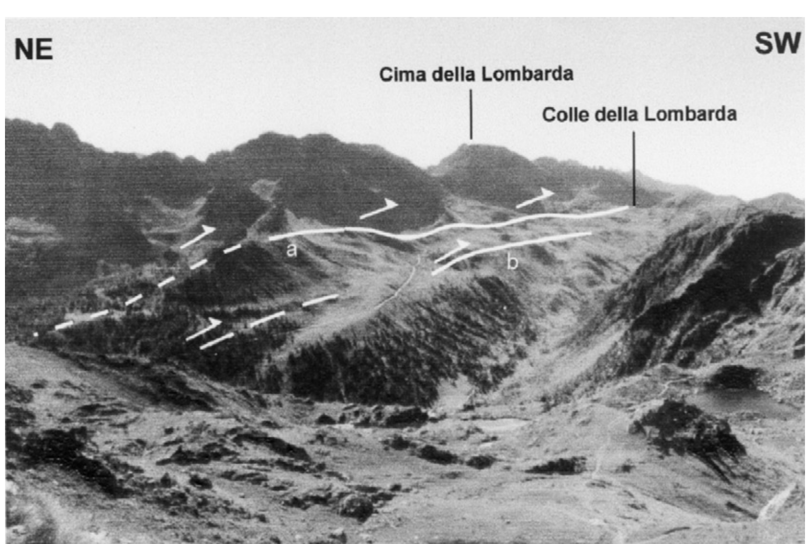
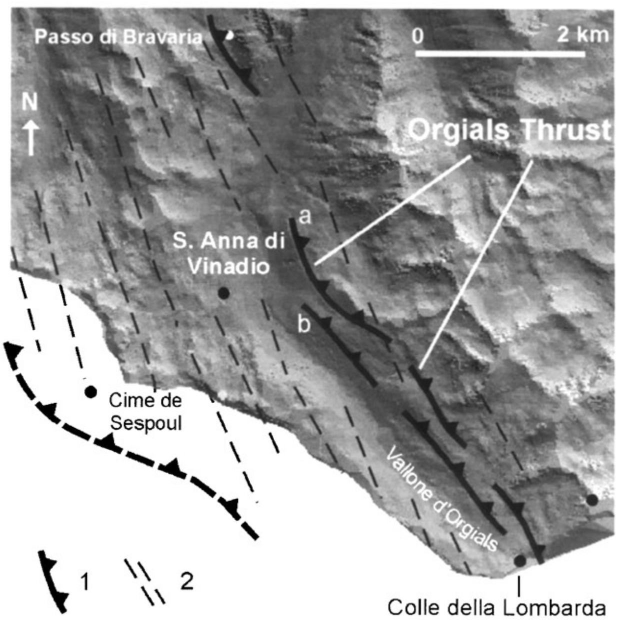
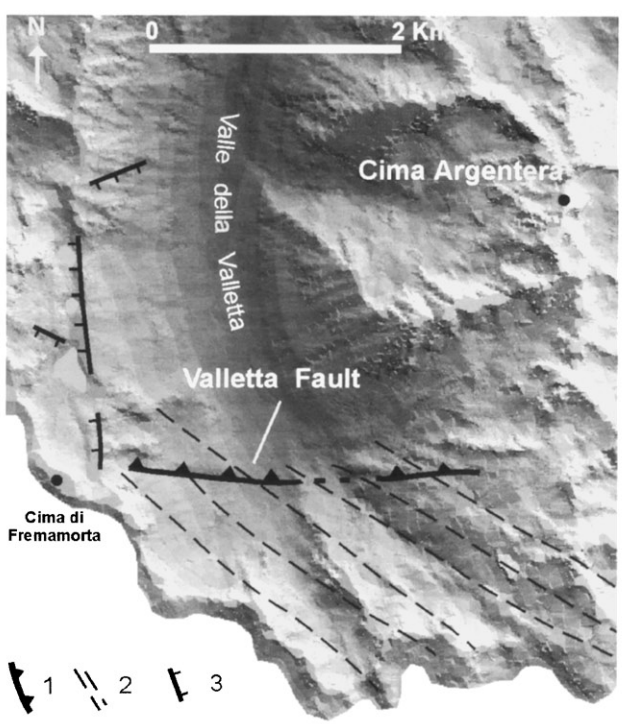


Fig. 5. Panoramic view of Orgials Fault in the Valle d'Orgials–Colle della Lombarda area; (a) main fault; (b) minor fault.

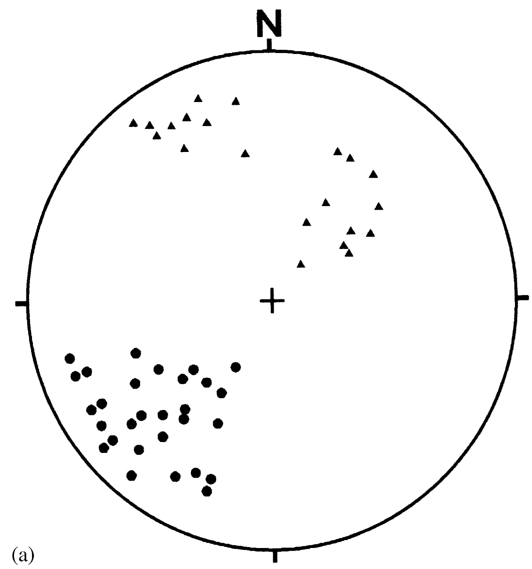


(a)

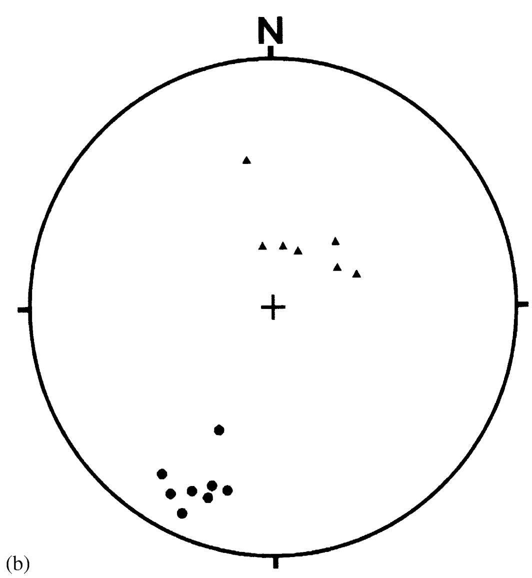


(b)

Fig. 6. Structural sketch map of (a) Vallone d'Orgials-Colle della Lombarda sector, (b) Valle della Valletta sector. (1) Alpine thrust; (2) mean trend of Variscan foliation; (3) Alpine normal fault.



(a)



(b)

Fig. 7. Stereographic projections (Schmidt net, lower hemisphere) of fault plane poles (filled circle) and slickenside lineations (filled triangles). (a) Orgials Fault, (b) Valletta Fault.

(Lister and Snoke, 1984) in which shear planes correspond to thin (a few millimeters) cataclastic layers (Fig. 8a). Shear sense indicators as S–C angular relationships and imbricate tiling of clasts (mostly feldspars), coupled with oblique slickenside striae on the shear planes, indicate an oblique top to the southwest movement with a component of right lateral slip. Minor fracture systems and open joints striking NE–SW and moderately to steeply dipping toward SE or NW are associated with the faults. The Orgials Fault is parallel to the Sespoul thrust cropping out immediately at westward of the Ferriere–Molliéres Line, along which basement rocks are thrusted onto the Triassic sedimentary cover (Fig. 6a).

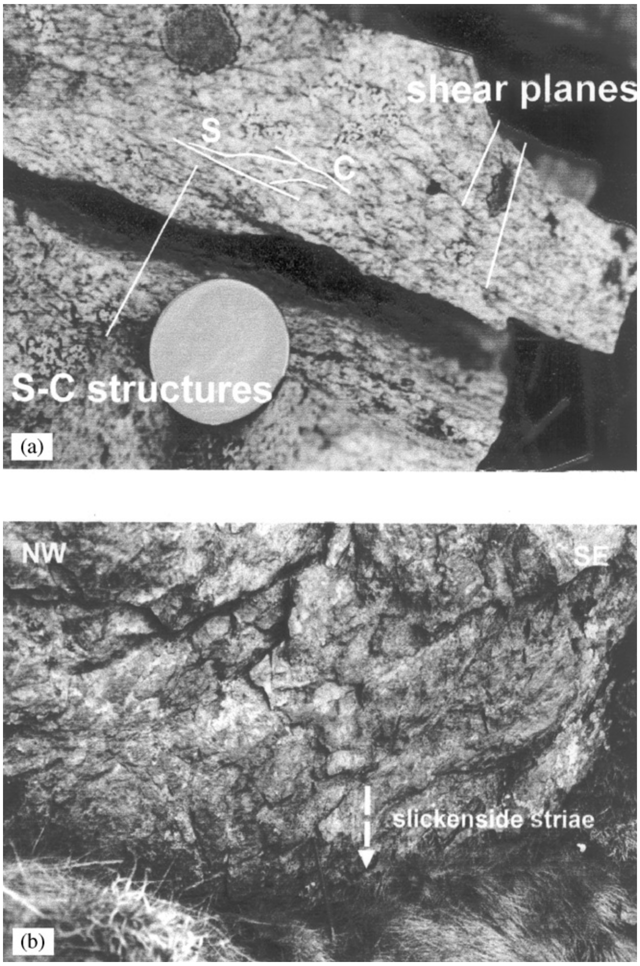


Fig. 8. (a) Brittle shear zone in granitic rocks with S–C texture associated with reverse fault (Colle della Lombarda); (b) reverse fault in granitic rocks with down-dip slickenside striae on the fault plane. Sense of movement top to SW.

5.2. Valletta Fault

Along the Valle della Valletta to the east of Cima di Fremamorta, a system of WNW-trending fault planes steeply dipping towards NE (Figs. 6b and 7b) corresponds to the Valletta Fault. On the fault planes, cross-cutting high-grade paragneiss and late Carboniferous intrusive rocks, down-dip slickenside striae plunge steeply towards NE (Figs. 7b and 8b) and the shear sense indicators are consistent with a reverse top to south sense of movement. Moreover, within the fault zone some centimeter wide brittle–ductile shear bands also occur with cataclastic and mylonitic deformation. These structures, parallel to the fault planes, strike WNW–ESE and dip steeply toward NNE. Down-dip to oblique slickenside striae on the shear planes indicate top to the south reverse movement with dextral lateral slip.

The geometric and kinematic features indicate that both these fault zones belong to the late Alpine fault system which cross-cut the basement of the Argentera massif. Indeed, the Orgials Fault lies on the southern prolongation of the late Miocene–Pliocene dextral strike-slip Bersezio Fault, (Horrenberger et al., 1978; Labaume et al., 1989). The Valetta Fault lies on the western prosecution of the late Miocene Colle del Sabbione south-facing thrust, along which Triassic rocks are tectonically pinched between basement rocks (Malaroda, 1974).

6. Discussion

In active orogenic belts the prevalence of linear erosion over areal erosion causes high values of local relief, slope angles and drainage density, features diagnostic of areas subjected to uplift processes (Gilchrist et al., 1994; Burbank et al., 1996; Centamore et al., 1996). In the Argentera Massif, the regional orographic properties highlight that the watershed separates an eastern region (Italian side) generally characterized by slope, local relief and E_{mean} values higher than those recognized in the western region (French side). Moreover, at the scale of the whole massif, (i) the spatial distribution of the drainage density, (ii) the local relief maximums and (iii) the summit culmination alignments (E_{max}), allow us to identify an area in correspondence to the Vallone d'Orgials-Colle della Lombarda sectors and the Gesso River Basin with orographic characteristics very different from the rest of the Massif. This wide area (central-southern portion of the Massif) is bounded on the western and southern side by the Orgials Fault and Valletta Fault. As shown in Figs. 9 and 10, the alignment of these fault zones defines a large-scale SW-vergent thrust zone, whose southeastern termination corresponds to the Colle del Sabbione Thrust. The dominant high angle reverse movement coupled with a dextral strike-slip shear along the Orgials Fault (Fig. 9a), indicates that the thrust zone developed in a transpressive tectonic setting, with the NNE–SSW mean shortening direction (Fig. 10). The hanging wall of the thrust zone corresponds to the Vallone d'Orgials-Colle della Lombarda and the Gesso River Basin sectors, east of the chain axis (Fig. 9); the footwall, with a smoother and gentler landscape, is located west of the chain axis. This reconstruction is consistent with the late Alpine compressional tectonics in the southern Western Alps (Fry, 1989), where earthquake focal solutions indicate a present-day NE–SW shortening direction for the Argentera Massif (Madeddu et al., 1996).

Therefore, on the basis of the above reported geomorphic and structural data, we suggest that Pliocene to recent active tectonics led to a higher degree of uplift in the central-southern section with respect to the other portions of the Argentera Massif. This is shown in Fig. 10, where this zone of highest uplift (large

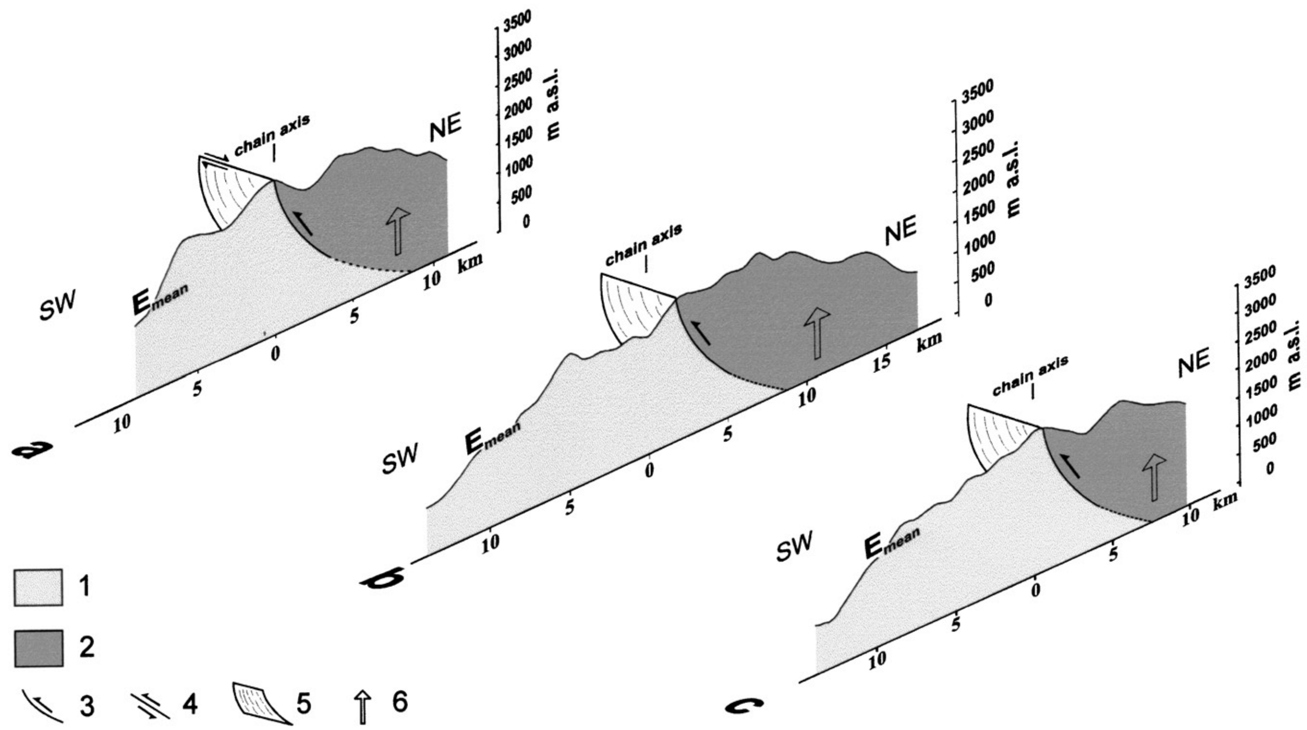


Fig. 9. Relationships between orographic trends (E_{mean} values) and the location of the late Alpine thrust faults. (a) Orgials sector (profile 3 in Fig. 1); (b) Valletta sector (profile 4 in Fig. 1); (c) Colle del Sabbione area (profile 5 in Fig. 1). (1) Tinèe Complex; (2) Malinvern Complex; (3) reverse fault; (4) strike-slip fault; (5) fault surface; (6) uplifted block.

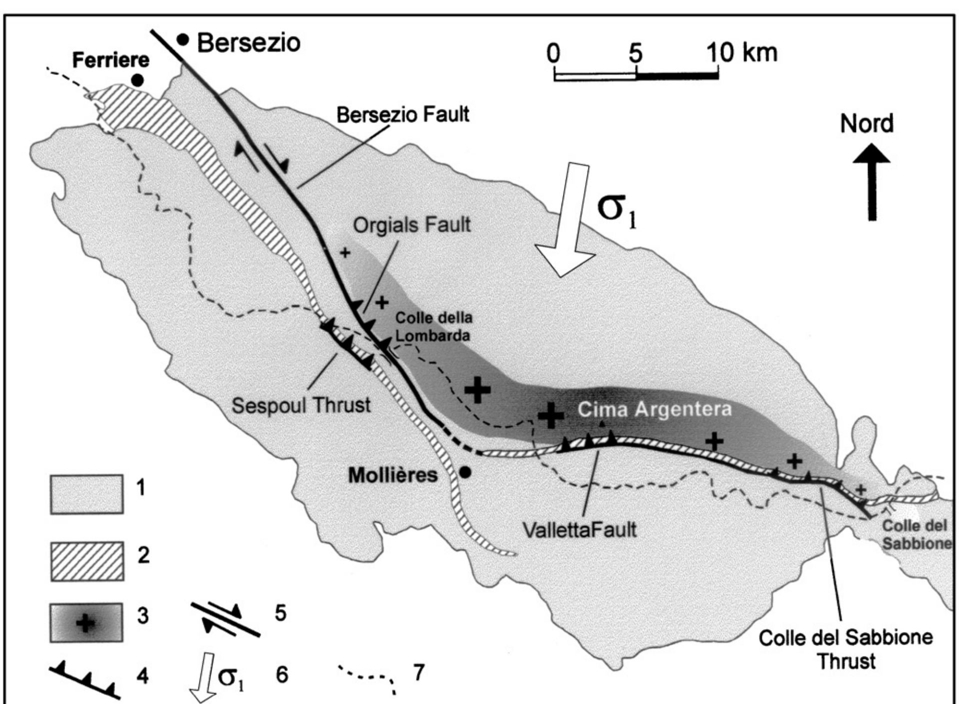


Fig. 10. Schematic reconstruction of the area affected by the highest degree of uplift in the Argentera Massif. (1) Basement; (2) late Variscan mylonites; (3) area of intense uplift (large cross corresponds to zones of highest culmination); (4) late Alpine thrust; (5) late Alpine fault; (6) main shortening direction; (7) Massif watershed and Italy France border.

crosses in the shaded area) lies immediately east of both the Orgials and Valletta Faults. This scenario is in good agreement with the recognized differential vertical motions of blocks within the Argentera Massif, evidenced by apatite fission track analysis (Bigot-Cormier et al., 2000). Moreover, Pliocene to recent denudation rate of 0.8–1 mm yr^{-1} for the central Argentera (Bogdanoff et al., 2000), matches well with the suggested tectonic uplift of this area as consequence of southwestward thrusting along Orgials and Valetta Faults.

7. Conclusions

In the southern portion of the Western Alps, late Alpine active tectonics affected the Argentera Massif landscape. Geomorphic analysis shows the presence of an area (Vallone d'Orgials-Colle della Lombarda sectors and the Gesso River Basin) with orographic and drainage characteristics that can be considered anomalous with respect to the other sectors of the Massif. As the lithology and the climate can be considered uniform, differentiated denudation processes can be identified as a tectonic signal in the long-term development of the landscape. The morphometric parameters specifically connected to active tectonics indicate that the central-southern part of the Massif underwent the maximum tectonic uplift with respect to the other sectors. The structural data make it possible to define this area of orographic and drainage anomalies, east of the chain axis, as the hanging wall of a thrust zone, constituted by the Orgials and Valletta Faults. This thrust zone developed in a transpressive regime consistent with the post-Pliocene tectonic evolution of the southern Western Alps. Therefore, combining geomorphic and structural results it can be argued that: (i) late Alpine tectonics is a forcing factor in the distribution of surface processes and (ii) different landscape development is consistent with an active tectonics and differentiated uplift processes within the Argentera Massif.

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References

Avena, G.C., Giuliano, G., Lupia Palmieri, E., 1967. Sulla valutazione quantitativa della gerarchizzazione ed evoluzione dei reticoli fluviali. Bollettino Società Geologica Italiana 86, 729–737.

Bigot-Cormier, F., Poupeau, G., Sosson, M., 2000. Dénudation différentielles du massif cristallin externe alpin de l'Argentera (Sud-Est de la France) révélés par thermochronologie traces de fission (apatites, zircons). Compte Rendu Académie Science Paris 330, 363–370.

Bogdanoff, S., 1986. Evolution de la partie occidentale du Massif Cristallin Externe de l'Argentera. Place dans l'arc alpin. Géologie de la France 4, 433–453.

Bogdanoff, S., Michard, A., Mansour, M., Poupeau, 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.

Burbank, D.W., 1992. Causes of recent Himalayan uplift deduced from deposited patterns in the Ganges basin. Nature 357, 680–682.

Burbank, D.W., Leland, J., Fielding, E., Anderson, R.S., Brozovic, N., Reid, M.R., Duncan, C., 1996. Bedrock incision, rock uplift and threshold hillslopes in the northwestern Himalayas. Nature 379, 505–510.

Centamore, E., Ciccacci, S., Del Monte, M., Fredi, P., Lupia Palmieri, E., 1996. Morphological and structural arrangement of north-eastern Abruzzo (Central Italy). Geomorphology 16, 127–137.

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

Federici, P.R., Pappalardo, M., 1991. Nota introduttiva alla morfologia glaciale della Valle del Gesso di Entracque (Gruppo dell'Argentera, Alpi Marittime). In: Gruppo Nazionale Geografia Fisica e Geomorfologia, Guida all'escursione primaverile 28–31 Maggio 1991, Cuneo, 55pp.

Federici, P.R., Pappalardo, M., Ribolini, A., 2001a. The Geomorphological Map of Argentera Massif, Western Alps, Italy. Proceedings of the Vth International Congress on Geomorphology, September 2001, Tokyo, Japan.

Federici, P.R., Pappalardo, M., Ribolini, A., 2001b. On the equilibrium line altitude and lower discontinuous permafrost boundary in the Maritime Alps (Italian side). Accademia Scienze Torino, Atti Scienze Fisiche 134, 23–29.

Ferrara, G., Malaroda, R., 1969. Radiometric age of granitic rocks from the Argentera Massif (Maritime Alps). Bollettino Società Geologica Italiana 88, 311–320.

Fielding, E., Isack, B., Barazangi, M., Duncan, C., 1994. How flat is Tibet? Geology 22, 163–167.

Frechet, J., 1978. Sismicité du SE de la France et une nouvelle méthode de zonage sismique. Thèse de Doctorat, Université Grenoble, 159pp.

Fry, N., 1989. Southwestward thrusting and tectonics of the western Alps. In: Coward, M.P., Dietrich, D., Park, R.G. (Eds.), Alpine Tectonics. Geological Society of London, Special Publication, Vol. 45, pp. 83–109.

Gilchrist, A.R., Summerfield, M.A., Cockburn, H.A.P., 1994. Landscape dissection, isostatic uplift, and the morphological development of orogens. Geology 22, 963–966.

Horrenberger, J.C., Michard, A., Werner, P., 1978. Le couloir de décrochement de Bersezio en Haute Stura, Alpes Externe, Italie, Structure de compression subméridienne. Science Géologique Bulletin 31, 15–20.

Iaworsky, G., Curti, M., 1960. La faune des poudingues de Roquebrune (Alpes maritimes). Compte Rendu Académie Science Paris 250, 399–400.

Julian, M., 1980. Les Alpes Maritimes Franco-Italiennes. Etude géomorphologique. Thèse de Doctorat d'Etat, édit Librairie Honoré Champion, Vol. 2, Paris, 833pp.

Labaume, P., Ritz, J.F., Philip, H., 1989. Failles normales récentes dans les Alpes sud-occidentales: leurs relations avec la tectonique compressive. Compte Rendu Académie Science Paris 308, 1553–1560.

Lister, G.S., Snoke, A.W., 1984. S–C mylonites. Journal of Structural Geology 3, 617–638.

Madeddu, B., Bértoux, N., Stéphan, J.F., 1996. Champ de contrainte post-pliocène et déformation récentes dans les Alpes sud-occidentales. Bulletin Société Géologique France 8, 797–810.

Malaroda, R., 1974. Prime osservazioni sulla tettonica ed il metamorfismo in corrispondenza del prolungamento sud-orientale della sinclinale intracristallina Lago del Vei del Bouc-Colle del Sabbione (Argentera Meridionale). Memorie Società Geologica Italiana 13, 319–325.

Malaroda, R., Carraro, F., Dal Piaz, G.B., Franceschetti, B., Sturani, C., Zanella, E., 1970. Carta Geologica del Massiccio dell'Argentera alla scala 1:50.000 e Note Illustrative. Memorie Società Geologica Italiana 9, 557–663.

Mark, D.M., O'Callaghan, J.F., 1984. The extraction of drainage networks from digital elevation data. Computer Vision Graphics Image Processing 28, 328–344.

Pappalardo, M., Rapetti, F., 2001. Frontal fluctuations of glaciers and climatic parameters: the case of Maritime Alps. Supplementi Geografia Fisica Dinamica Quaternaria V, 135–144.

Ribolini, A., 2000. Relief distribution, morphology and Cenozoic differential uplift in the Argentera Massif (French–Italian Alps). Zeitschrift für Geomorphologie 44, 363–378.

Strahler, A.N., 1957. Quantitative analysis of watershed geomorphology. Transactions of the American Geophysical Union 38, 913–920.