

Kinematics and structural properties of an active fault zone in the Sila Massif (Northern Calabria, Italy)

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ABSTRACT

In this paper we analyse the geometry, kinematics and dimensional characteristics of fault segments in the northern-central sector of the Sila Massif (Calabria). The fault zone (named here LF) extends beyond the Ampollino Lake and the Arvo River, and is thought to be the seismogenic structure responsible for the 1638 earthquake. Our data show that LF is composed of two main right-stepping segments arranged *en-échelon*. The stepover zone corresponds to a relay zone between the two active segments, as proved by the occurrence, in the area, of faulted Holocene sediments. The presence of compressive and extensional jogs with associated push ups and sag ponds along the fault trace, as well as the overall architecture of the fault zone, indicate that the LF is a NW-SE striking left-lateral feature. The structural and dimensional properties of the fault zone, also suggest that active deformation processes associated to LF include mechanical interaction between neighbouring fault segments indicating that those may be considered as part of a single seismogenic structure.

KEY WORDS: *strike-slip tectonics, fault interaction, seismic hazard, Sila Massif, Calabria.*

RIASSUNTO

Cinematica e proprietà strutturali di una zona di faglia attiva nel massiccio silano (Calabria, Italia).

In questo lavoro sono state analizzate le proprietà strutturali e dimensionali di una zona di faglia attiva affiorante nel settore centrale del massiccio silano: la Faglia dei Laghi (LF). Questa struttura è ritenuta responsabile del terremoto del 9 Giugno 1638. Per caratterizzare la Faglia dei Laghi è stato usato un approccio integrato volto da un lato a definire i principali elementi morfotettonici associati alla faglia e dall'altro a studiarne le proprietà geometriche, dimensionali e cinematiche. La Faglia dei Laghi, orientata NW-SE, si estende complessivamente per una lunghezza di circa 30 Km e mostra forti indizi geologici di attività tettonica recente. Essa si sviluppa dal Lago Ampollino, a sud, fino al Fiume Arvo, a nord. Le indagini di terreno hanno evidenziato che, in realtà, LF è costituita da due principali segmenti di faglia organizzati *en échelon* con stepover destro che mostrano, nella zona di relay, specifici caratteri di interazione meccanica.

Da un punto di vista geologico, nel settore settentrionale, la faglia taglia i graniti paleozoici del batolite silano, mentre nel tratto centro-meridionale essa riutilizza una zona di debolezza meccanica di età alpina costituita da una *shear zone* ubicata al passaggio tra i suddetti graniti e gli gneiss dell'Unità di Polia-Copanello. Le evidenze mesostrutturali hanno mostrato che la deformazione fragile legata alla faglia attiva si sovrappone alle strutture duttili e fragili-duttili

sviluppatasi durante le fasi deformative alpine. Oltre ai litotipi paleozoici, LF taglia anche depositi clastici di età olocenica, rappresentati da sedimenti in facies da fluviale a lacuo-palustre, affioranti in varie località lungo la zona di faglia. Ciò consente di affermare che la Faglia dei Laghi anche episodi di riattivazione recente.

Da un punto di vista morfologico, LF è caratterizzata da scarpate di faglia orientate da N30W a N100W, sviluppate sia nel bedrock paleozoico che nei depositi olocenici. Le scarpate impostate nel bedrock caratterizzano versanti di faglia fortemente alterati ed in arretramento a causa dell'azione erosiva. Alla base delle scarpate di faglia arretrate sono stati osservati e misurati tratti di scarpata a maggior pendenza interpretati come evidenza morfologica della riattivazione di LF relativamente all'ultimo evento sismico ad essa associato (ovvero il terremoto del 1638). Il valore di altezza stimato per queste scarpate varia tra circa 50 cm e circa 80 cm.

I piani di faglia striati, misurati alla base della scarpata di faglia morfologicamente più fresca, sono stati raggruppati in 16 stazioni mesostrutturali distribuite lungo le principali scarpate di faglia affioranti. Gli elementi utilizzati per definire le loro proprietà cinematiche, però, evidenziano come le mesofaglie misurate non sono mostrano caratteri cinematici univoci. L'analisi strutturale e l'utilizzo di un approccio geostatistico hanno mostrato come le mesofaglie transpressive ed inverse si concentrano principalmente lungo le scarpate orientate N30W, mentre le mesofaglie oblique o normali sono state acquisite essenzialmente lungo scarpate di faglia orientate da circa N40W a circa N100W.

In base alla sua architettura e organizzazione strutturale LF può quindi essere considerata come una faglia con cinematica trascorrente sinistra. Le scarpate orientate N30W, caratterizzate da morfologie di tipo push up sono state interpretate come *jog* compressionali, mentre le scarpate orientate da N40W a N100W sono state interpretate come *jog* estensionali associati al piano di faglia principale. Alla base delle scarpate di faglia lungo i *jog* compressionali ed estensionali si riconoscono laghetti di sbarramento interpretati come sag ponds legati allo sbarramento del drenaggio a causa della riattivazione di LF.

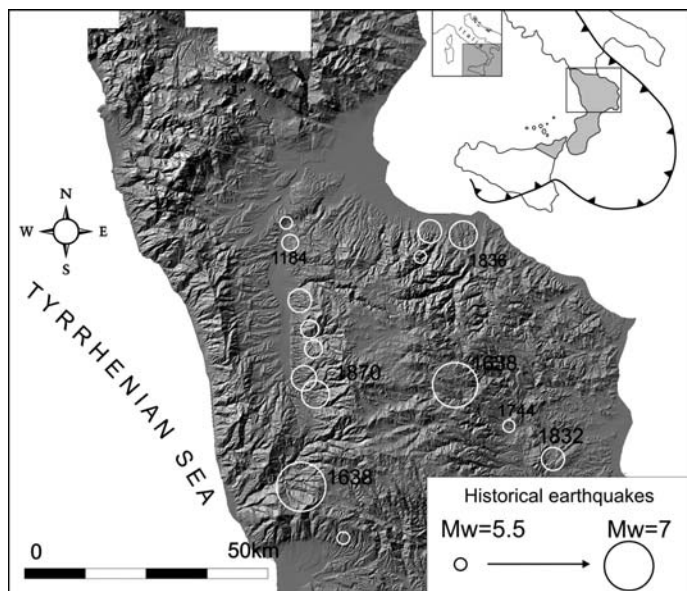
L'inversione dei dati strutturali raccolti ha evidenziato che il regime tensoriale responsabile degli episodi di riattivazione recente è caratterizzato da una direzione di compressione massima sub orizzontale orientata circa E-W e da una direzione di massima estensione, anch'essa sub orizzontale, orientata circa N-S. Tenendo in considerazione le caratteristiche cinematiche di LF e l'altezza delle scarpate basali misurata in vari settori lungo la faglia, è stato possibile stimare un valore di slip cosismico per il terremoto del 1638 variabile tra 81 cm e 113 cm. Questa scarsa variabilità nei valori di slip ottenuti può essere interpretata come l'evidenza che entrambi i segmenti di faglia, collegati nella zona di *relay* da faglie minori (*hard linkage*), si siano riattivati in maniera costante e per tutta la loro lunghezza, comportandosi così come elementi appartenenti ad un'unica struttura sismogenetica.

Per confermare l'ipotesi che l'attuale architettura della faglia sia il risultato dell'evoluzione dello stato di interazione meccanica tra due segmenti inizialmente isolati, è stata riprodotta, attraverso una simulazione, la distribuzione del *Coulomb Failure Stress* (CFS) lungo LF relativo ad una riattivazione di entrambi i segmenti di faglia, facendoli lavorare in maniera indipendente. La distribuzione dello stress a 15 Km di profondità è compatibile con quella che si otterrebbe considerando una struttura unica con caratteristiche dimensionali e cinematiche analoghe a quelle del sistema di faglie studiato. Ciò, unitamente alla forte concentrazione di stress nel settore di *underlap*, confermerebbe l'ipotesi che i due segmenti di faglia principali appartengono ad un'unica struttura sismogenetica. I risultati otte-

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nuti dalla simulazione effettuata permettono, inoltre, di effettuare alcune considerazioni legate alla pericolosità da terremoto in questo settore della Calabria. Infatti, faglie orientate NW-SE, confrontabili con la LF da un punto di vista cinematico e dimensionale, disposte *en-échelon* rispetto ad essa, tendono ad occupare i lobi di accumulo dello stress relativi alla LF stessa e, perciò, possono essere considerate come le strutture che, già caricate in condizioni statiche, sono maggiormente soggette ad una riattivazione in condizioni sismiche.

Ciò costituisce una valida ipotesi di lavoro per altri due forti terremoti avvenuti in epoca storica in Calabria Settentrionale: il terremoto del 1744 e quello del 1832.

TERMINI CHIAVE: *tettonica trascorrente, interazione tra faglie, rischio sismico, massiccio silano, Calabria.*

Fig. 1 - Main historical earthquakes in Northern Calabria ($M > 5.5$), and summary of events ($M > 6$) occurred in the area in the last millennium. Modified from: GALLI & BOSI (2003); WORKING GROUP CPTI (2004); GALLI & SCIONTI (2006).

- Principali terremoti storici in Calabria Settentrionale ($M > 5.5$). Questa parte della regione è stata anche caratterizzata da altri forti terremoti ($M > 6$) avvenuti nell'ultimo millennio e non ancora ben vincolati circa le relative aree epicentrali. Modificato da: GALLI & BOSI (2003); WORKING GROUP CPTI (2004); GALLI & SCIONTI (2006).

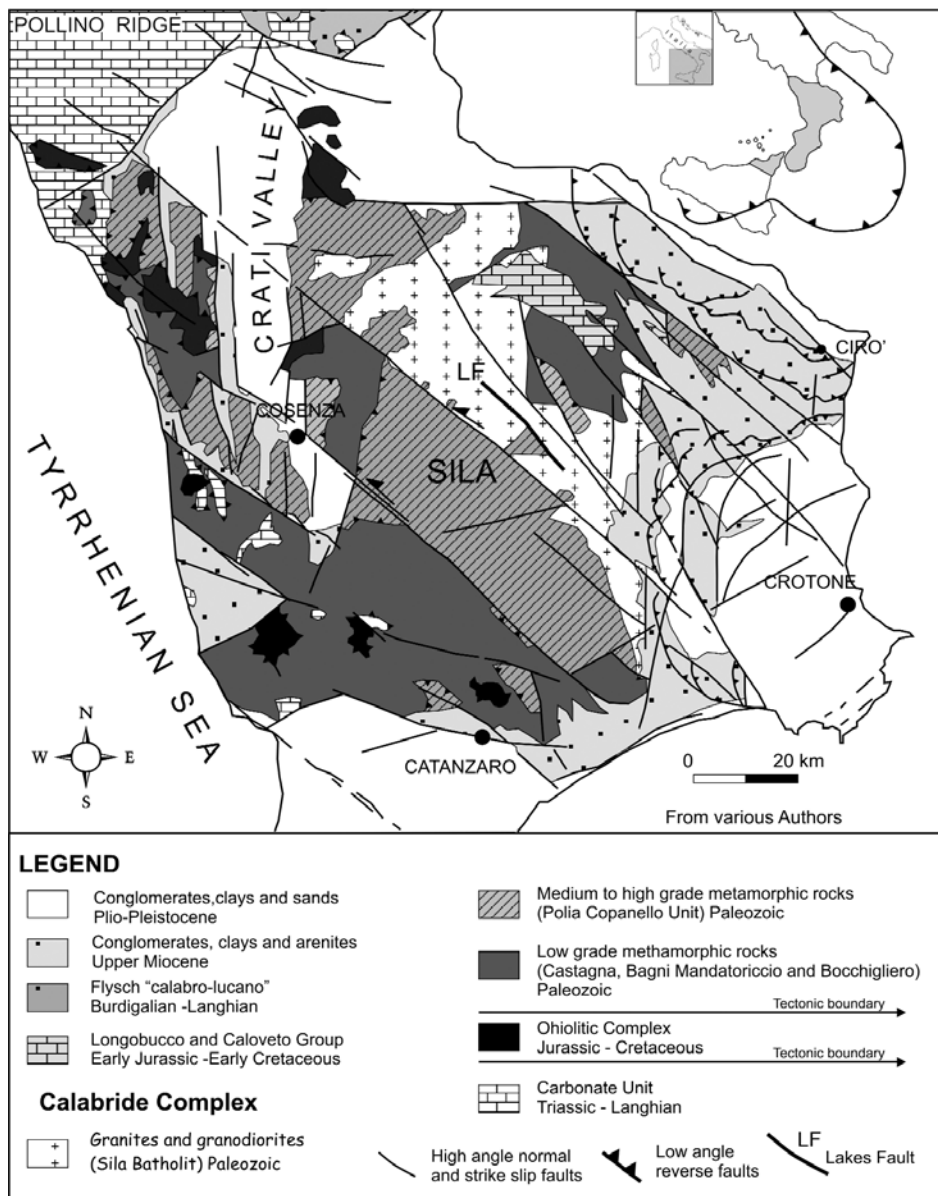


Fig. 2 - Geological sketch map of Northern Calabria.

- Schema geologico della Calabria Settentrionale.

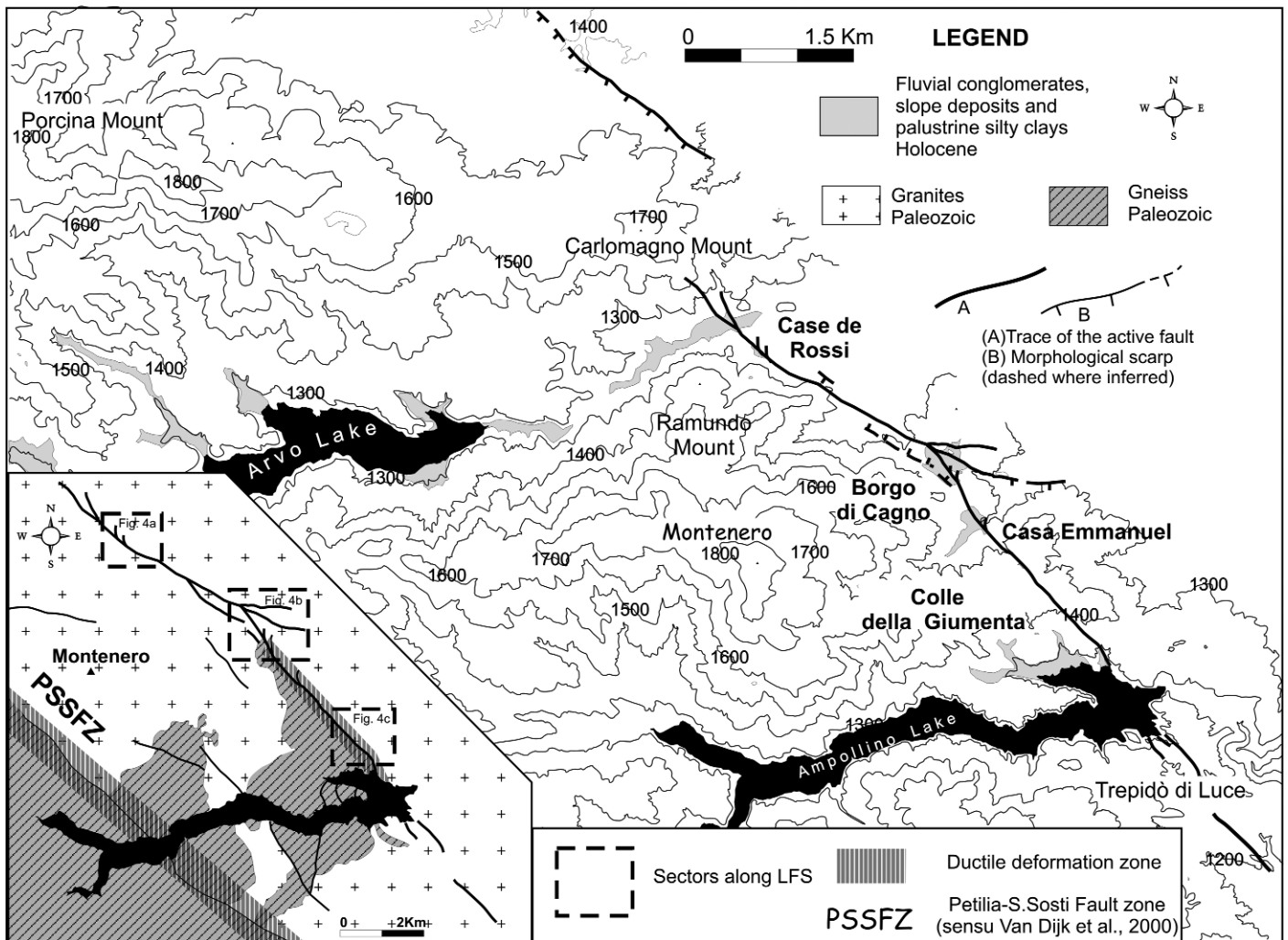


Fig. 3 - Schematic map of the area between the Ampollino and the Arvo Lakes.
 - Schema geologico e mappa topografica dell'area compresa nella zona tra i Laghi Ampollino e Arvo.

INTRODUCTION

Calabria is characterized by one of the highest seismicity levels in Italy, both in term of magnitude and frequency of earthquakes. In Northern Calabria, between the Catanzaro Strait and the Pollino ridge (fig. 1), at least 14 earthquakes with $M > 6$ occurred since 951 B.C. (WORKING GROUP CPTI; 2004), whereas a moderate seismicity ($M < 6$; fig. 1) characterizes the western sector of Northern Calabria. This is commonly related N-S striking normal faults, associated with the opening of the Crati basin (TORTORICI, 1982). In the Sila Massif, GALLI & BOSI (2003) related the 9th June 1638 earthquake ($I_0=11$ MCS and inferred $M_w = 6.7$) to the Lakes Fault (LF) that they interpreted as an oblique normal fault.

According to those authors, the oblique component of motion accounts for the observed geomorphic expression (pressure ridges, push-up swells and sag depressions) located at releasing and restraining bends. Several workers (see, for example, CATALANO *et alii*, 1993; VAN DIJK, 1994; VAN DIJK *et alii*, 2000) recognize the role of strike-slip tectonics in the recent structural evolution of the Calabrian Arc. In particular, VAN DIJK *et alii* (2000) lightened the role of pre-existing NW-SE

striking shear zones in the Neogene evolution of the orogenic edifice. These authors suggest that the above shear zones display a left-lateral component of motion and control the development of Plio-Quaternary basin system occurring in the external zones of the Calabrian Arc (i.e. Croton Basin System).

In order to better constrain active deformation in the central sector of Northern Calabria, we analysed in detail the geometric, dimensional and kinematic characteristics of the Lakes Fault (LF). This allowed us to investigate the degree and type of mechanical interaction between neighbouring fault segments belonging to the LF. Integrating the results of structural analysis with computed values of the co-seismic rupture length and offset, we also estimated the maximum expected magnitude for this structure.

GEOLOGICAL SETTING

The geological structure of the northern sector of the Calabrian Arc is characterized by a thrust stack geometry, including crystalline-metamorphic rocks belonging to the former European-Iblean margin, resting on ophiolite-

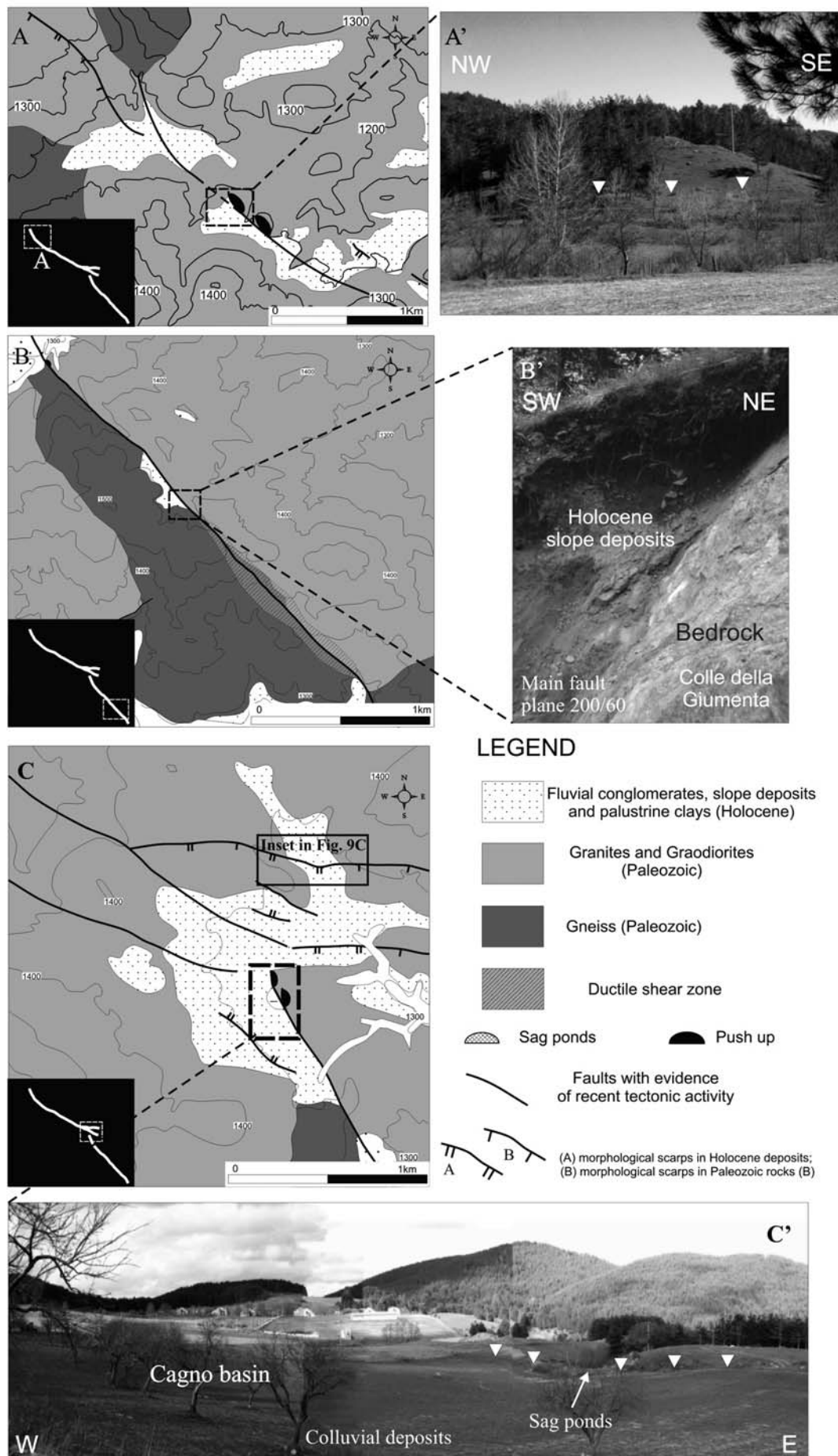


Fig. 4 - Geological and morphological evidence of LF (see fig. 3 for location). (A) Geological sketch map of the north-western fault segment represented by a NNW striking fault scarp. (B) Geological sketch map of the south-eastern fault segment of LF. In this area the geological evidence of its recent reactivation is represented by faulted Holocene slope deposits in contact with Paleozoic rocks (the photo corresponds with the location of trench 1 in GALLI & BOSI, 2003). (C) Geological sketch map of the Cagno basin area. This area is characterized by E-W and NNW striking fault scarps.

– *Evidenze geologiche e morfologiche della LF (vedi fig. 3 per la loro ubicazione).* (A) Mappa geologica schematica del settore di terminazione nord occidentale della LF. (B) Mappa geologica schematica della zona di terminazione meridionale della LF; in questo settore l'evidenza geologica dell'attivazione recente della faglia è rappresentata da depositi di versante fagliati ed accostati geometricamente al bedrock cristallino (la foto corrisponde alla trincea 1 in GALLI & BOSI, 2003). (C) Mappa geologica schematica del Bacino di Cagno, nella zona centrale della LF. Questo settore è caratterizzato da scarpate di faglia orientate E-W e NNW-SSE.

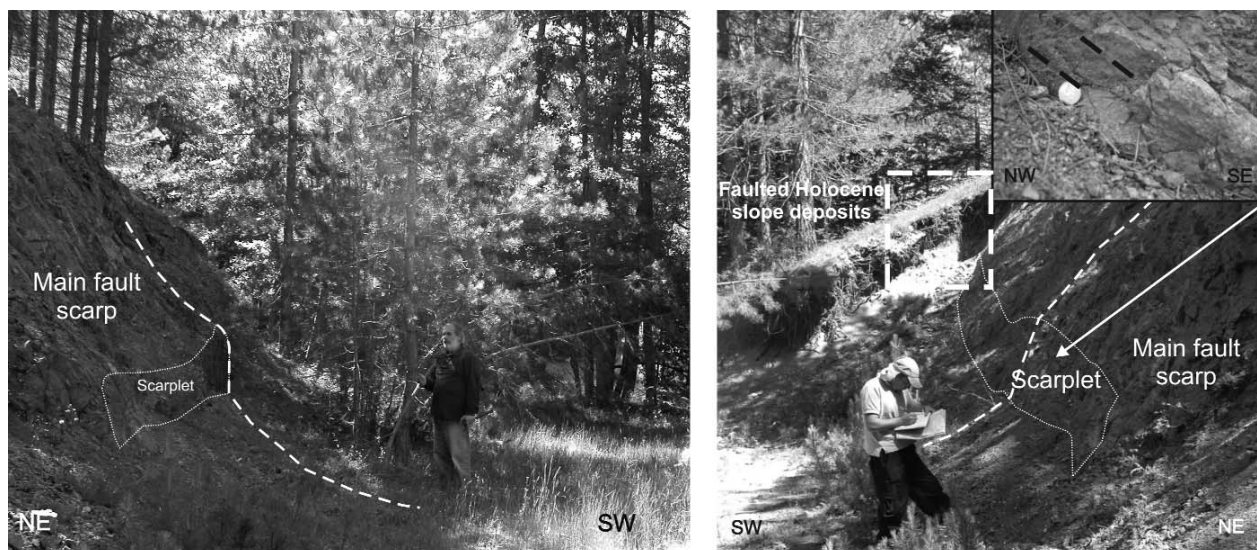


Fig. 5 - Retreat fault scarp in the southern sector of LF, near Colle della Giumenta. The whole feature may be considered as the result of the long-term tectonic activity of LF (see figs. 3 and 4 for location). At the base of the fault scarp we recognized a morphological offset interpreted as the basal scarplet associated with the 1638 earthquake. Structural evidence indicates that the scarplet records an oblique left-lateral kinematic character.

– Scarpata di faglia arretrata ubicata nel settore centro meridionale della LF, nei pressi di Colle della Giumenta. Detta struttura può essere considerata come una scarpata dovuta all'attività di lungo periodo della faglia (vedi figg. 3 e 4 per ubicazione). Al piede della scarpata è possibile riconoscere un tratto a maggior pendenza (scarplet) interpretato come evidenza morfologica della riattivazione di LF durante il terremoto del 1638. Evidenze strutturali dimostrano che, in questo settore, la scarplet basale è caratterizzata da una cinematica obliqua sinistra.

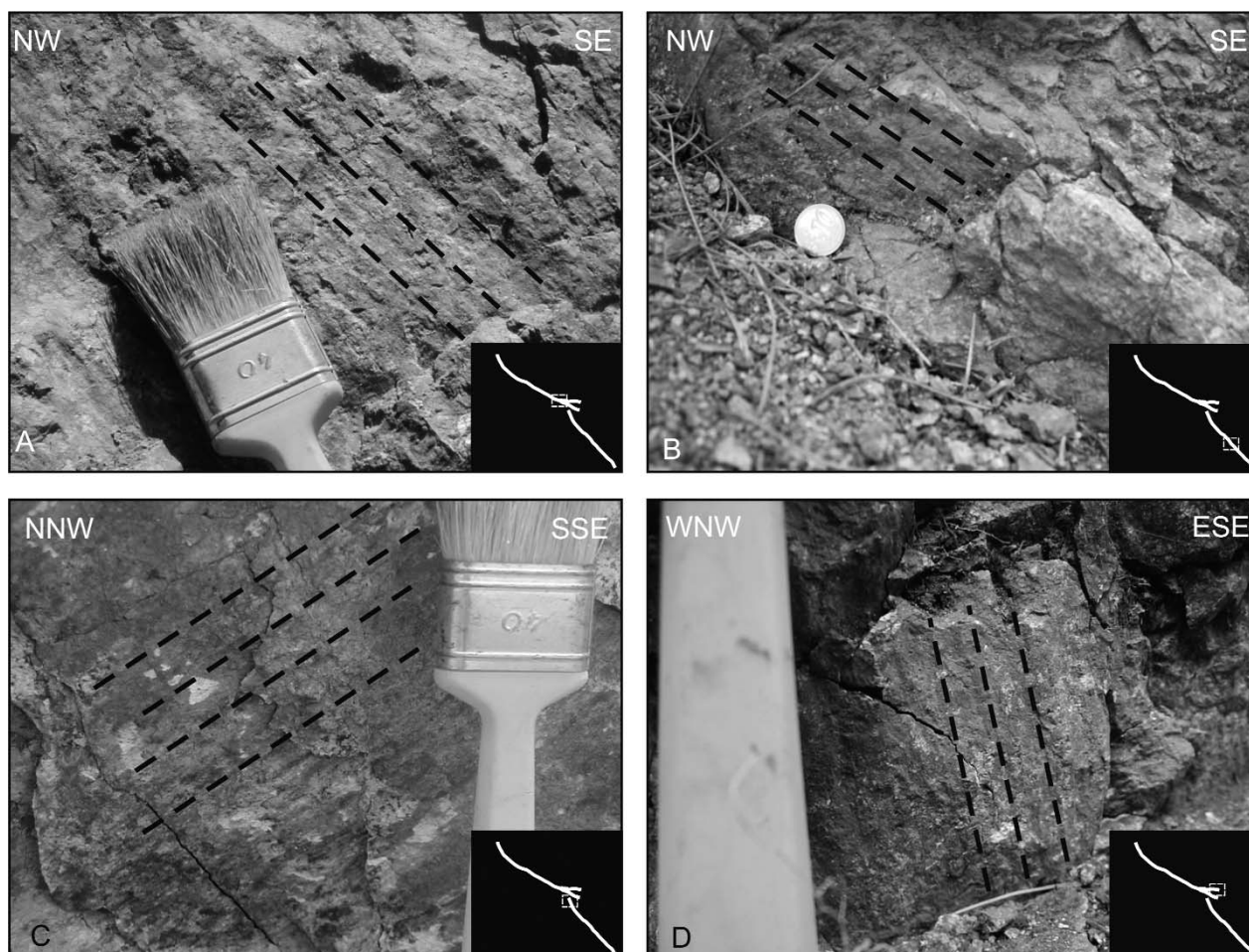


Fig. 6 - Striated fault planes on the basal scarplets show variable kinematic behaviour in various sectors of LF.

– Piani di faglia striati riconosciuti lungo le scarplets, in vari settori della LF, mostrano differenti caratteristiche cinematiche.

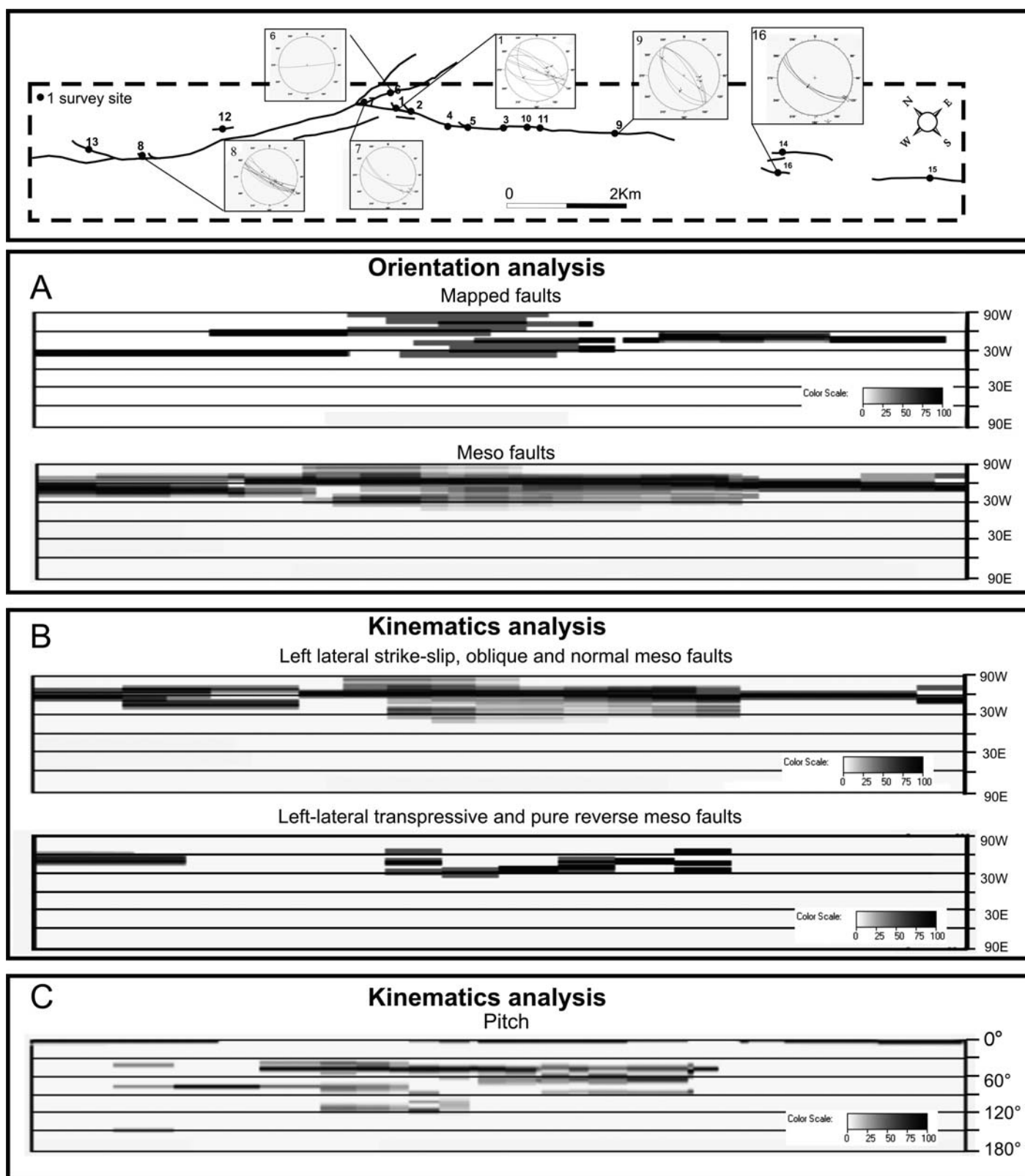


Fig. 7 - Transect Analysis. (A) Comparison between the azimuthal distribution of mapped faults and mesofaults along a fault-parallel transect. (B) Comparison of the distribution and azimuthal variations between left-lateral/oblique mesofaults and transpressive/reverse mesofaults. (C) Distribution and pitch values variations.

– Transect Analysis. (A) Confronto tra la distribuzione azimutale delle faglie cartografate rispetto a quella delle faglie misurate alla meso scala. (B) Confronto tra la distribuzione, e la corrispondente variazione azimutale, dei differenti tipi di meso faglie misurate; nel primo diagramma sono rappresentate tutte le faglie trascorrenti ed oblique, nel secondo sono invece rappresentate solo le faglie inverse e transpressive. (C) Distribuzione e variazione dei valori di pitch misurati sui piani striati.

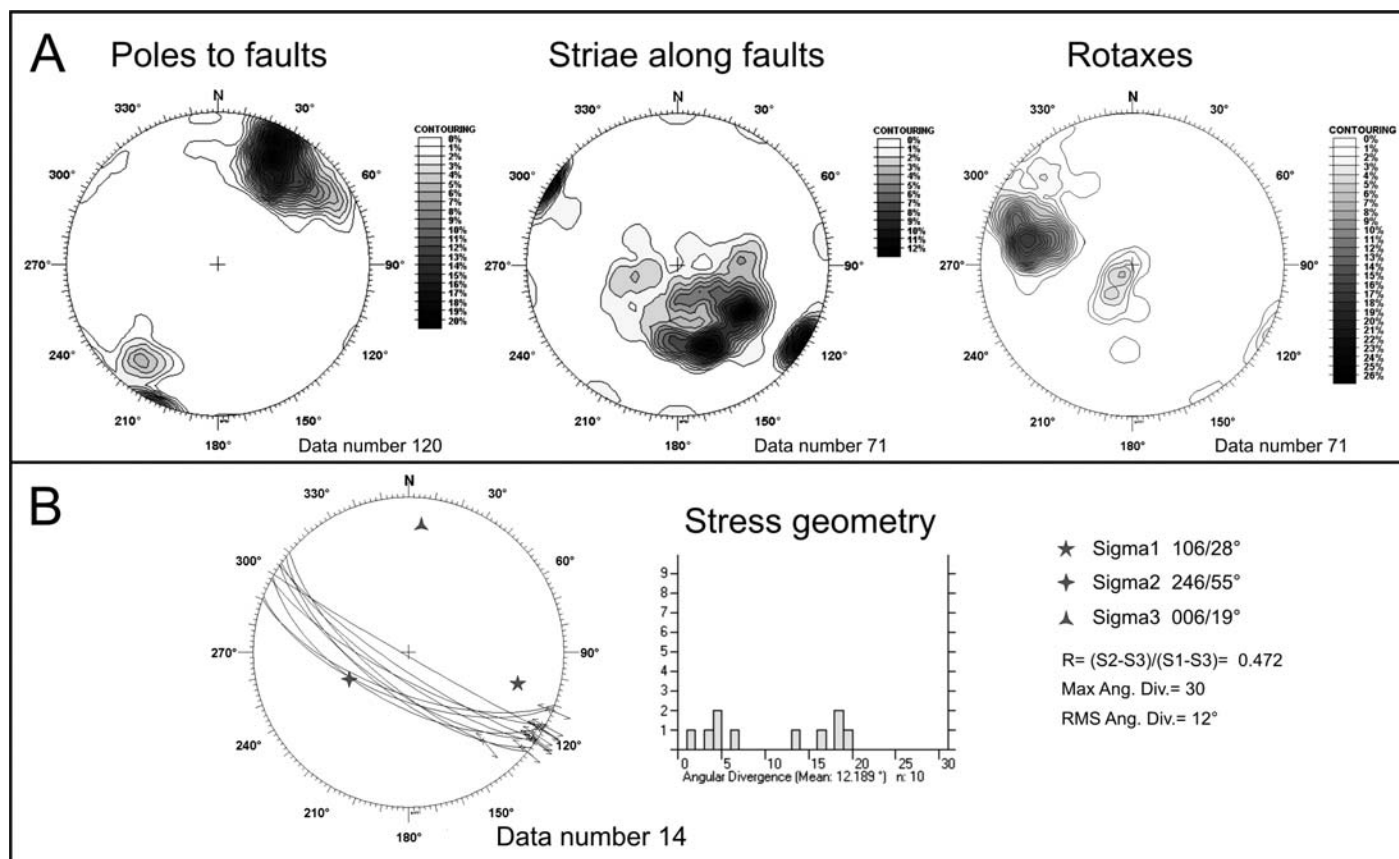


Fig. 8 - Structural data. (A) Contour diagrams of poles to mesofaults, striae and rotaxes. (B) Inferred stress field geometry.
– Dati strutturali. (A) Contour diagrams dei poli delle mesofaglie, delle strie e dei rotaxes. (B) geometria del campo di stress.

bearing units (AMODIO MORELLI *et alii*, 1976; ROSSETTI *et alii*, 2001; SCANDONE, 1979; see fig. 2).

VAN DIJK (1994) and VAN DIJK *et alii* (2000) observe that NW-SE striking crustal shear zones border the main contacts between these units.

From a morphological point of view, the Sila Massif represents a plateau with gently raised edges and with a gently depressed internal sector, where several lakes were established in Pleistocene times (HENDERSON, 1970; DRAMIS *et alii*, 1990; GALLI & BOSI, 2003). N-S striking Plio-Quaternary faults (TORTORICI, 1982) with impressive morphological evidence mark the western border of the massif (fig. 2). These high angle, west facing normal faults, bring into contact Paleozoic rocks and the Plio-Pleistocene deposits of the Crati basin.

In the central sector of the Sila Massif, the most important geomorphological element is given by remnants of a gently dipping paleo-landscape («paleosuperficie sommitale» *auct.*; DRAMIS *et alii*, 1990; MOLIN *et alii*, 2004), whereas along the western border of the massif, two other generations of paleosurfaces could be related to the Plio-Quaternary evolution of the area.

The main erosional phase responsible for the formation of the paleo-landscape has been constrained by THOMSON (1994) using Apatite Fission Track Thermochronology (AFT). This suggests a rapid cooling of the crystalline basement occurred between 35 and 15 My. Thomson (1994) related this phase to a Oligocene-Miocene extension that produced uplift increasing and subaerial erosion of the Sila Massif.

THE LAKES FAULT

The Lakes Fault is a part of a 30 Km long structural lineament extending from the Ampollino to the Cecita lakes. LF is composed of two main segments, one is about 6 Km long and the other is roughly 9 Km long; those two fault segments are nicely exposed in the area comprised between the Ampollino lake, to the south, and to the Arvo River, in the north (fig. 3). As a whole, LF strikes roughly NW-SE, but some fault-related lower-rank features trend from NNW-SSE to E-W (fig. 3). The Lakes Fault, which is thought to be the seismogenic structure responsible for the June 1638 earthquake ($M_w=6.7$; GALLI & BOSI, 2003) runs parallel to the Petilia-Sosti shear zone, a 130 Km long feature bounding the main contact between the gneisses of the Polia-Copanello Unit and granites of the Sila batholith (VAN DIJK, 1994; VAN DIJK *et alii*, 2000, fig. 3).

At the northern fault termination, in the Arvo River area, the north-western segment trends roughly NNW-SSE and cuts through both in the granites of the Sila batholith and coarse grained fluvial sediments of Holocene age (fig. 4, a and a').

The south-eastern segment, in the Ampollino lake area, cuts across both the boundary between gneisses and granites and Holocene slope deposits (fig. 3; fig. 4, b and b'). In this area, typical plutonic and metamorphic foliations in the granites and gneisses, records the oldest alpine deformation phases (CAGGIANELLI *et alii*, 2000; CAGGIANELLI & PROSSER, 2001; LIOTTA *et alii*, 2004),



Fig. 9 - Fault scarps in different sectors along LF.
– Scarpe di faglia riconosciute lungo diversi settori di LF.

whereas a cataclastic fault zone with a width ranging between 1m-5m cuts the latter features and records the youngest fault-related deformation. The morphological expression of the south-eastern segment (fig. 4, b and b'), is given by a rectilinear escarpment with a sub-vertical W-facing fault scarp.

The Cagno basin (fig. 4c and c'), which is characterized by a large flat area filled by clays, silty clays and sands of Holocene age, is located in the underlapping zone between the two main fault segments. Here, the southernmost segment displays a NNW-SSE orientation, whereas the northernmost one is marked by roughly E-W trending fault scarps (fig. 4c). Shorter fault segments and E-facing fault scarps link the two main fault segments of the array in the Cagno area.

Here, the recent activity of LF is marked by the presence of fresh fault scarps both in bedrock units and in Holocene continental deposits (GALLI & BOSI, 2003; GALLI *et alii*, *in press*). In several locations along LF, the fault scarps dam the drainage, hence determining the formation of small lakes and sag ponds (fig. 4c and c'). In fig. 5, it may also be observed a fresh morphological break located at base of longer fault scarp; this has been

interpreted as the basal scarplet connected to the 1638 earthquake.

GEOMETRIC AND KINEMATIC ANALYSIS

The structural evidence found at meso scale along the LF are represented by striated fault planes characterized by kinematic indicators: left-lateral, oblique and normal faults have been measured both in bedrock and Holocene deposits along the main fault plane of the LF (fig. 6).

In order to characterize the geometric and structural properties of LF, we used the geo-statistical approach proposed by SALVINI *et alii*, (1999). This approach (called Transect Analysis) allows one to evaluate the spatial variations of the fault properties along selected transects (fig. 7). Using the Transect Analysis we assessed the trend variations of LF-related macrofaults along a transect parallel to the main fault trace (fig. 7). In order to compare fault segments of varying length, we normalized our measurements to the length of the shortest fault segment mapped in field. The results of our analysis show that although the fault main trend is roughly NW-SE, in the Cagno basin area, LF exhibits slightly different trends

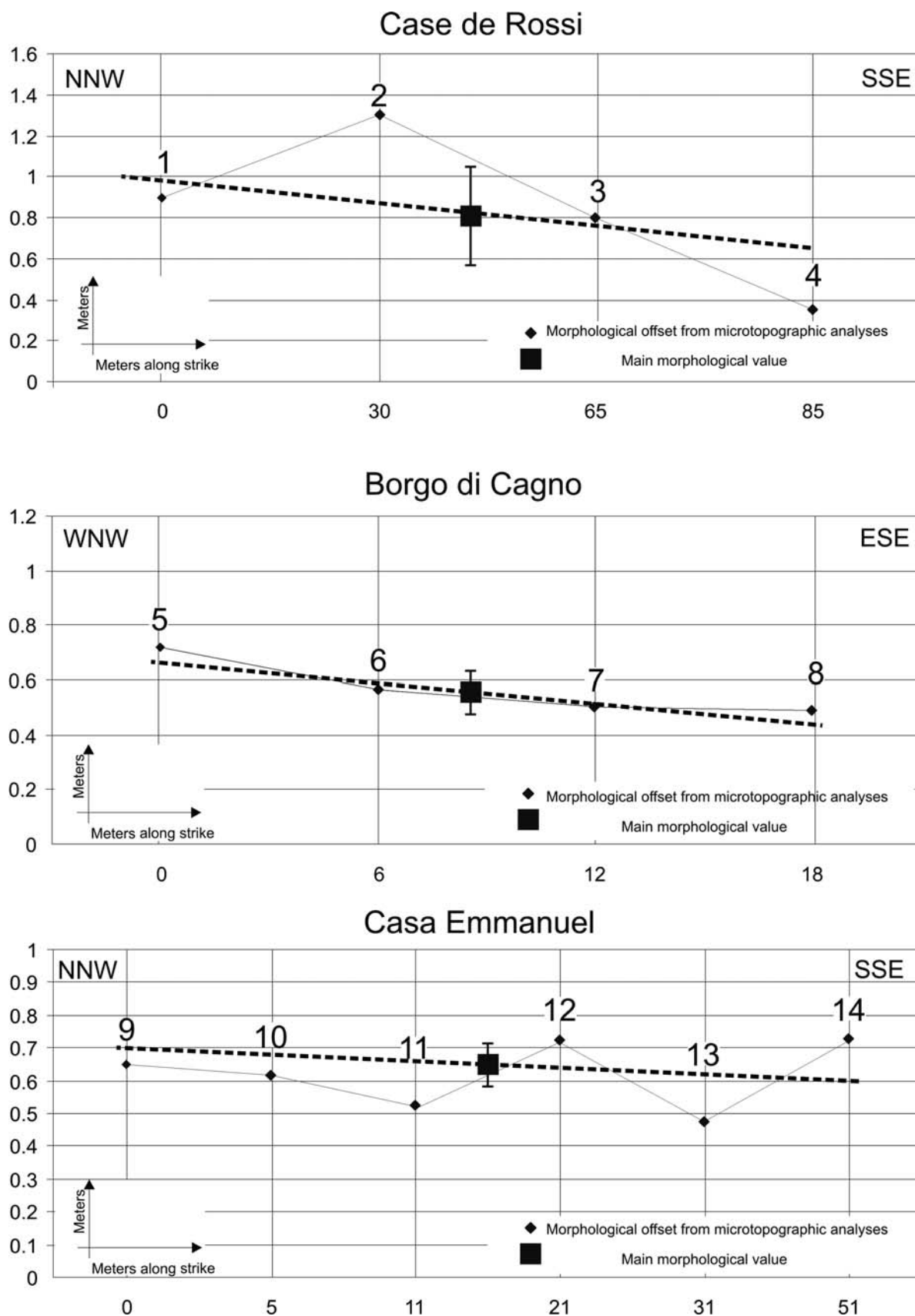


Fig. 10 - Results of microtopographic surveys. The height of the scarplets has been measured in three different sectors along LF. Different numbers in the diagrams refer to different micro topographic profiles. The black squares represent the most statistically representative value for every group of microtopographic profiles.

– Risultati dei rilievi microtopografici. L'altezza della scarplet alla base della scarpata di faglia cumulativa è stata misurata in tre differenti settori lungo LF. I numeri riportati nei diagrammi sono riferiti ai diversi profili microtopografici eseguiti. I quadrati neri rappresentano i valori statisticamente più significativi dei gruppi di profili eseguiti nei vari settori analizzati.

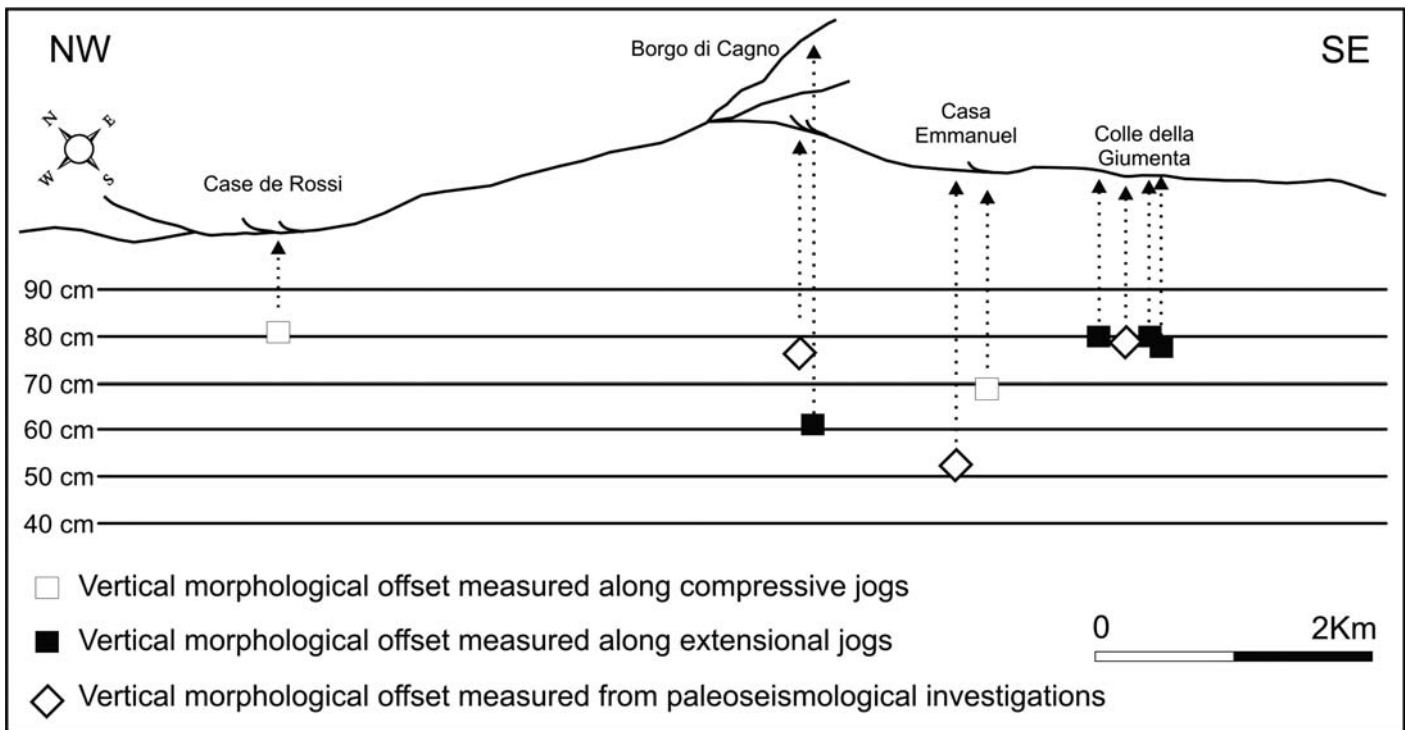


Fig. 11 - Distribution of the topographic offset related to the 1638 earthquake. The data collected in field along both compressional and extensional jogs are compared with those obtained from trenches (GALLI & BOSI, 2003).
 - Distribuzione del rigetto topografico relativo al terremoto del 1638. Nel diagramma, i dati ottenuti attraverso l'analisi geologico-strutturale sono stati confrontati con quelli provenienti da indagini paleosismologiche (GALLI & BOSI, 2003).

(fig. 7a): one striking NNW-SSE (with two peaks at N30W), and the other striking NW-SE (with a peak at N55W; see fig. 7a).

The same approach was also used to analyze the distribution of the mesofaults collected in 16 survey sites distributed along LF. In this case, Transect Analysis allowed us to assess that, in the central sector of LF, the strike of the mesofaults ranges from N35W to N70W (fig. 7a), whereas moving from the central sector towards the southern termination of the fault, orientation vary from N35W to N50W (fig. 7a).

We also investigated the distribution of different types of mesofaults along LF (fig. 7b). Our results show that the NW-SE striking left-lateral and oblique normal faults are distributed all along the fault, from the Arvo River to the Ampollino lake (fig. 7b). In contrast, the NNW-SSE trending transpressive and reverse mesofaults are concentrated in the central sector of the Lakes Fault, and the roughly E-W oriented normal mesofaults occur only in connection with the WNW-ESE striking escarpments.

If one also look at the kinematic variations along the Transect Analysis, it may be observed again that a left-lateral component of motion have detected all along the fault (fig. 7c)

However, in the northern sector, two statistical peaks (with pitches around 150° and 90°) have been found (fig. 7c). These values are representative of left-lateral transpressive motion observed in stations 8 and 13, in association with fault scarps trending N30W.

Pitch variations in the central sector also exist (fig. 7c); those include two peaks with pitches around 120°

and 90°, indicating a left-lateral transpression (in stations 1, 2, 5 and 9) along N30W striking fault scarps (fig. 7c). In the same area, pitch values ranging from 40° to 60° are representative of oblique faults collected in stations 12, 7, 6, 4, 3, 10 and 11, in association with fault scarps oriented from N50W to N100W.

Contour diagrams of poles to mesofaults, striae, and rotaxes (fig. 8a), also allowed us to derive the geometry of remote stress field acting in the area and the stress axial ratio R (fig. 8b). As may be observed, the inferred orientation of the principal stress components is compatible with left-lateral shear along NW-SE oriented faults (fig. 8b).

In addition to the above analysis, we performed serial micro-topographic profiles in order to quantify the vertical morphological offset across the cumulative fault scarp associated to LF (fig. 9) and to evaluate its co-seismic value at three localities along the fault (refer to fig. 10). The values obtained from micro-topographic profiles range from 62 cm and 80 cm (figs. 10 and 11). Those were compared with offset measured in trenches (fig. 11, GALLI & BOSI, 2003; GALLI *et alii*, *in press*) and the result was that we found only small differences between the latter values. Near Casa Emmanuel, however, the value measured in a paleoseismological trench was about ~50 cm (GALLI *et alii*, *in press*).

Integrating the latter data with those available from structural analysis, we were able to evaluate the effective co-seismic slip. We did so by using the best fit value from the contour diagrams of the poles to transpressive mesofaults and the histogram of the corresponding pitch, to constrain the kinematics and the geometry of the most

representative fault plane of those sectors (fig. 12a). As may be observed in fig. 12b, the most representative transpressive fault plane strikes N30W and differs in respect the most representative fault plane of the complete array (fig. 12b).

Using both the dip of the fault plane, measured along the basal scarp, and the kinematics of the representative fault plane, we were able to estimate the effective displacement (comprised between 81 cm and 113 cm). Because scarplets represent the morphological expression of the latest fault re-activation, we argue that this value may be considered as the co-seismic slip value related to the 1638 earthquake.

STRESS DISTRIBUTION ANALYSIS

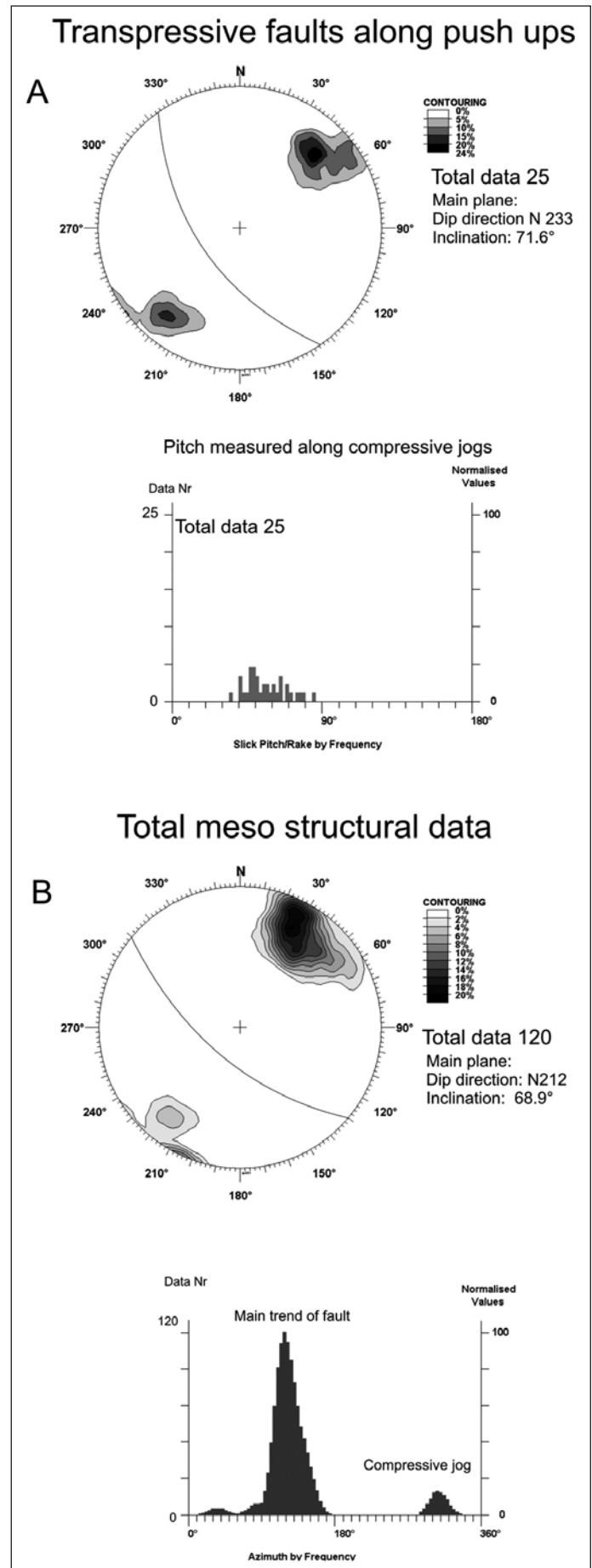
In order to determine whether the two fault strands are interacting and behaving as a single seismic source, we calculated the co-seismic stress distribution along LF by using the GNStress software (vers. 2.17). This allowed us to visualize Coulomb Failure Stress changes (CFS) on a flat surface at 5 km and 15 km, corresponding to the thickness of the seismogenic layer (GASPARINI *et alii*, 1985). We modelled LF as composed of two segments: one of about 6 km of length the other about 9 km long. Those two NW-SE striking fault segments are organized *en-échelon* with a right stepover. The δ_s angle between the main slip plane and the *offset jog*, measured in the central sector, is less than 90° . This observation confirms that the Cagno basin area represents an *underlapping* zone between the two fault segments (fig. 13).

The computed CFS distribution exhibits an asymmetric pattern (fig. 14), typical of transcurrent faults, and is characterized by areas with stress increase and release. The stress increase in the area between the neighbouring tip points (almost +0.5 MPa) records a stress perturbation related to their mechanical interaction. This is also confirmed by the geometry of the fault system, which displays a separation value (S) of 1.5 Km, about 10% of the total length of LF. Such a value is typical for transcurrent interacting faults, as shown by AN (1997) and WILLEMSE (1997).

The stress increase in the underlapping area, and the stress pattern found at 5 Km and 15 Km depth, also suggests that the two individual fault segment exposed at surface, although physically linked at surface by shorter faults, could be connected also at depth (fig. 14b, d, e).

Fig. 12 - (A) Contour diagrams of poles to the transpressive and reverse mesofaults analysed along compressive jogs, and related representative fault plane for those sectors. The histogram depicts the pitch value distribution in compressive jogs. (B) Contour diagram of poles to the total collected mesofault. The associated fault plane can be considered as the most representative fault plane of the entire LF. The histogram shows the statistical weight of mesofault with different orientations.

– (A) Contour diagram dei poli delle meso faglie transpressive ed inverse misurate alla base delle scarpate interpretate come jog compressionali. Il piano medio calcolato può essere considerato come quello rappresentativo per questi settori. L'istogramma di frequenza mostra il valore di pitch statisticamente più rappresentativo per questi settori e può essere usato per caratterizzare da un punto di vista cinematico i jog compressionali. (B) Contour diagram dei poli di tutte le meso faglie misurate. Il piano medio che è stato calcolato può essere considerato come quello rappresentativo di tutta la LF. L'istogramma di frequenza mostra il peso statistico delle meso faglie con diversa orientazione.



DISCUSSION AND CONCLUSION

The results of our analysis show that the roughly NW-SE striking Lakes Fault, in the Sila Massif, is a left-lateral feature composed of two underlapping segments and lower-rank reverse and oblique normal faults oriented N30W and almost N100W respectively.

The N30W striking fault bends are associated with morphological scarps interpreted as push up structures, whereas the N100W striking tails, also characterized by morphological scarps along which we measured mainly normal mesofaults have been interpreted as extensional jogs. Both compressive and extensional jogs are associated with small lakes and sag ponds located in the hangingwall of the fault, connected to the damming of the drainage system in the area.

The inversion of slip data from the mesofaults (fig. 8b) depicts a stress field characterized by a sub-horizontal δ_1 striking N106E, and a sub-horizontal δ_3 striking N006E (with $R = 0.472$). This stress conditions are representative of the active stress field acting in this sector of the Sila Massif.

The effective co-seismic slip calculated along LF varies from 81 cm and 113 cm. This confirms that, during

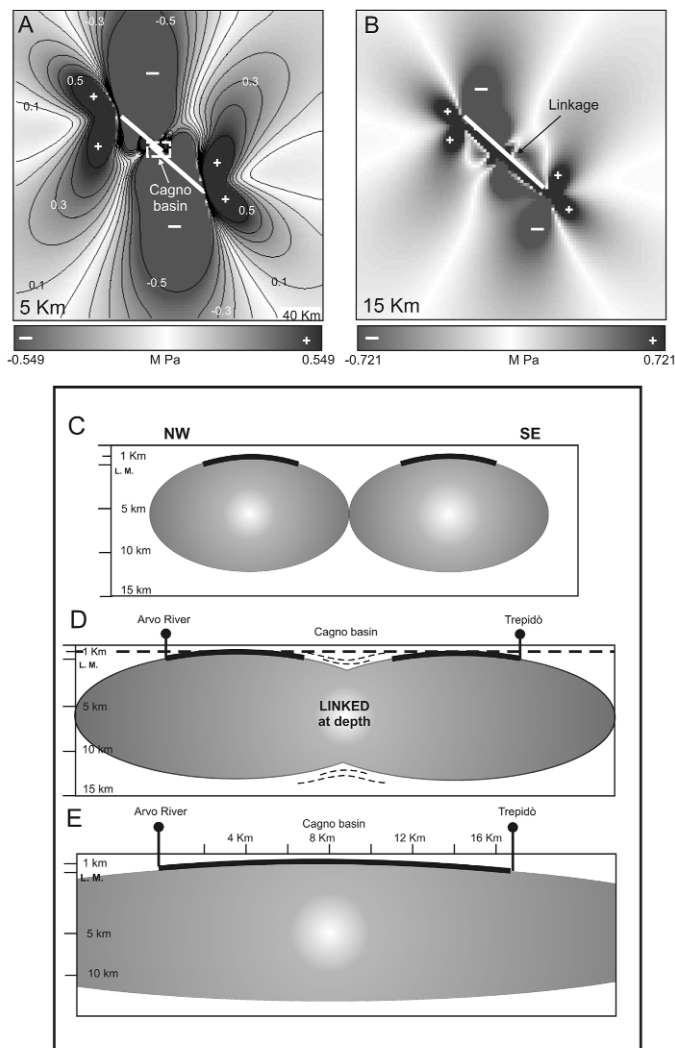


Fig. 13 - (A) Schematic diagram showing the general architecture LF. The southernmost fault segment, ends, to the north, with a compressive jog associated with push ups and sag ponds. The northernmost one ends, to the north, with a compressive jog; nevertheless, it ends with extensional tails, to the south. (B) Geometric relationships between the two fault segments. The central part of the array represents an underlapping zone with an offset jog showing a right stepover.

– (A) Diagramma schematico che mostra l'architettura generale della LF. Il segmento di faglia più meridionale termina, verso nord, con un jog compressivo e associati push up e sag ponds. Il segmento di faglia più settentrionale, invece, termina, verso nord con un jog compressivo e, verso sud, con tails estensionali. (B) Relazioni geometriche tra i due segmenti di faglia. La zona centrale della LF rappresenta una zona geometricamente complessa in cui i due principali segmenti sono caratterizzati da uno stepover destro.

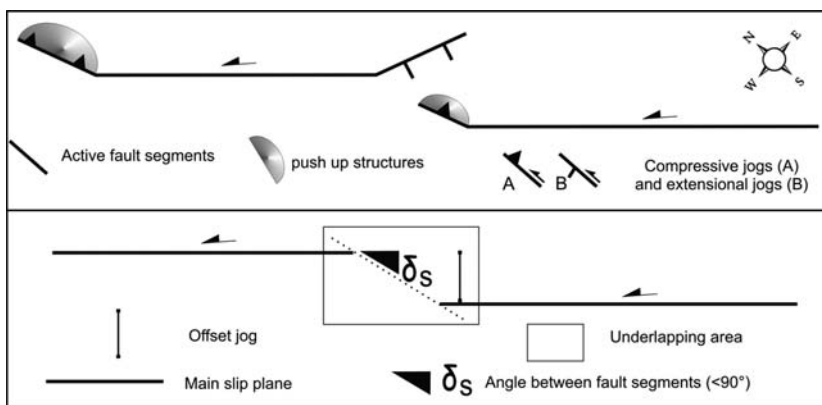


Fig. 14 - CFS (Coulomb Failure Stress) change, at 5 Km (A) and 15 Km (B) depth (thickness of the seismogenic layer) induced by the re-activation of both fault segments during the 1638 A.D. earthquake. The diagram shows the asymmetric distribution of stress accumulation and stress fall zones, typical of strike slip faults. The central part of LF is characterized by high CFS values, hence suggesting mechanical interaction between the two fault segments. C, D and E. Conceptual space-time evolution of the state of mechanical interaction. (C) The first stage in the evolution is characterized by two separated faults. (D) Lateral growth of both fault segments determines their linkage at depth and mechanical interaction at surface in the relay zone. (E) The latest stage, which is representative of the actual state of interaction, is characterized by hard linkage between the two fault segments also at surface. In this stage, the two fault segments are strongly interactive and may possibly work together as a single fault.

– Distribuzione del Coulomb Failure Stress (CFS), a 5 Km (A) e 15 km (B) di profondità, indotto dalla riattivazione di entrambi i segmenti di faglia in occasione del terremoto del 1638. Il diagramma mostra la distribuzione asimmetrica dello stress con zone di accumulo e caduta dello stress, tipica di faglie trascorrenti. La parte centrale della faglia, nel settore di relay tra i due segmenti principali, è caratterizzata da alti valori di CFS che confermano la forte interazione meccanica tra le due faglie in questo settore. C, D, E Modello concettuale dell'evoluzione spazio-temporale dell'interazione meccanica tra i due segmenti di faglia. (C) Il primo stadio è caratterizzato da due segmenti di faglia indipendenti. (D) Nel secondo stadio, la crescita laterale di entrambi i segmenti di faglia determina una certa interazione meccanica superficiale nella zona di relay e un loro collegamento più deciso in profondità. (E) L'ultimo stadio, rappresentativo dell'architettura di faglia osservabile attualmente, è invece caratterizzato da un collegamento tra i due segmenti di faglia principali anche in superficie, oltre che in profondità. L'evidenza di una riattivazione pressoché omogenea di entrambi i segmenti di faglia conferma come essi possano essere considerati come l'espressione superficiale della stessa struttura sismogenetica.

the 1638 A.D. earthquake, both segments ruptured with a similar offset, hence suggesting that they are part of a single fault at depth.

In order to test this hypothesis, we analyzed the static stress re-distribution due to the coeval activation of both segments. We found a stress concentration in the overlapping area (fig. 14a) which is consistent with what expected for a single fault (fig. 14b). We consider this configuration representative of an intermediate step in the evolution of LF; i.e. when the two principal segments are linked at depth and mechanically interacting at surface in the neighbouring tip points (fig. 14d).

Considering the re-activation and the kinematics of the LF as the result of the regional stress field, we can assume that the orientation of the stress shadow and accumulation zones, asymmetrically distributed along LF, in a long-term scenario represent an important element for the seismic hazard assessment. It could be argued, in fact, that NW-SE striking left-lateral faults, organized *en-échelon* with LF are loaded in static conditions because they tend to be located in the stress accumulation zones related to the LF re-activation. In this way, in dynamic (seismic) conditions, those faults are favourably oriented for their re-activation.

Further the 1638, the 1744 and 1832 earthquakes struck the north eastern sector of Calabria (GALLI & BOSI, 2003; SCIONTI *et alii*, 2006), with an epicentral area shifting from NW, in the Sila Massif (1744 earthquake), to SE, in the Marchesato basin (1832 earthquake; see fig. 1). Both the latter two historical earthquakes can be associated, in agreement with some authors (GALLI & SCIONTI, 2006), to unknown NW-SE striking faults cutting across the Sila Massif. This hypothesis fits with the stress configuration found for the LF; the activation of unknown structures, in fact, could be determined by stress triggering phenomena connected to stress increase related to faults previously re-activated in older earthquakes (i.e. the LF could load the 1744 earthquake, see also GALLI & SCIONTI, 2006).

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