The relationship between seismic deformation and deep seated gravitational movements during the 1997 Umbria-Marche (Central Italy) earthquakes

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Abstract

This paper re-evaluates the origin of some peculiar patterns of ground deformation observed by space geodetic techniques during the two earthquakes of September 26th of the Colfiorito seismic sequence. The surface displacement field due to the fault dislocation, as modeled with the classic Okada elastic formulations, shows some areas with high residuals which cannot be attributed to unsimulated model complexities. The latter was investigated using geomorphological analysis, by recognising the geologic evidence of deep seated gravitational slope deformations (DSGSD) of the block-slide type. The shape and direction of the co-seismic ground displacement observed in these areas are correlated with the expected pattern of movement produced by the reactivation of the identified DSGSD. At least a few centimetres of negative Line of Sight ground displacement was determined for the Costa Picchio, Mt. Pennino, and Mt. Prefoglio areas. A considerable horizontal component of movement in the Costa Picchio DSGSD is evident from a qualitative analysis of ascending and descending interferograms. The timing of the geodetic data indicates that the ground movement occurred during the seismic shaking, and that it did not progress appreciably during the following months. In this work it has been verified the seismic triggering of DSGSD previously hypothesized by many authors. A further implication is that in the assessment of DSGSD hazard it is necessary to consider the seismic input as an important cause of acceleration of the deformation rates.

Keywords: Deep seated gravitational slope deformations; InSAR; photogeological analysis; Umbria – Marche seismic sequence; seismic triggering; DSGSD hazard assessment.

1. Introduction

Deep seated gravitational slope deformation (DSGSD) can be described as gravitational movements that involve large rock volumes in high relief mountain areas. They typically affect the whole hillslope for thicknesses higher than several tens of meters and lengths of some kilometers (Zischinsky, 1966, 1969; Radbruch-Hall et al., 1976, 1977; Agnesi et al., 1978; Savage and Varnes, 1987). Peculiar morphological and structural features associated to DSGSD are: double crests, scarps and counter-slope scarps, slope-parallel trenches, tension cracks in the upper slopes, and bulging lower slopes not necessarily associated to a continuous slip surface; also small-scale landslides, debris flows, and talus slope deposits are commonly associated to DSGSD (Ter-Stepanian, 1966; Radbruch-Hall et al., 1977; Varnes et al., 1988; Agliardi et al., 2001; Tibaldi et al., 2004). The origin and evolution of DSGSD are influenced, more often than in the case of smaller-scale gravitational phenomena, by the local structural setting and the presence of rheological contrasts (Dramis, 1984; Varnes et al., 1989; Dramis and Sorriso-Valvo, 1994; Thompson et al., 1997; Agnesi et al., 2000; Agliardi et al., 2001; Kellogg, 2001; Onida, 2001; Di Luzio et al., 2004a,b).

The kinematic processes involved in the evolution of a DSGSD are still not completely understood, although it is widely accepted that DSGSD show, in the initial and intermediate deformational stages, an evolution by gravitational creep (Genevois and Tecca, 1984) characterized by small displacement rates (Saroli et al., 2005). This process can change to accelerated creep, and then evolve to catastrophic collapse, for several different causes (Dramis, 1984; Genevois and Prestininzi, 1979; Nemcok and Pasek, 1969; Panizza, 1973). In tectonically active areas, one of the most invoked, but seldom observed, triggering factors is the seismic shaking (Dramis, 1983; Radbruch-Hall, 1978; Sorriso-Valvo, 1988). The technique of satellite Differential SAR Interferometry (DInSAR, Massonnet and Feigl, 1998), allows to quantify the surface deformation due to large, earthquake induced, gravitational phenomena, as we will show in the following for the area of the Umbria-Marche seismic sequence.

In September – October 1997, a seismic sequence occurred in the Umbria – Marche Apennines (Central Italy). The sequence started on September 26, with two mainshocks that were close in time (Mw = 5.7 at 00:33 GMT, and Mw = 6.0, at 09:40), and struck the Colfiorito basin, a Quaternary tectonic depression filled with continental deposits. A third event (Mw 5.7) was recorded on October 12, in the Sellano area, about 15 km south. The seismic sequence induced surficial breaks over a NW-SE 25 km-long area (Galli et al., 1997; Cello et al., 1998; Cinti et al., 1999), controlled by two major SW-dipping normal faults: the M. Pennino-M. Prefoglio and the M. Civitella-Preci faults (Boncio and

Lavecchia, 2000). Focal mechanism solutions and aftershock distributions defined fault planes characterized by a dip of about 40° SW (Fig. 1; Amato et al., 1998; Ekström et al., 1998).

A clear representation of the static displacement field due to the three mainshocks, was obtained through Differential SAR Interferometry (InSAR) and campaign Global Positioning Surveys (GPS) (Stramondo et al., 1999; Anzidei et al., 1999). These observations were used, together with seismological data, to model the fault dislocations and their slip distribution (Hunstad et al., 1999; Salvi et al., 2000; Lundgren and Stramondo, 2002; Santini et al., 2004; Hernandez et al., 2004). A minor part of the interferometric fringes (Fig. 1) were not explained by the co-seismic deformation models, and residuals between modeled and observed displacements remained large at some places (Salvi et al., 2000). Moreover, numerous field observations reported the actual presence of non-tectonic deformation on a local scale, as ground fractures and centimetric slip on pre-existing tectonic fault planes (Galli et al., 1997; Basili et al., 1998). In fact, the ground shaking triggered hundreds of landslides in the epicentral area (Esposito et al., 2000), mainly due to the steep relief and the favourable clayey lithologies (Fig. 2).

In this paper we revisit the geodetic observations, and based on a detailed photo-interpretation and new field surveys, we propose that part of the surface deformation observed by InSAR and GPS during the Colfiorito seismic sequence, was caused by reactivation of pre-existing deep seated gravitational slope deformations. Our results also suggest that the identification of DSGSD is a useful step in a geophysical modeling procedure.

2. Seismotectonic framework and geological setting

Since Neogene time, the Central Apennine developed as an east-verging fold and thrust belt (Bally et al., 1986), accreted owing to the contemporaneous flexural-hinge retreat of the Adria plate and the back-arc opening of the Tyrrhenian basin (see Meletti et al., 2000 and references therein). This portion of the Apennines exhibits a complex pattern of thrusts, strike-slip faults, folds and normal faults due to the superposition of two main phases of tectonic activity, (Lavecchia et al., 1994; Barchi et al., 1998; Tavarnelli, 1999). The first compressional phase took place during the Upper Miocene-Lower Pliocene and is responsible for the formation of the E-NE verging fold and thrust belt. The second phase started in the Upper Pliocene and generated extensional basins bounded by NW-SE to N-S trending normal faults (Fig. 2).

The present-day NE trending extensional stress field, revealed by geodetic data (D’Agostino et al., 2001), focal mechanisms (Chiaraluce et al., 2003) and borehole breakout (Mariucci et al., 1999), is related to the persistence of back-arc extension. Evidence of active faulting on NW-SE trending, SW-dipping, normal faults, is mainly concentrated along the axial belt, where the strongest historical (Intensity = XI) and instrumental seismicity (M > 5.8) occurs (Fig. 1; Working Group CPTI, 1999; Barchi et al., 2000 and references therein).

From a geological point of view the study area is localized in a portion of the Umbria-Marche Apennines known as the Inner Ridge (Scarsella, 1951; Lavecchia and Pialli, 1980), a carbonatic sequence constituted by rift and passive margin sediments. The stratigraphy shows Lower Liassic massive carbonate platform (Calcare Massiccio fm), superimposed on a Middle Lias-Middle Eocene pelagic sequence of cherty limestones (Corniola fm to Scaglia Rossa fm) and marly formations (Rosso Ammonitico fm to Scaglia Cinerea fm, Fig. 2).

In the sector of the Mt. Le Scalette-Mt. Prefoglio anticline, a reduced Jurassic sequence is present, comprising also the Marne a Fucoidi and the Scaglia Bianca fms (Colacicchi et al., 1970; Centamore et al., 1971). In the M. Prefoglio area, near Colfiorito, these units are in stratigraphical contact with the Liassic Calcare Massiccio fm; in the M. Pennino area the latter is instead in tectonic contact driven by Jurassic normal faults (Fig. 2).

The last deformational phase recognized in this portion of Apennines generated a local high relief that, together with the weakness of some of the rocks, are responsible for the development of deep-seated gravitational slope deformation (DSGSD) processes (Pasquarè, 2001 and references therein).

3. Surface deformation from DInSAR

Differential SAR Interferometry (DInSAR), is a processing technique which uses two Synthetic Aperture Radar (SAR) satellite images, to obtain a map of the ground deformation occurred in the time interval Δt between the data acquisitions (Massonnet and Feigl, 1998). If any deformation has occurred, an interferogram obtained from the image pair will show some bands (fringes) depicting, in a way similar to contours, the patterns of ground movement, as phase values varying from $-\pi$ to $+\pi$ (for the ERS satellites this interval equals 2.8 cm). Interferograms may then be “unwrapped”, i.e. the actual spatial variation of the ground movement can be restored. The latter must be seen in terms of lenghtening or shortening of the distance between the satellite and the ground, thus directed along the so-called Line of Sight (LoS). The LoS has an angle to the ground vertical of ~23°, but its direction varies: it looks approximately from the East during the descending pass, and from the West from the ascending one. This makes possible sometime to obtain information on the vertical and East-West horizontal components of the ground movement.

A large literature is available on DInSAR applications to several fields of the Earth Science (see ASF, 2006), with the majority of them being relative to mapping of the co-seismic displacement field of large earthquakes.

The moderate-magnitude mainshocks of the Colfiorito seismic sequence were the first to occur in Italy after the technique of Differential SAR Interferometry was fully developed. Notwithstanding the strong temporal decorrelation, due to the unfavourable environmental conditions, well defined fringe patterns associated with the coseismic surface deformation were visible in at least four different SAR differential interferograms from ascending and descending orbits (Salvi et al., 2000; Lundgren and Stramondo, 2002). These data were modeled by various authors using direct and inverse approaches, based on the Okada (1985) formulations. In the modeling, other independent constraints such as geometrical parameters from CMT solutions (Ekström et al., 1998), GPS displacements (Hunstad et al., 1999), ground motion data (Hernandez et al., 2004), hypocentral distribution of aftershocks, and surface geology (Salvi et al., 2000) were used. Models elaborated using different approaches and data yielded essentially similar results for parameters as dip, strike, length and depth of the seismogenic faults, indicating that the Colfiorito sources could be well resolved.

Still, the proposed models do not explain all the observed deformation. Fig. 3 shows the absolute value of the difference between the deformation field simulated using the best fault model by Salvi et al., 2000 (ModColf) and the deformation actually observed by DInSAR. Although the residuals in some areas show a RMS within the data uncertainty (2 cm, Salvi et al., 2000), in other areas they were as much as a factor of 3-4 higher. In the following section we will examine these areas of high residuals (A to E in Fig. 3) to establish whether the high residuals might be attributed to unmodeled dislocation complexities or might instead be related to other geological causes. Next, we will jointly discuss the DInSAR data and the geological and morphological evidence to seek for an explaination of these “anomalous” deformations.

3.1. Area A – Costa Picchio

The high residuals north of Nocera Umbra are caused by some isolated fringes (twoo on the ascending interferograms, and three on the descending ones; Fig. 4), showing a sense of ground displacement not compatible with the expected displacement pattern of a fault dislocation (Fig. 3).

The anomalous fringes are evident in all the interferograms, starting from the one temporally closer to the mainshocks (only few minutes after the 09:40 event), meaning that the related ground movement was indeed co-seismic (Salvi et al., 2000). The observed deformation was not caused by seismic dislocation, since an earthquake of at least magnitude 5 would be required to cause such surface displacement (Wells and Coppersmith, 1996), and none occurred in that area during the entire seismic sequence. For this area only the displacement signal is visible on both the descending and the ascending interferograms, allowing an estimate of the actual ground displacement direction.

The descending interferograms show a ground displacement of ~8 cm away (westward) from the satellite (Fig. 4), while along the ascending LoS the ground-to-satellite distance was shortened by a minimum of ~5 cm, also in the westward direction (Fig. 4). Hence, we roughly estimate a bulk horizontal ground movement of a few centimetres towards the West, and a minor vertical negative displacement.

3.2. Area B – Mt. Pennino

In this area, according to Salvi et al., (2000), the unwrapped DInSAR phase yields a slightly negative co-seismic displacement, on the descending Line Of Sight (-0.9 cm), within the InSAR data uncertainty, while the GPS monument named PENN (located close to the top of Mt Pennino) shows a planar displacement of ~11 cm towards the NE, and a vertical movement of -3.5 cm. However, the co-seismic displacement at PENN should show an uplift, since this station is located in the footwall of the normal fault. For this reason, this “anomalous” negative displacement was attributed to an observational error and was never used in any of the modeling attempts.

3.3. Area C

As shown in Fig. 3 there are in general high residuals along the area of maximum fringe gradient. Here the differences between model and observations can either be attributed to a larger error in the data, and/or to unmodeled local complexities of the displacement field. The former can occur where the displacement gradient is higher than one fringe per pixel (Massonnet and Feigl, 1998), or where the dense fringe pattern degrades the phase unwrapping (Rosen et al., 2000). The latter might arise from near-surface effects along the fault surfaces, as co-seismic tilts or rotations of small blocks (Peltzer et al., 1994).

3.4. Areas D and E – Mt. Prefoglio and Mt. Le Scalette

Here the SAR data, although sparse and rather noisy, indicate negative ground displacements of 2-4 cm, while the best fit model yields 2-3 cm of uplift (Fig. 5). The upper termination of the modeled normal-oblique dislocation is located at a depth of ~ 2 km (Salvi et al., 2000), and its surface projection along the fault dip corresponds to a normal fault trace along the Mt. Le Scalette-Mt. Prefoglio south-western slope (Figs 1, 2 and 5). Here the observed displacement is underestimated (Fig. 5), showing a peculiar pattern which cannot be easily reconciled with the modeled fault, even allowing for an heterogeneous slip complexity. The relative subsidence of 2-3 cm (along the LoS direction) observed across the SW mountain front of the Mt. Prefoglio range (Fig. 5), is well over the observation uncertainty (conservatively estimated as ±2.5 cm, rather than ±2 cm reported in Salvi et al., 2000), and cannot be explained by the fault model.

4. Evidences of deep seated gravitational slope deformations

We carried out a detailed photogeological analysis over the areas where anomalous surface deformation was observed. Except for area C, such analysis allowed us to identify widespread evidence of morphological elements associated to DSGSD (Fig. 6), as double crest lines, scarps and counter-slope scarps, trenches, fractures, and depression alignments.

In particular, in the high relief areas of the Costa Picchio monocline, Mt. Pennino and Mt. Prefoglio, double crest lines and trenches, associated with a high production rate of debris deposits, landslides, and talus slope deposits, have been observed. The upper limits of the DSGSD, appear in the most cases close to large fault surfaces, and typically show a downslope concavity. The orientation and density of the morphological elements related to the DSGSD do not seem to be compatible with the main tectonic fabric, but with gravity-related processes. Other observed elements, such as scarps and counterslope scarps, suggest the recent activity of the DSGSD.

Costa Picchio (Fig. 6) is a gentle W-facing, <10°-dipping slope belonging to a NNW-striking monocline; here the largest DSGSD observed is a ~200 m-thick block slide of downslope dipping strata of the pelagic carbonatic units (“Scaglia Rossa”, “Scaglia Bianca”, and “Calcare rupestre” formations). In this context, the more plastic “Marne a Fucoidi” formation seems to act as a weak layers which favors the mass movement towards the WSW. A more local, but similar type of DSGSD has been recognized also on the northern side of Costa Picchio, where two blocks show a movement direction towards the NNW, inside the Feggio Valley (Fig. 6). The direction of the ground displacement detected by DInSAR is consistent with the geologically-determined direction of block sliding of the main DSGSD in the Costa Picchio monocline.

Mt. Pennino is part of a NS, east verging asymmetric fold, characterized by the presence of block sliding on both sides. Along its western flank this process is driven by the strata configuration, i.e. downslope dip. At the foot of this slope, during a paroxystic event, the DSGSD dammed the N-S valley which originally drained to the north. This caused a drainage flow inversion and the formation of the Piana di Annifo basin. On the eastern and steeper flank of the Mt. Pennino there is also evidence for block sliding with a movement direction towards the east. The PENN GPS station is located on the upper part of the eastern DSGSD, and its mentioned "anomalous" negative displacement may reasonably be attributed to the reactivation of such block sliding. Since PENN should have recorded the co-seismic uplift of the fault footwall, we consider the -3.5 cm displacement as a minimum value for the DSGSD vertical movement. As for the planar displacement of PENN, the fact that most dislocation models could not explain more than 60% of the observed 11 cm (Fig. 3), strongly suggests that a fraction of it should be attributed to gravitational movement. The exact timing of the latter cannot be ascertained, since the first GPS campaign dates back to 1995.

In areas D and E, other evidence of block sliding has been found (Fig. 6), the largest of which is affects the Mt. Prefoglio anticline. Here the top of the DSGSD is limited by a deep trench (Figs. 6 and 7), which follows in the upper part the trace of an old NW-SE oriented, SW dipping, normal fault. The observed morphological patterns indicate a direction of movement towards the Colfiorito plain (west). The deformation observed by DInSAR along the Mt. Prefoglio western slope corresponds to what could be expected in case of reactivation of this DSGSD (Fig. 5). In this case too the vertical and horizontal components of displacement cannot be separated, but they are in the range 2-5 cm.

The last area, C, does not show any evidence of large gravitational movements that could have caused the high residuals discussed in the previous section.

5. Conclusions

We re-assessed the origin of the ground deformation observed by DInSAR and GPS that occurred during the two events of September 26th of the Colfiorito seismic sequence. We found four main areas which display deformation patterns not compatible with fault dislocation models; a detailed photogeological analysis and field investigations allowed us to identify widespread surficial evidence of deep seated gravitational slope deformations.

In all these areas the observed ground deformation is compatible with block slide mechanisms of large masses of carbonatic units, driven by tectonic or lithological/rheological discontinuities. The DSGSD are located on the footwall areas of large normal faults, and represent the result of the long term gravitational response to the tectonic uplift. The strong seismic input (ground accelerations over 1g were observed in the area by Bouchon et al., 2000) triggered a reactivation of the movement of these block slides. For the Costa Picchio and Mt. Prefoglio areas, the gravitational deformation was actually co-seismic, since the fringes are observed in an interferogram only few minutes after the 09:40 mainshock. For the Mt. Pennino and Mt. Le Scalette structures, the timing of the deformation is not similarly well defined, but we found no triggering causes (i.e. weather–related) other than the seismic input. The DInSAR data also show that the ground movement did not increase considerably later in the seismic sequence, at least up to October 12th (date of last post-seismic image, see Salvi et al., 2000).

The maximum range of observed DInSAR displacements is between +5 and -8 cm, and at least for area A (Costa Picchio), a strong horizontal component is evident from the comparison of the descending and ascending data.

The use of space geodetic data, coseismic dislocation modeling, and photogeological analysis allowed us for the first time to verify the seismic triggering of DSGSD previously hypothesized by many authors. The general pattern and amount of displacement were well resolved, although the noisy DInSAR data did not allow a more quantitative and spatially continuous evaluation of the deformation.

The amplitude of the ground shaking induced by the moderate-magnitude Colfiorito earthquakes was sufficient to trigger reactivation of movement of pre-existing DSGSD. Although this cause-effect relationship does not likely follow a linear behaviour, we hypothesize that the effects of stronger amplitudes and durations associated to larger earthquakes, might increase the number of reactivated DSGSD, statistically increasing the possibility of a catastrophic collapse of one of them.

As a final remark, we note that, in particular geologic contexts, the surface displacement field observed after a strong earthquake may contain a term due to the actual fault dislocation, and an additional term due to large scale gravitational processes (DSGSD). Although the latter will show in general a much shorter spatial wavelength (kilometres vs. tens of kilometres), it can affect the quality of those models which attempt to explain the local complexities of the fault dislocation. In this cases it is advisable to carry out a detailed investigation to separate the deformation terms due to DSGSD from those due to shallow fault slip heterogeneities.

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Figure Caption

Fig. 1. Instrumental seismicity of the study area during the period between 1981 and 2002. The 1997 Umbria-Marche earthquake focal solutions and the trace of the normal active faults (red lines) are also shown. White lines represent displacement contours extracted from the interferometric fringes; contour interval is 2.8 cm. Dashed white line represent the area in figure 2.

Fig. 2. Simplified geological sketch map of the study area. (1) continental deposits (Holocene-upper Pliocene; (2) terrigenous deposits (upper Miocene); (3) (a): carbonatic-marly deposits (Oligocene-Dogger); (b): Marne a Fucoidi fm (middle Cretaceous); (4) Calcare Massiccio fm and Corniola fm (Lias-upper Trias); (5) anticline axis; (6) fault.

Fig. 3. Absolute residuals, in cm, between the observed and the modeled co-seismic deformation (data and model from Salvi et al., 2000). Colour scale shows the residuals to the DInSAR observations. Red and black arrows show observed and model-predicted GPS displacements, respectively. Letters A to F indicate the areas with largest residuals, discussed in the text. Black contours as in figure 1. Noisy areas of the interferogram have been masked.

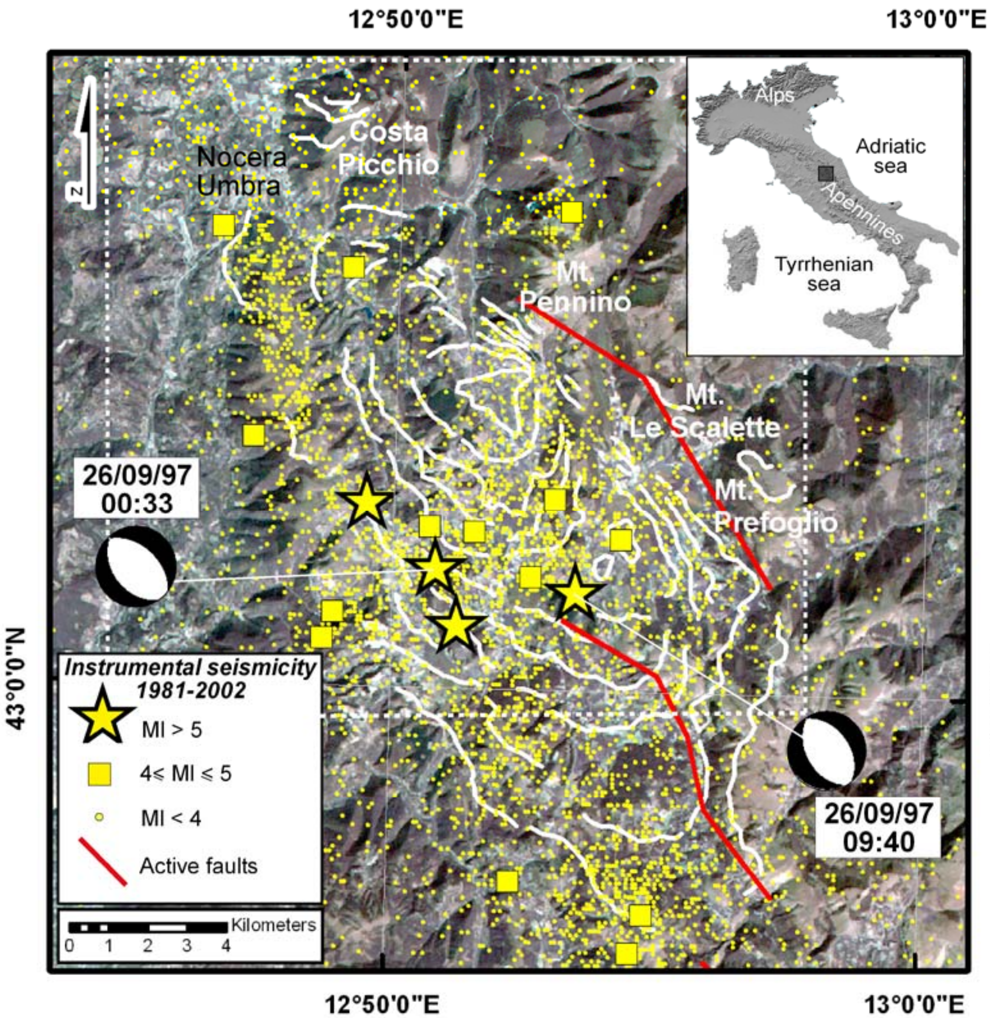
Fig. 4. Ground displacement measured by DInSAR interferograms in the Costa Picchio area (A in Figure 3). a) ascending LoS interferogram; b) descending LoS interferogram; c) displacement profile on the ascending interferogram; d) displacement profile on the descending interferogram; e) shaded relief showing the profile trace, and the general direction of ground movement resultant from the composition of the displacement observed along the two LoS. In a) and b) the visible fringes are outlined in black.

Fig. 5. Profiles showing: topography (thin line), observed ground displacement (thick line), and modeled ground displacement (dashed line, from Salvi et al., 2000). Error bars show maximum uncertainty of displacement observations (±2.5 cm). The arrow shows the approximate location of the up-dip projection of the best fit model fault of the 00:33 earthquake.

Fig. 6. (a) Aerial photography 9142, Strip 40, Volo Italia 1988–89, 1:70 000 in the Costa Picchio and Mt. Pennino areas; (b) observed features of DSGSD from the photography; (c) aerial photography

9076, Strip 41, Volo Italia 1988–89, 1:70 000 in the Mt. Prefoglio area; (d) observed features of DSGSD from the photography.

Fig. 7. Three-dimensional view and simplified geological cross-section for the Mt. Prefoglio DSGSD. (1) carbonatic deposits (Lower Cretaceous); (2) continental deposits (upper Pliocene-Holocene); (3) normal fault; (4) principal shear surfaces reactivated by gravity.



12°50'0"E
13°0'0"E
Costa Picchio
Nocera Umbra
Mt. Pennino
Mt. Le Scalette
Mt. Prefoglio
Alps
Adriatic sea
Apennines
Tyrrhenian sea
26/09/97 00:33
26/09/97 09:40
43°0'0"N
Instrumental seismicity 1981-2002
Ml > 5
4≤ Ml ≤ 5
Ml < 4
Active faults
Kilometers
0 1 2 3 4

Fig. 1

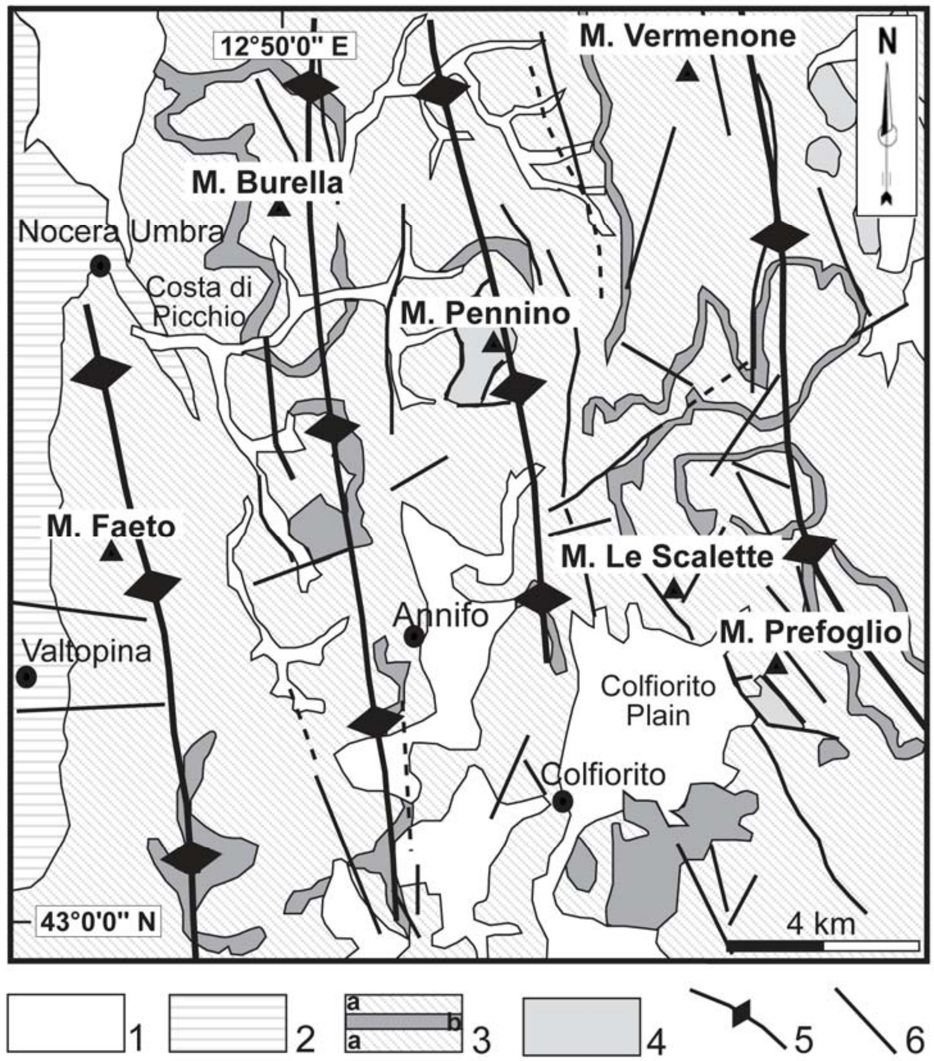

12°50'0'' E
M. Vermenone
N
M. Burella
Nocera Umbra
Costa di
Picchio
M. Pennino
M. Faeto
M. Le Scalette
Annifo
M. Prefoglio
Valtopina
Colfiorito
Plain
Colfiorito
43°0'0'' N
4 km
1
2
a
b
a
3
4
5
6

Fig. 2

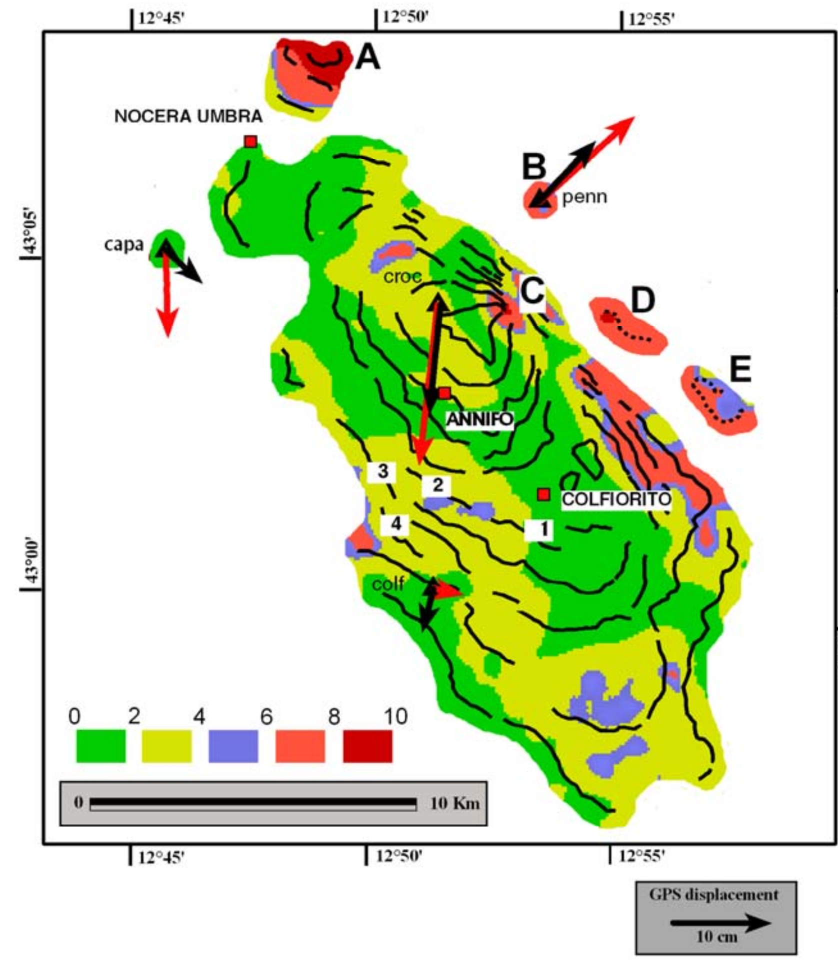

12°45'
12°50'
12°55'
43°05'
43°00'
A
NOCERA UMBRA
B
penn
capa
croe
C
D
E
ANNIFO
3
2
COLFIORITO
4
1
colf
0
2
4
6
8
10
0
10 Km
GPS displacement
10 cm

Fig. 3

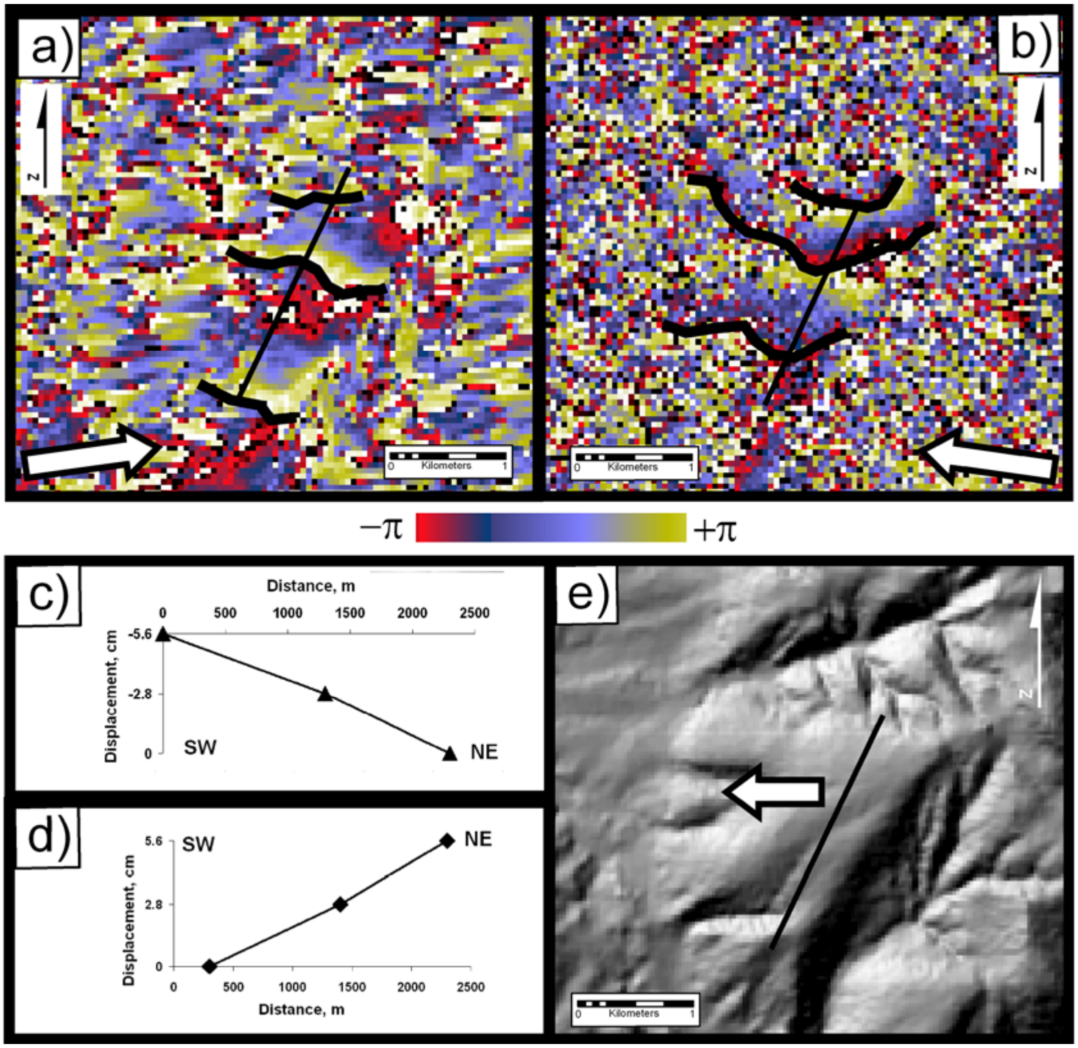

a)
b)
Kilometers
0
1
−π
+π
c)
Distance, m
0
500
1000
1500
2000
2500
-5.6
-2.8
0
Displacement, cm
SW
NE
d)
5.6
2.8
0
Displacement, cm
SW
NE
0
500
1000
1500
2000
2500
Distance, m
e)
Kilometers
0
1

Fig. 4

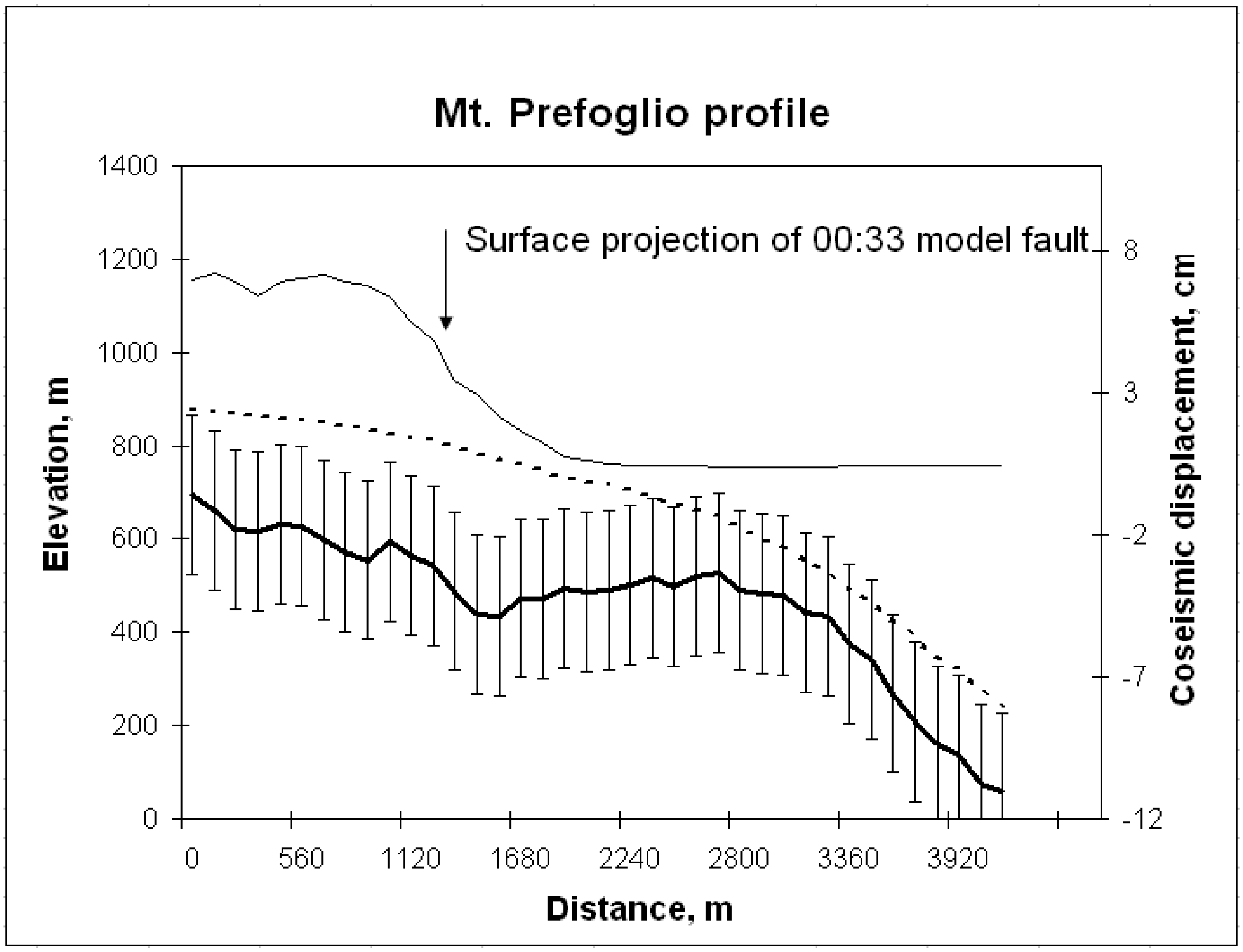

Mt. Prefoglio profile
Surface projection of 00:33 model fault
Elevation, m
Coseismic displacement, cm
Distance, m
1400
1200
1000
800
600
400
200
0
8
3
-2
-7
-12
0
560
1120
1680
2240
2800
3360
3920

Fig. 5

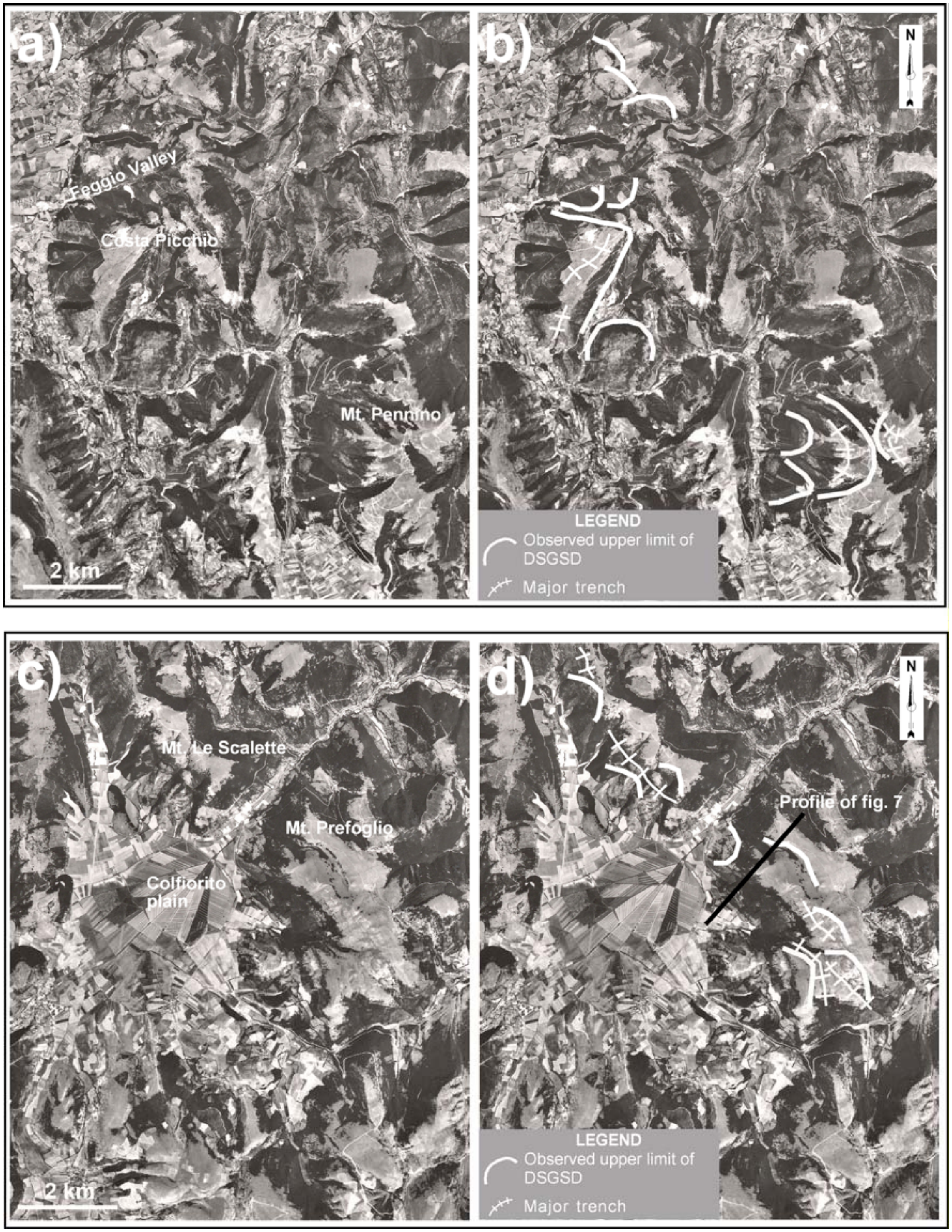

a)
Feggio Valley
Costa Picchio
Mt. Pennino
2 km
b)
N
LEGEND
Observed upper limit of DSGSD
Major trench
c)
Mt. Le Scalette
Mt. Prefoglio
Colfiorito plain
2 km
d)
N
Profile of fig. 7
LEGEND
Observed upper limit of DSGSD
Major trench

Fig. 6

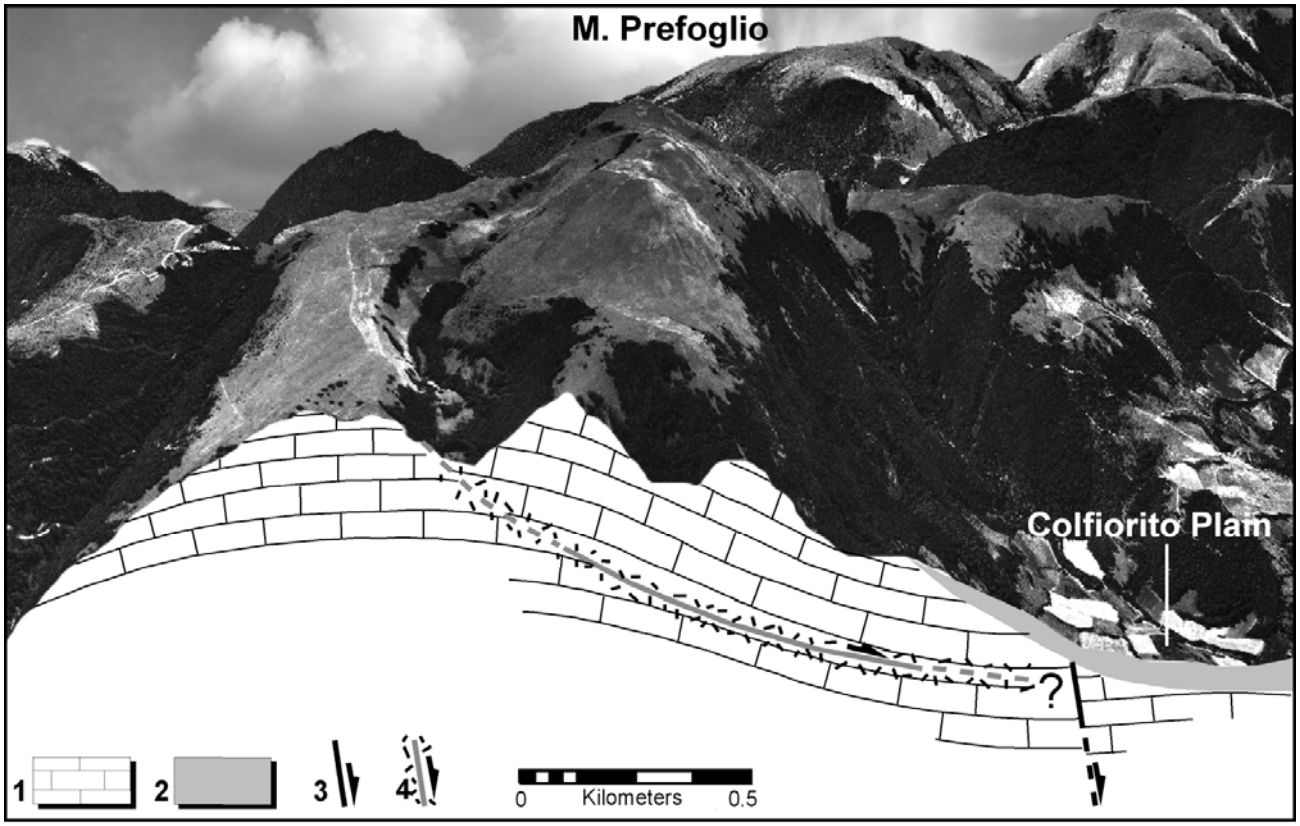


Fig. 7