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ORIGINAL PAPER

Structurally controlled earth flows of the Benevento province (Southern Italy)

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Abstract The paper reports an investigation into the distribution and type of landslides in the Benevento province in southern Italy, between 2001 and 2008. Field mapping was undertaken at various scales up to 1:10,000 depending on the features identified. Landslide types were recognized within 5-group litho-technical sequences cropping out in the province, grouped according to their similar mechanical and lithological features. The analysis showed a widespread diffusion of Earth Flows, with reactivation linked to both rainfall and seismic events. They are structurally controlled related to bedding, stratigraphic/tectonic contact between more and less competent sequences and a high degree of tectonisation.

Keywords Landslides · Earth flows · Structural control · Mapping · Benevento Southern Italy

Résumé L'article présente une recherche sur la répartition et les types de glissements dans la province de Benevento dans l'Italie du Sud entre 2001 et 2008. La cartographie de terrain a été réalisée à diverses échelles jusqu'au 1/10,000 en fonction des caractéristiques identifiées. Les mouvements de terrain ont été identifiés au sein de 5 ensembles lithostratigraphiques présents dans la province, définis sur la base de caractéristiques géomécaniques et lithologiques similaires. L'analyse montre une large répartition des coulées de boue, leur réactivation étant liée à la fois à des événements pluviométriques et sismiques. Elles sont contrôlées par des facteurs structuraux relatifs à la stratification, à des contacts stratigraphiques ou tectoniques entre des unités de compétences différentes et à des forts degrés de tectonisation.

Mots clés Glissements · Coulées boueuses · Contrôle structural · Cartographie · Benevento · Italie du Sud

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Introduction

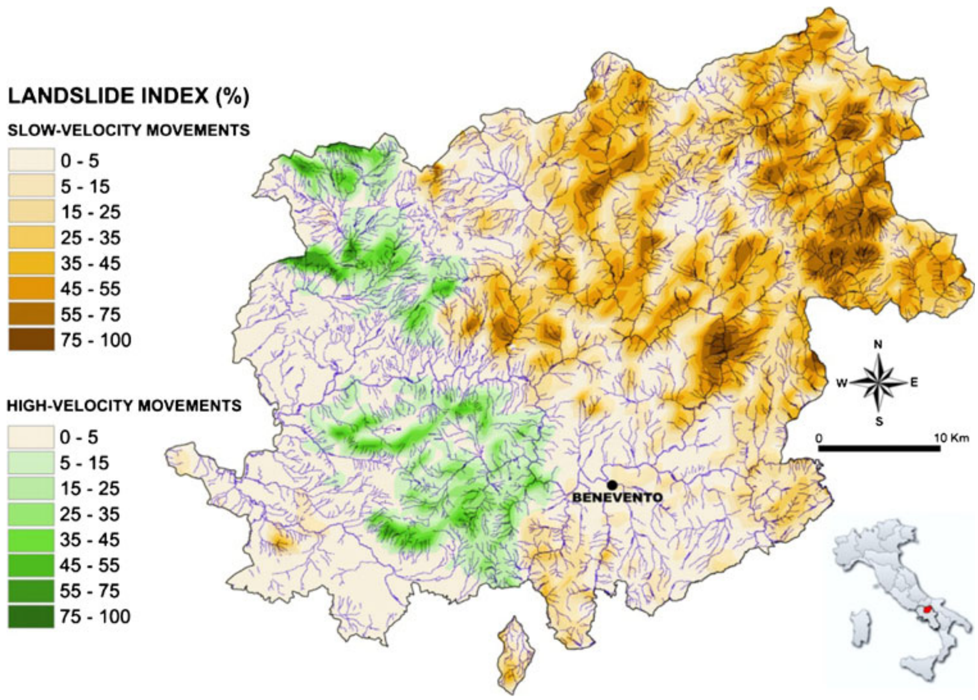
The Campania Apennines are characterised by slope instabilities which recur in both time and in space, such that a large part of the area can be considered one of high risk (Guadagno et al. 2005; Revellino et al. 2008).

As a consequence of the outcropping of clayey and structurally complex formations, earth flows are particularly widespread in the Benevento province and mass movements involve built-up areas and infrastructures. Figure 1 shows the Landslide Index (LI), calculated as the percentage of area affected by landslide events per 1 km^2 grid for the whole province. The figure differentiates high-velocity landslides, such as rock falls, debris avalanches and debris flows and slow movements (mainly earth flows) and it can be seen that in some locations the LI reaches values as high as 75% or more.

The landsliding processes are the result of the complex geological setting and evolution of the region, although recent occurrences demonstrate that man's activities, e.g. increasing urbanization, agricultural and forestry practices etc., have an important effect on land degradation. The change in the activity of the landslides is the key point for planning in these areas. Where the landslides occur is mainly influenced by the geo-structural setting and hence an understanding of this is essential when evaluating the future behaviour of slopes.

Geological and geomorphological surveys were carried out to produce a multi-temporal landslide inventory map of

Fig. 1 Spatial distribution of landslides in the province of Benevento and location of the study area



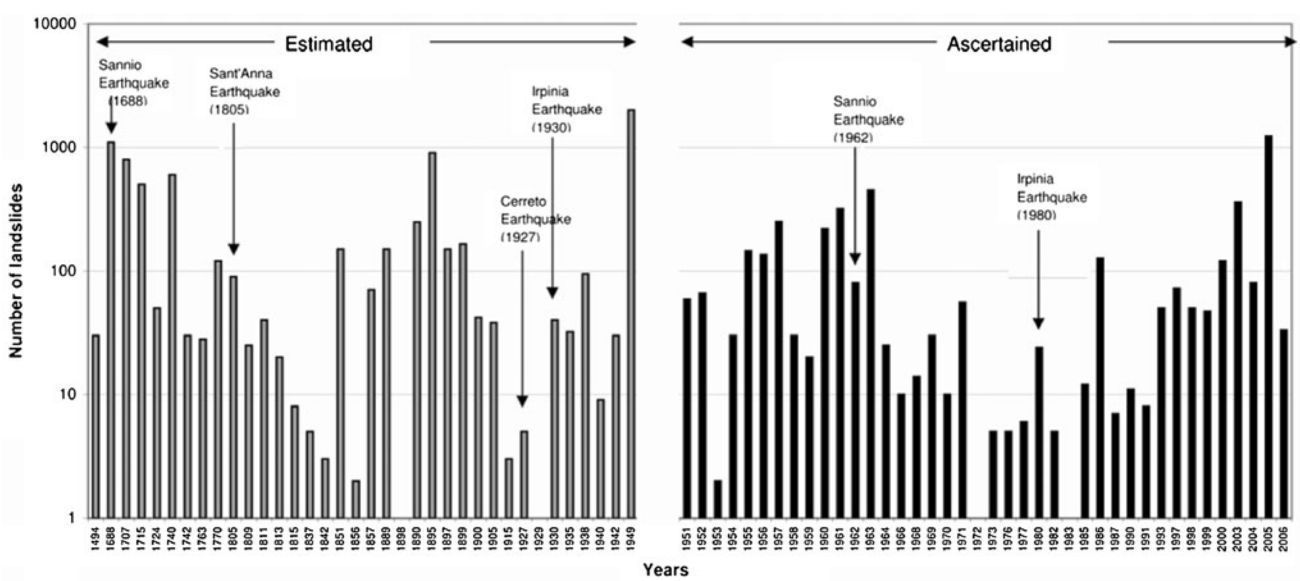


Fig. 2 Distribution of the estimated and/or ascertained number of landslides per year, from 1494 to 2006, in the province of Benevento

the Benevento sector of the Apennines (Guadagno et al. 2006). Basis on this information, the paper points out the influence of the geological and structural setting on the occurrence and evolution of earth flows in the study area, highlighting the role of the distribution of the activity proposed in WP/WLI in hazard assessments (1993a, b).

Historical landsliding

Guadagno et al. (2006) provide a background to the analysis of landslides in this area and discuss a number of historical documents which describe the damage scenario and the social effects. In addition, data on the occurrence of landslides have been obtained from such authors as Magnati (1688), Valentini (1967), Vallario (1973), Corniello et al. (1979), D'Elia et al. (1985), Abate and L'Altrelli (1995), Esposito et al. (1998). All the past work has drawn attention to the fact that the landslides are generally linked to either heavy/cumulative rainfall and/or to seismic events with specific characteristics in terms of intensity.

Figure 2 shows the estimated (a) and ascertained (b) number of landslides per significant seismic and/or

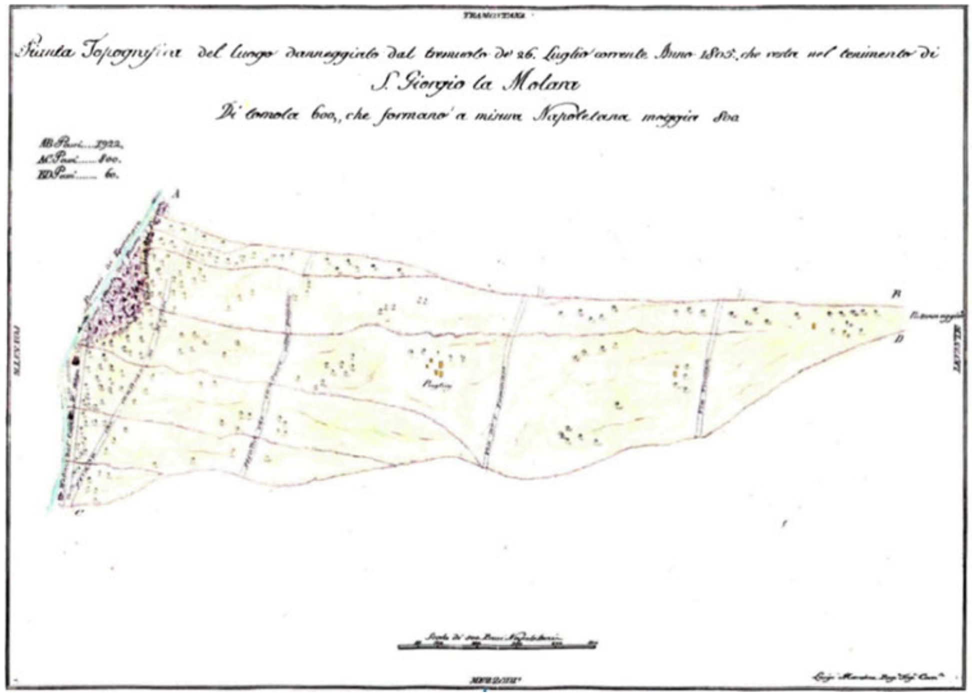


Fig. 3 Historical schematic map of part of the *Santo Ianni* landslide, draw up by eng. Luigi Marchese after the 1805 earthquake, showing the ground effects (Archivio Di Stato Di Napoli)

meteorological event from 1494 to 2006 for the whole of the Samnite area, highlighting the recurring and widespread nature of the landsliding. From 1951 (Fig. 2b) the number of occurrences for each event are based on objective data including that obtained from aerial photos and other records. The number of landslides for the previous time period (Fig. 2a) was estimated comparing the effect of recent rainfall/seismic events on the environment with reconstructions of the consequence of historical floods provided by Diodato (1999) and Mazzarella et al. (2002).

The Benevento area is one of high seismic hazard and landsliding can be an important secondary effect. A number of landslides were recorded for each strong earthquake, e.g. 1688 and 1805 (Fig. 2). The "*Santo Ianni*" landslide, for example, which reactivated in the municipality of San Giorgio la Molara following the earthquake of 1805, was recorded by Luigi Marchese (Fig. 3). He shows the displacement of the infrastructure as well as the landslide itself and records the overall length was about 3,545 m (AB on Fig. 3) and the maximum width, about 1,470 m (AC on Fig. 3), based on the measurements used at the time (*passo*, literal translation *step*; 1 *passo* is equivalent to about 1.84 m). The reactivation of the landslide body dammed the course of the Tammaro River for a section of about 750 m, forming a temporary lake upstream.

When earthquakes occur in clayey environments such as the study area, landsliding is a significant associated hazard. As demonstrated by the May 2008 Sichuan earthquake in China (Tang et al. 2009), earthquake-triggered landslides not only have severe consequences of themselves in inhabited areas but can also lead to serious delays in the aid operations, e.g. by blocking roads etc.

The geological environment

The Benevento province, which extends for about 2,000 km^2, is in one of the most geologically complex areas of the Southern Apennines, with Neogene thrust-belt structures resulting from north-east tectonic movements of the African-Adriatic plate (D'Argenio et al. 1973; Patacca and Scandone 1989). The regional unconformity is a consequence of the development of wedge-top/piggy-back basins on top of the forward-migrating thrust sheets. As a consequence, marine successions from the Cretaceous to the Pliocene and continental deposits of Pleistocene age outcrop in the area.

The morphology is strongly influenced by the structural setting. The western portion of the province is characterized by the presence of calcareous mountains, while the eastern sector has a hilly morphology. In contrast, the central area is a depression where marine and continental clastic deposits of Pleistocene age outcrop and through which the main rivers flow.

The deposits outcropping in the province were grouped into successions on the basis of their lithology and engineering-geological/geomechanical features in order to elucidate the relationship between landslides and the geological formations (Table 1). Following Guadagno et al. (2006), a rough evaluation of GSI (Hoek et al. 1998),

Table 1 Mechanical and lithological characteristics of the sequences outcropping in the province of Benevento

Group of sequences		Lithotechnical sequences		Competence	Setting	Indices **GSI** ***RMR*** ESU (1997)
1	Dominantly pelitic, from low-degree to medium-degree of tectonization	Clayey-silty (Ag-L)		Incompetent	Stratified, generally monoclonal	**25–36** A1–B2 A2
2	Dominantly pelitic, high-degree of tectonization	Clayey-marly (Ag-M) Clayey (Ag)		Complex dominantly incompetent	From mildly to intensely folded scaly clay	**15–31** B3
3	Stony, from low-degree to medium-degree of tectonization	Calcareous (Ca)		Stony	Well stratified strata and layers (from 30–40 cm to 5–10 m)	**34–84** ***24–77***
		Conglomeratic (Cg)		Stony	Sometimes stratified	
		Tuffaceous (Tf)		Weakly lithified	Up to 30 m banks. Columnar jointing	**48–65**
4	Stony and complex, high-degree of tectonization	Calcareous (Ca)	Fully Calcareous	Stony	Well stratified and highly tectonized	**9–42** ***23–52*** B2–B3
			Calcareous-clayey	Complex, dominantly stony	Well stratified strata and layers. Intensely jointed and folded.	
		Arenaceous-clayey Arenaceous- conglomeratic (Ar-AgCg)		Complex	Arenaceous and conglomeratic layer, thin horizons of marl, clay and conglomerate. Intensely jointed and folded.	
5	Coarse clastic and/or inhomogeneously lithified	Sandy-arenaceous (S–Ar)		Inhomogeneous lithification	Generally stratified and well stratified	
		Alluvial (Al) Fluvial (Fl)		Incompetent or weakly cemented	Unclear bedding	
		Cemented detrital (Dc)		Inhomogeneous lithification	Irregular bedding	
		Uncemented detrital (Ds)		Incompetent or locally weakly cemented	Irregular bedding	

Approximate values of GSI indices (Hoek et al. 1998), RMR (Bieniawski 1989) and types of complexities (ESU 1977) after Guadagno et al. (2006)

Fig. 4 Typical successions outcropping in the province of Benevento: **1** Clayey-silty succession (Group 1), **2** Alternations of scaly red clays and marly limestone (Group 2), **3** Typical carbonate sequence with medium degree of tectonization (Group 3), **4** Sandstone with silty clay horizons (Group 4), **5** Terraced alluvium (Group 5)

RMR (Bieniawski 1989) and types of complexities (ESU 1977; AaVv 1985) was undertaken to qualitatively classify the stony masses and structurally complex formations. Soil formations were classified on the basis of laboratory tests, such as reported by Grelle and Guadagno (2010).

The main groups identified are listed below and some examples of the lithotypes are given in Fig. 4

1. Group 1—dominantly pelitic sequences (from low-degree to medium-degree of tectonization);
2. Group 2—dominantly pelitic sequences (high-degree of tectonization);
3. Group 3—stony sequences (from low-degree to medium-degree of tectonization;);
4. Group 4—stony and complex successions (high-degree of tectonization;);
5. Group 5—coarse clastic and/or inhomogeneously lithified sequences.

The map in Fig. 5 shows the areal distribution of the lithotechnical sequences forming the five groups described in Table 1. It can be seen that the highly tectonized clayey and stony formations (Groups 2 and 4) outcrop widely. Comparison with Fig. 1 indicates these areas correspond to the sectors which are the most involved in erosion and landslide processes.

Landslides of the Province of Benevento

In order to investigate the distribution and type of failures and their correlation with the lithostructural and morphological setting, a landslide inventory map of the province was compiled on a 1:75,000 scale (Guadagno et al. 2006; a hard copy of the map can be requested by e-mail from the authors). The surveys were performed on the basis of a 1:25,000 scale topographic map, whereas specific areas, characterized by the presence of typical landslides and towns or infrastructures, were surveyed on more detailed maps (greater than 1:10,000 scale).

Analyses were carried out by means of an interpretation of aerial photos from different time periods, dating from 1954, together with geological surveys carried out between

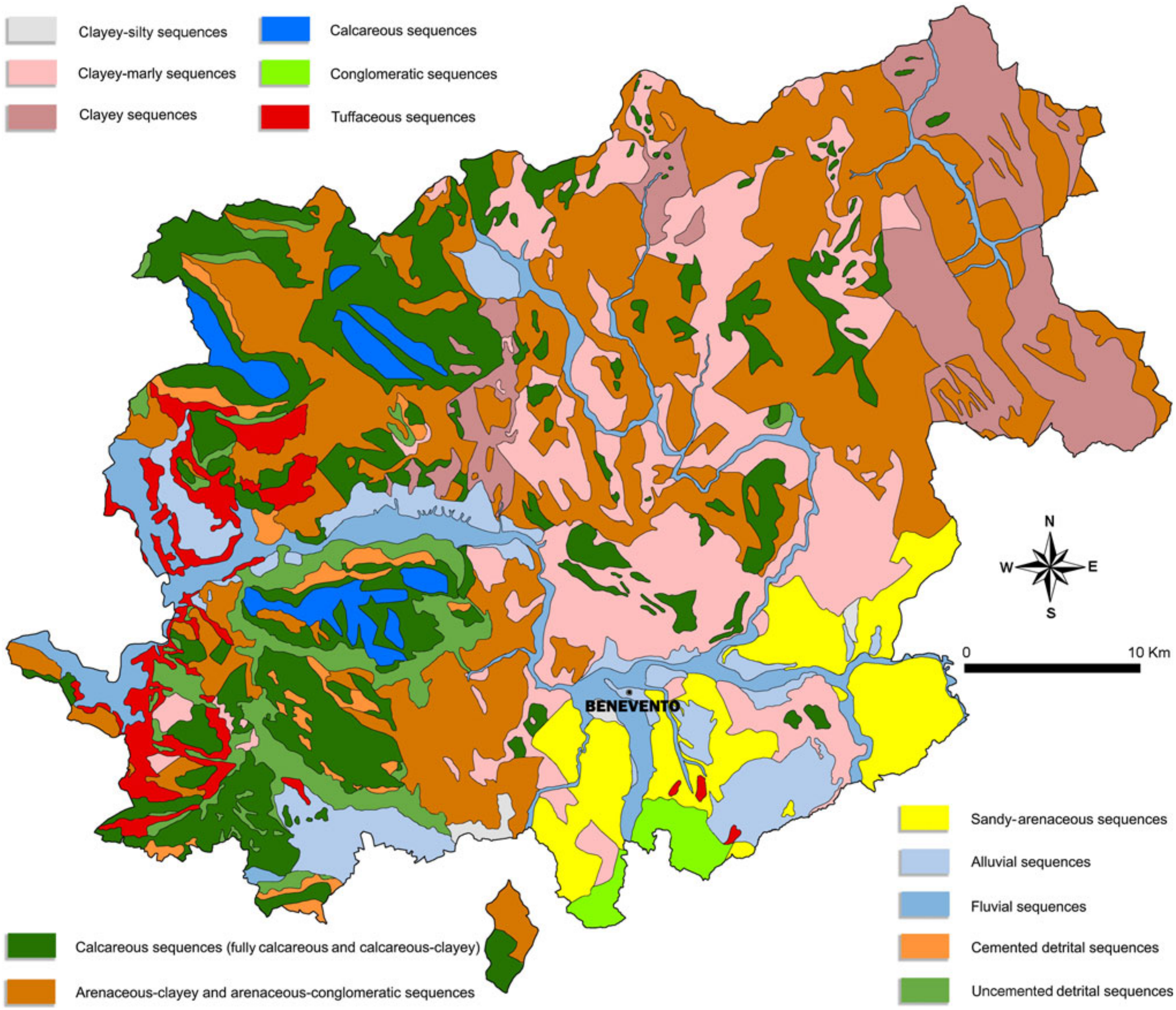


Fig. 5 Lithotechnical sequences outcropping in the province of Benevento forming the groups in Table 1

the years 2001 and 2008. It should be noted that during 2003 and 2005 two heavy rainfall events triggered the reactivation of hundreds of landslides (Fig. 2).

The classification criteria adopted refer to well-known classification systems (Varnes 1978; Hutchinson 1988; Cruden and Varnes 1996; Hungr et al. 2001). As described below, they are also based on some specific characteristics of landsliding processes which are worth pointing out.

Classification criteria

Taking into account the survey results, in addition to the usual categories, such as falls and topples, rock and debris avalanches, debris flows, translational, rotational and composite slides, in this study earth flows were also distinguished as (a) single (Fig. 6a), (b) multi-source (Fig. 6b) and (c) coalescent (Fig. 6c). This categorization was made in order to be able to distinguish the different morphological elements of the earth flows, which are the predominant form of mass movements, allowing a better understanding of the landslide mechanisms.

(a) With single earth flows, the movement of the landslide bodies is generally translational, with a well defined shear surface. The slopes involved frequently have angles similar to the residual friction angle of the clayey component and landsliding occurs within the superficial/weathered zone of the more or less homogeneous sequences. A typical example of such landslides is the "Rusciano" event in Sant'Agata de' Goti which occurred in January 1997 (Fig. 6a). It involved mainly a clayey-flysch substratum covered

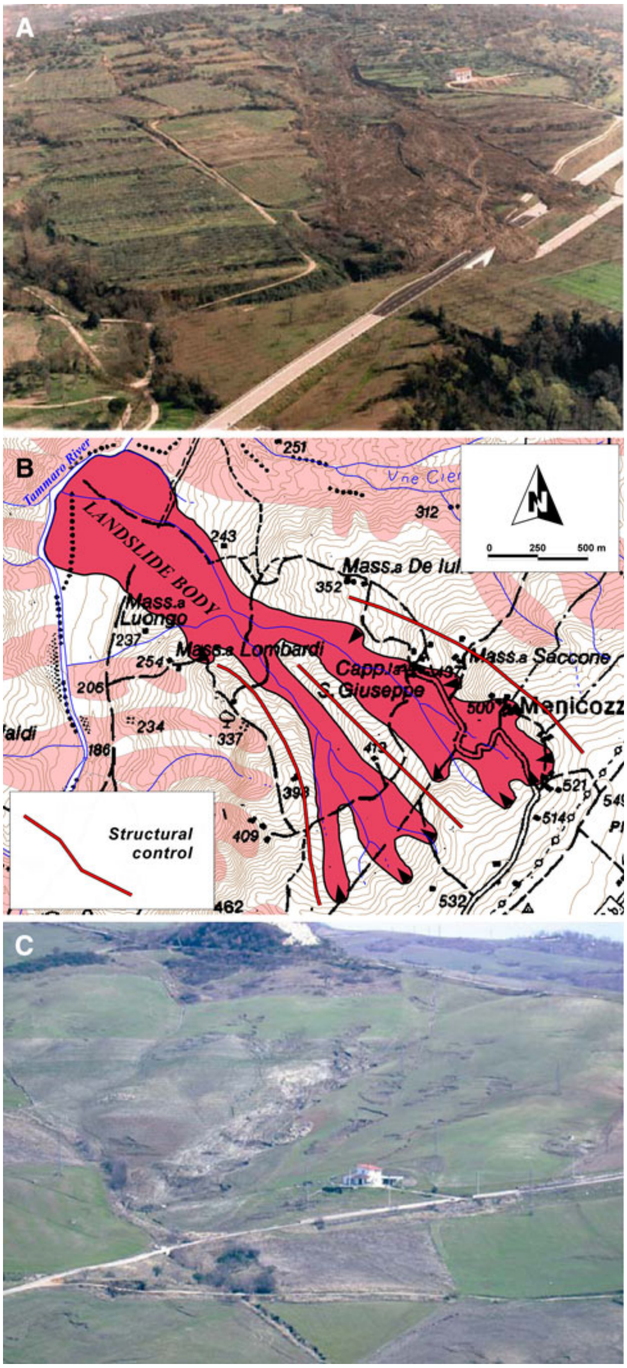


Fig. 6 Three types of earth flows: **a** Oblique aerial view of the Sant' Agata de' Goti landslide of 11 January 1997 (Photo courtesy of Italo Abate), **b** Multi-source earth flow from a segment of the Landslide Inventory Map (Guadagno et al. 2006), **c** "Basin" affected by coalescent earth flows

by weathered pyroclastic soils on a low-gradient slope (5°–10°). The translational character is evidenced by the presence of large slabs which retain their integrity and the formation of sag ponds.

(b) Multi-source earth flows reflect the complex litho-structural settings in the source areas. In specific areas, alternating sequences of competent and less competent material result in differential erosion/recession. As a result, this type of earth flow commonly has several sources/branches. Figure 6b, from a segment of the landslide inventory map (Guadagno et al. 2006) shows a multi-source earth flow with typical branches from the source area. It also highlights the influence of the lithostructural element in the evolution of the landslide, with both retrogressive and advancing phases. As a consequence of the structural setting the landslide movement may be laterally restricted, such that long, narrow flows occur with one or both sides coincident with competent slopes.

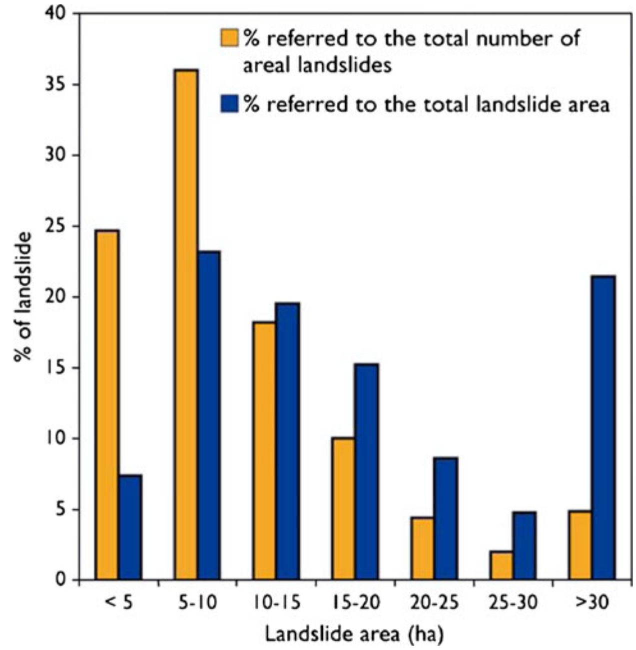


Fig. 7 Percentage of landslides of different sizes. Total number of landslides: 3,160; total area affected by landslides: 35,800 ha

(c) In coalescent earth flows, several generations of landslides mobilise and interact. Such earth flows generally occur where there is a medium to high degree of tectonization of sequences. These groups of landslides can be considered as an entity from a morphological point of view as they occur within a sub-catchment (Fig. 6c).

These characteristics of earth flows help define the likely activity (WP/WLI 1993a, b) and as they are frequently linked to litho-structural controls, are useful in landslide susceptibility evaluation.

Spatial distribution of the earth flows

In the study area, 3,160 earth flows were inventoried, covering an approximate area of 358 km^2, equal to about

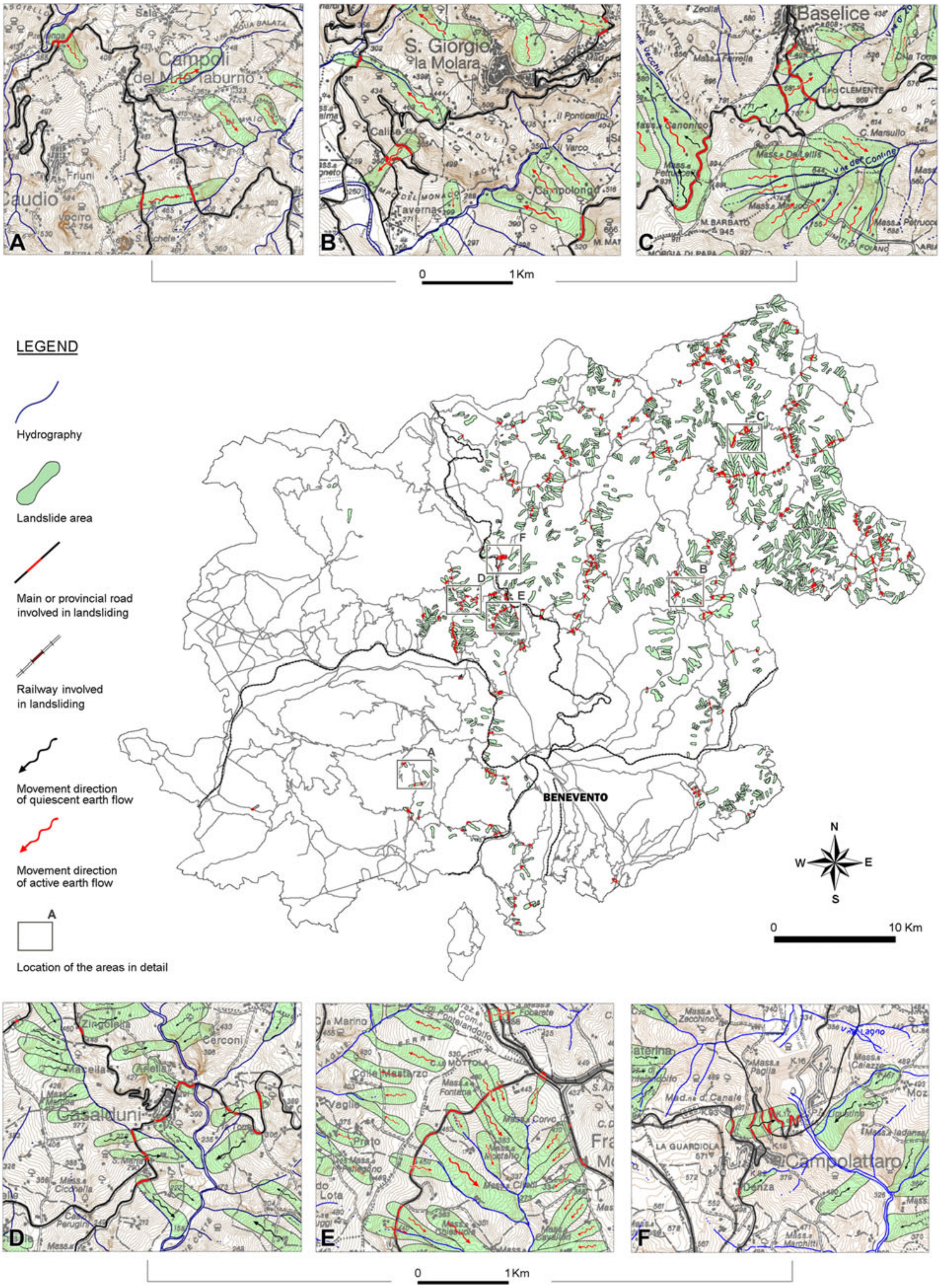


Fig. 8 Map of landslides activated associated with a rainfall event in March 2005

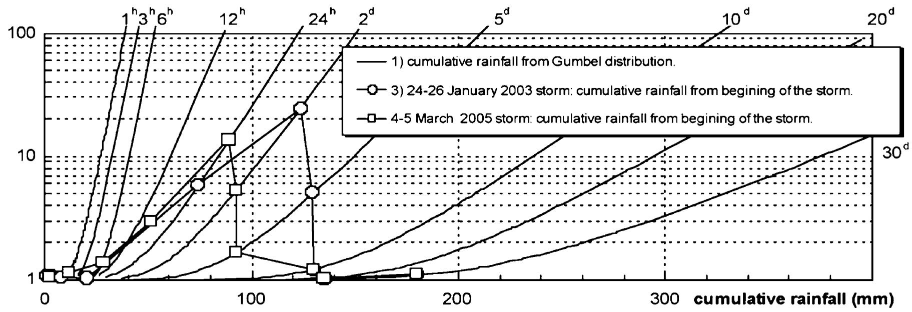


Fig. 9 Return period of accumulated rainfall triggering the landslide events of January 2003 and March 2005 according to the Gumbel distribution function (after Fiorillo and Revellino 2006)

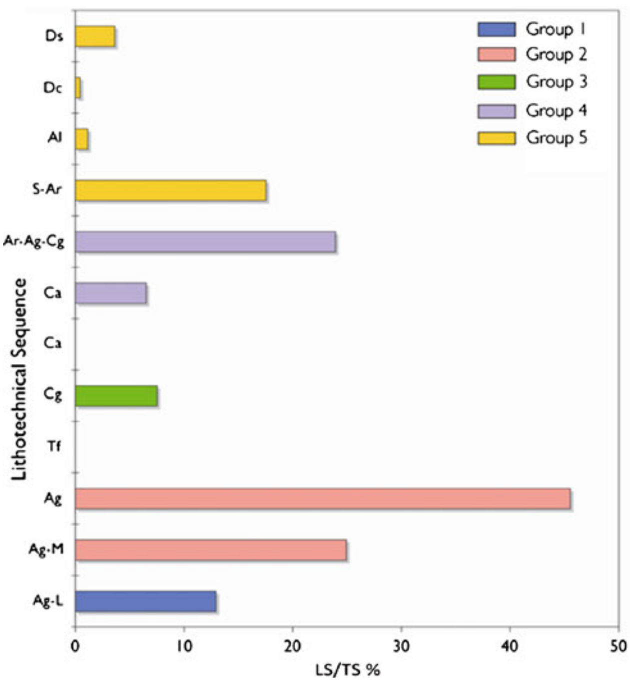


Fig. 10 Percentage ratio between area involved in landsliding (*LS* Landslide Surface) and total outcropping area (*TS* Total Surface) for each litho-technical sequence. Refer to Table 1 for symbols used

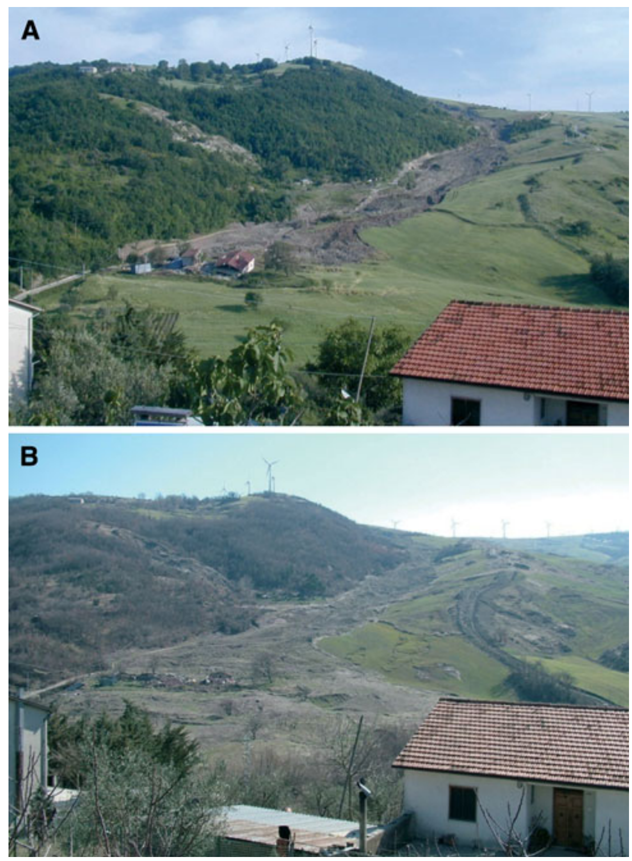


Fig. 11 Earth flow structurally controlled by a marly-clayey hill which affected some houses **a** November 2003 (photo courtesy of Donato Tornesiello), **b** March 2005

18% of the whole surface. This value refers to parts of the territory already affected by landsliding and mappable on the scale of representation (1:75,000). It does not include those areas where predisposing conditions and factors indicate potential future landsliding.

Figure 7 shows the percentage distribution of the earth flows in dimensional classes. The data refer to single events, even if they are part of a coalescent group. It is interesting to note that landslides <10 ha constitute over 50% of the inventoried phenomena, whereas the few larger events (ha > 25) represent over 20% of the areas affected by landslides.

Landslide surveys were carried out over some 8 years. During this period, as a consequence of a significant rainfall event in March 2005, an extensive re-analysis of the areas involved in landsliding was undertaken and some important features in the slope failure evolution were identified as most of the landslides were reactivations of pre-existing phenomena—1,236 events or 39% of the total number inventoried. Figure 8 shows the main communication system/infrastructure in relation to the earth flows triggered by the 2005 rainfall.

The 2005 rainfall event was not particularly exceptional (Centro funzionale per la previsione meteorologica e il monitoraggio meteoidropluviometrico e delle frane 2005), even though it followed some significant rainfalls. Figure 9 shows analyses carried out by Fiorillo and Revellino (2006)

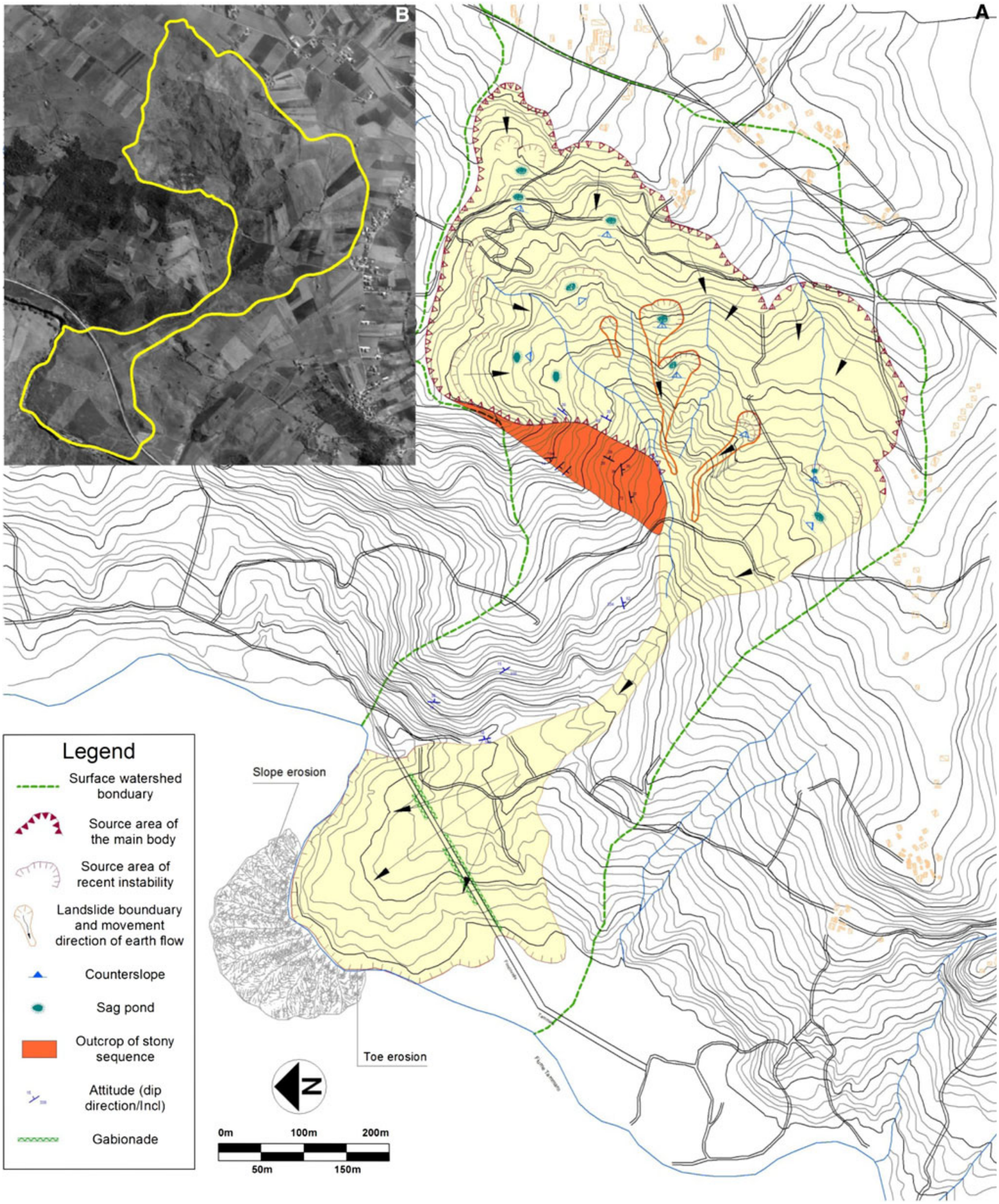


Fig. 12 **a** Map of the *Serra delle Forche* landslide to the north of the village of Paduli, **b** Landslide boundary superimposed on the image of Satellite Eros A, 16 April 2006 (image courtesy of MARSec, of Benevento, Italy)

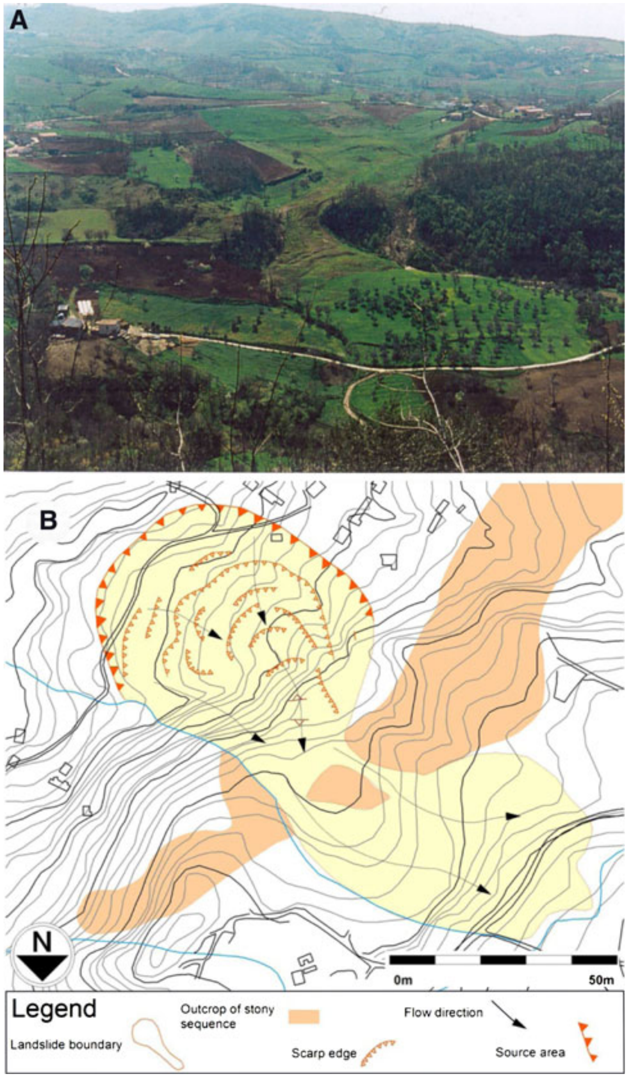


Fig. 13 The *Sant'Andrea* landslide in the municipal district of San Giorgio la Molara **a** View of the landslide, **b** Landslide chart

from data recorded at the rain gauge of Colle Sannita, located in the north east sector of the study area. The results indicate return times for the events of 2003 and 2005 of 23 and 12 years respectively for accumulated rainfall for 48 and 24 h, confirming the basic importance of the long-period antecedent rainfall.

As is well known, the pore pressure conditions related to the triggering of instabilities significantly depends on the duration and intensity of the rainfall (Caine 1980) and the depth of the sliding surface. In the study area, most of the earth flows (about 98%) can be considered as shallow (<15 m). On the basis of these analyses, antecedent rainfall greater than 60% of the annual average (about 920 mm) and/or >90 mm in a 24 h period appears to be sufficient to trigger widespread landsliding.

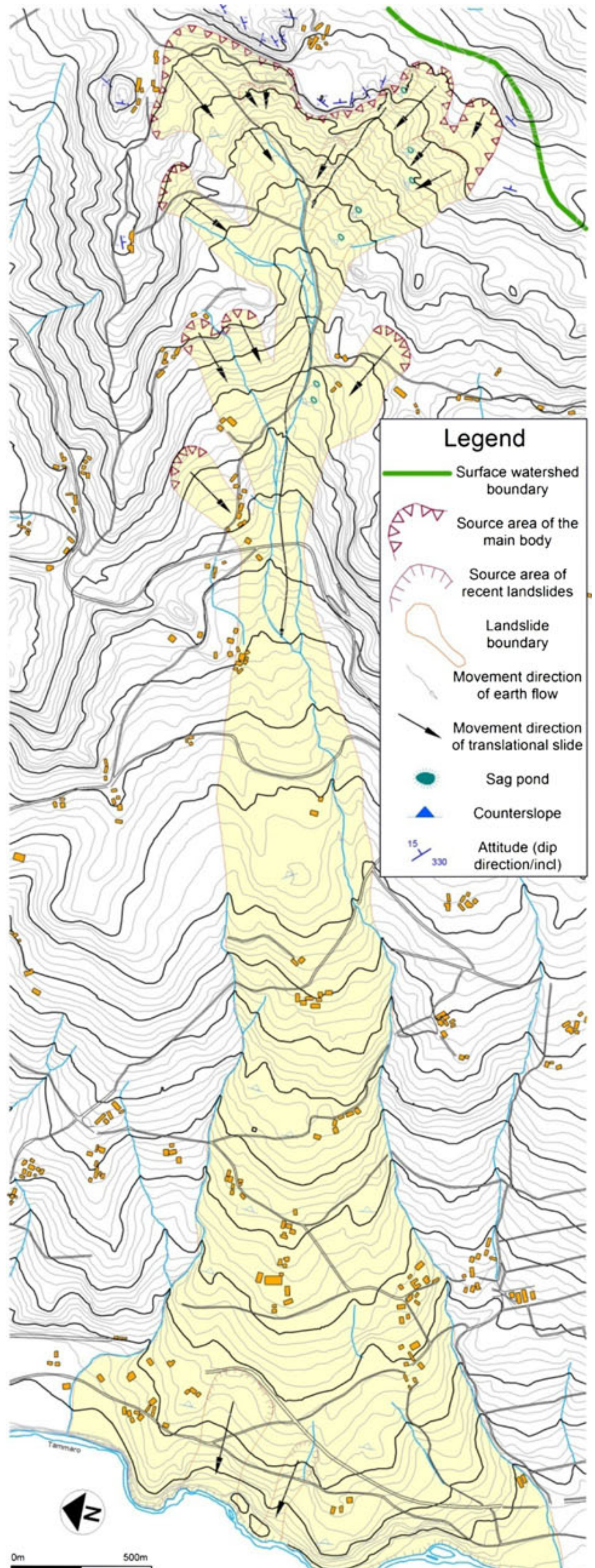


Fig. 14 Detailed map of the *Santo Ianni* multi-source earth flow (San Giorgio la Molara)

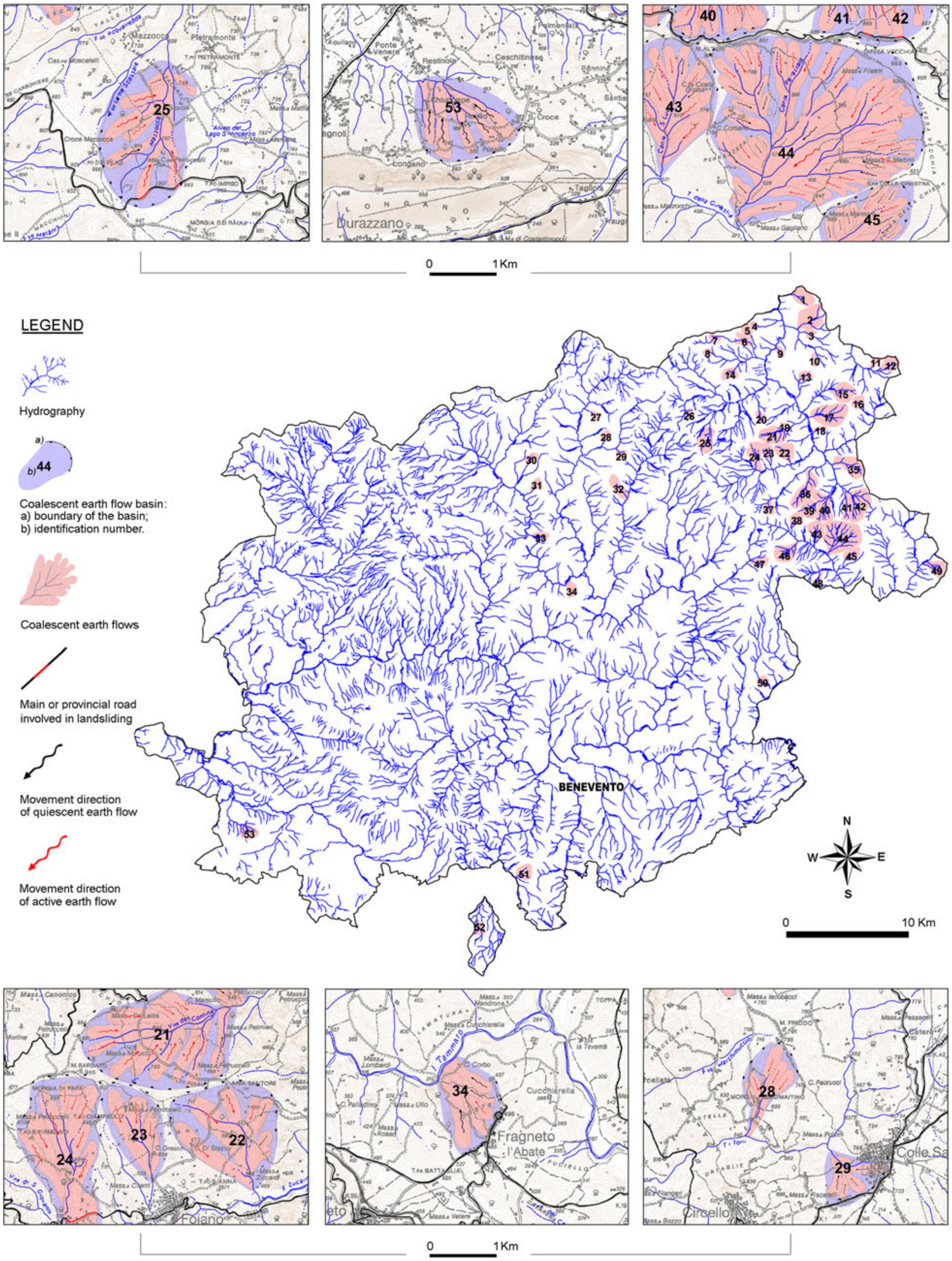


Fig. 15 Map of basins affected by coalescent flows

Controlled evolution of earth flows

As noted above, the geology of the area means that it is prone to the development of landslides hence analyses were carried out in respect of the five groups of sequences identified in Table 1. As shown in Fig. 10, the percentage of outcropping surface affected by earth flows is up to 46% of the total. More than 80% of the inventoried phenomena occurred in dominantly pelitic and complex sequences with a high degree of tectonization while over 40% of the areas where clayey formations outcrop is affected by landslides. Most landslides occur in the clayey, clayey-marly and arenaceous-clayey/arenaceous-conglomeratic deposits (2a, 2b and 4b on Fig. 5).

As noted above, such structural elements as the bedding of the homogeneous and complex sequences; the stratigraphic or tectonic contact between deposits with a different competence; and zones of intense fracturing linked mainly to the presence of axes of folds and faults, are fundamental in understanding earth flow source areas and channels.

Where geological bodies with a different competence outcrop, the lithostructure indicates movement will recur (Fig. 11). For example, Fig. 12 shows an instability related to the presence of a bedding plane (N125°/40°) which controls the shape, orientation and development at the source area. From here the mass movement forms a channel-like feature passing towards the north west. The influence of the geological structure is also seen in the *Sant'Andrea* landslide in the municipal district of San Giorgio la Molara (Fig. 13). The mass movement divides around more competent strata and comes together again further to the north west. Figure 14 shows the morphological characteristics of multi-source instabilities and the distribution of activity. The peculiar shaping of the source areas is due to the presence of stony sequences within the highly tectonized, pelitic materials.

In contrast, as seen in Fig. 15, there are some 50 "basins" in the study area where relatively homogeneous lithological conditions leaded to the formation of coalescing earth flows; some 390 events (size < 10 ha). In each basin, about 60% of the surface has suffered landslipping and in some areas this rises to 72%.

Conclusions

In the Benevento province, the geology is mainly characterised by clayey and flysch sequences which have been variably tectonised by thrust movements.

Not only are the source areas of the earth flows related to the lithology and structure, but the movements are often constricted to form linear channel-like phenomena due to the presence of more competent horizons. Reactivation frequently occurs associated with earthquakes and heavy/long periods of rainfalls. Although many of the hillslopes only have farms/isolated buildings and small roads, the landslides also affect some of the more built-up areas and road networks.

As the earth flows cover such vast areas, they have been divided into three main types related to their lithological characteristics, taking into account the degree of fracturing and the geological setting, i.e. single source; multi-source and coalescent landslides.

It is considered that in addition to the morphology, the structural condition of the source area and channel (lithological contacts, folds, faults and shear zones) is the main factor in controlling the spatial evolution of earth flows and should always be included in landslide susceptibility maps. As a consequence, the distribution of the activity becomes a relevant characteristic in understanding the landslide evolution mechanisms and hence in any prediction of the likely features of future occurrences.

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