ANNALI DI GEOFISICA, VOL. XXXVI, N. 1, April 1993

Slope stability maps in areas of particular seismic interest: a short report on the researches in Garfagnana and Lunigiana (Tuscany)

Giacomo D'Amato Avanzi, Alberto Puccinelli and Mario Trivellini
Dipartimento di Scienze della Terra, Università di Pisa, Italia - S.G.L. 1.3.2. of the C.N.R. «Gruppo Nazionale Difesa dai Terremoti»

Abstract
In this report, the state of the art of the researches on the evaluation of landslide hazard in Garfagnana and Lunigiana (northwestern Tuscany) is illustrated; these regions are both highly exposed to seismic hazard and prone to landslide. Particularly, the researches have been directed to get ready a methodology for drawing slope stability maps.
After a synthetic description of geological features of Garfagnana and Lunigiana, the methodology is exposed. It contemplates the carrying out of detailed geological and geomorphological surveys (1: 5000 scale) on which to base the drawing of the map; this will show active and quiescent landslides, as well as areas potentially exposed to mass-movements due to their morphological and lithological features.
At the present time, many slope stability maps, concerning the most important areas of Garfagnana and Lunigiana, have been published; then, the main results of the researches are shown.
The maps obtained are both exhaustive and easily readable, and constitute an instrument of particular usefulness in studies of the hazard of earthquakes and in those of territorial planning. They will be the foundation of the future researches on relations between landslides and earthquakes in these regions.

1. Introduction

Garfagnana and Lunigiana, in northwestern Tuscany, are regions affected by remarkable seismicity, recorded from historical times to now(1); this peculiarity puts them among the areas classified as highly exposed to seismic hazard.

In these regions, a large number of landslides occur; many of them are either in evolution or not yet definitely stabilized. The causes of the large diffusion of these instabilities must mainly be sought after in the geological-structural features (there are vast outcrops of formations marked by strong clay or shaly predominance), as well as in meteo-climatic conditions, that are characterized by relatively high values of average and concentrated rainfall.

If one takes into account the presence, in these regions, of densely-populated areas, lines of communication, industrial plants and infrastructures of great economical and social importance, as well as of the above-mentioned «seismic hazard», it seems quite justified to conduct an accurate survey on the slope stability in these territories, where the occurrence of such phenomena often represents the main hazard resulting from earthquakes.

2. Geological features of Garfagnana and Lunigiana

Garfagnana lies entirely in the Lucca district and covers the middle and upper valley of the

River Serchio; its widespread territory is limited by Apuane Alps on the West and Apennines on the East. It may structurally be traced back to a wide tectonic depression, born during the post-paroxysmal tectonic phases.

The region, which lies East of the tectonic culmination of the Apuane metamorphic massif, is essentially characterized by the tectonic units overtopping it. These units are represented by the nonmetamorphic Tuscan Succession, a.k.a. «Tuscan Nappe», made up of a succession of formations spanning from the Upper Triassic to Oligocene, and of units of the Ligurian type tectonically superposed: the latter crop out in the northernmost part of the region and are formed by a basal shaly complex, on which thick sequences of calcareous-marly or arenaceous flysch («Helminthoid flysch», «Mount Gottero sandstones») are superimposed. Upon these units, there are more or less complete portions of a Pliocene and Pleistocene lacustrine and fluvial-lacustrine cycle, formed by clays and polygenic gravels; they can especially be found in the surroundings of Barga and Castelnuovo Garfagnana, in the middle Serchio Valley, and are traceable to the subsidence phases that followed the Tortonian tectogenesis. Alluvial sediments, unconformable to substratum and to Villafranchian deposits, rest even higher: they belong to several fluvial cycles, datable to middle/upper Pleistocene-Olocene.

Lunigiana includes the middle and upper Magra Valley in the Massa Carrara district, and it also coincides with an extensive tectonic depression which, like Garfagnana, structured itself in the lower Pliocene. This region is characterized by the outcrop of several superimposed tectonic units that, starting from bottom, are: the metamorphic Tuscan Succession, which crops out on the northwestern extension of the Apuane massif structure; the above-said nonmetamorphic Tuscan Succession; the Ligurian and sub-Ligurian Successions, characterized by a predominantly shaly basal part and a flysch at the top, in calcareous-marly facies («Helmintoid flysch», «Groppo del Vescovo» limestone) or arenaceous facies (mostly «Mount Gottero sandstones»). Over this substratum, there are the lacustrine and fluvial-lacustrine Pliocene and Pleistocene sediments of Aulla-Olivola-Villafranca and Pontremoli basins, formed by clays and polygenic gravels; finally, on top of these, there are several fluvial cycles whose age spans from middle-upper Pleistocene to Olocene.

Thus, the formations outcropping in these regions are characterized by a strong clay predominance (in extended areas: shales of Ligurian Units s.l.; in smaller areas: «Scaglia Rossa» shales and lacustrine clays).

Because of these features, these areas present a lot of instability phenomena of small and large dimensions, that can be old, recent or still in an evolutionary stage.

3. Slope stability maps

The methodology here employed to construct slope stability maps has followed or partially modified hypotheses, principles and evaluations previously signified in slope stability papers by other authors, in order to carry out this type of results (for example, we want to quote the metodologies proposed by Lucini, 1969; Panizza, 1973; Papani and Tellini, 1973; Amadesi *et al.*, 1977; Amadesi and Vianello, 1978; Bosi, 1978).

In the authors' opinion, the attempt to analyse and quantify the most important parameters (among the several that influnce and condition the slope stability) requires an extreme complexity in the studies; moreover, in this way, a satisfying connection is not achieved between the theoretic evaluation and the real stability conditions, verifiable on the spot.

Furthermore, to quantify those factors by usual geotechnical methods in so vast and geologically complex areas is not possible, at least for economic reasons; then, the evaluations would be by force equally approximate.

Finally, for a practical utility and a prompt use, thematic maps of slope stability should also contain every geological information which may allow the introduction of the areas at issue, with a different landslide hazard, into the regional geological context: that will enable the reader to evaluate, although in a qualitative way, the relationship between the degree of stability attributed to an area and its lithological and structural features, acclivity, nature, distribution and progress of fracture surfaces, tectonic discontinuities, etc..

For these reasons, the methodology provides first the geological survey (on a great scale, 1:5000) and then (after the definition of criteria and parameters to employ) the elaboration of the thematic maps concerning the slope stability. So, the geological survey and the geomorphological analysis have represented important and significant classification factors: in fact, together with the lithology, they have permitted the outlining of a quite complete and objective sketch of the stability situation of the area.

This research started out in Garfagnana by means of studies that intended to put in relation the earthquake effects to the instability of the main residential centres and lines of communication. There followed up the studies conducted all over the Pistoia District, which analyzed the slope stability in relation to the geological and geomorphological features of the region. The results were published on a 1:25 000 scale (Nardi *et al.*, 1981).

In the cartography of the Pistoia district and later on, in the «maps of slope stability in the Serchio Valley, between Pieve Fosciana and Camporgiano», on a 1:10 000 scale (Nardi *et al.*, 1986a), performed in order to assess the hazard induced in a seismic area, in the course of studies referred to in the volume «Progetto Terremoto in Garfagnana e Lunigiana» (C.N.R -Regione Toscana, 1986), the problem of representing geology and slope stability was solved by means of a single map, supplied with a double legend: one was a classical, geological one, while in the other, formations were evaluated by numbers expressing various levels of hazard in relation to lithology. Documents of synthesis were thus obtained, rather valid for their contents but perhaps not quite available for an immediate reading, because the geological part prevailed graphically; the evaluation of the overall hazard in an area, every time compelled the reader to consult the two legends simultaneously.

In parallel to these surveys, defined by the above-mentioned methodology, in 1983 and 1984 within the scope of the research line «Forecast and prevention of earthquake effects upon the stability of natural slopes» of the National Research Council - National Group for the Defence against Earthquakes (C.N.R.-G.N.D.T.), an evaluation of the landslide hazard was started all over Garfagnana and Middle Serchio Valley (Nardi, 1985).

This project has produced 27 slope stability maps on a 1:10 000 scale (from surveys on a 1:5000 scale) which correspond to as many elements of the Technical Map of the Tuscan Region. Most of them have already been published (Nardi *et al.*, 1986b; Nardi *et al.*, 1987; Dallan *et al.*, 1991); the others are being printed.

The methodology employed, the same for all elements, allows one to work out the slope stability maps, so that they can easily and quickly be read. However, two distinct cartographic documents are worked out and published, the geological map and the slope stability map.

On the contrary, for Lunigiana, where research on slope stability began in 1987 by both general studies (Nardi, 1988) and investigation on sample areas (D'Amato Avanzi and Puccinelli, 1988), only the slope stability map is published; a bit different graphic solution has been adopted which, by further emphasizing the geological simbology, improves the readibility of the geological features. Four elements have so far been published (Nardi *et al.*, 1990a, 1990b, 1990c, 1990d) while many others are in print.

More specifically, in the Garfagnana and Lunigiana slope stability maps, geology is represented by contacts and abbreviations which individualize and identify the various formations, otherwise not represented by colours. However, the pieces of geological information supplemented with conventional symbols are all present, so that the basic geological map can still be read.

Colours are then reserved to the evaluation of both real and potential conditions of instability.

– In the first place, active and quiescent landslides are charted and emphasized; together with the detachment scarp and the accumulation zone, they are recognized by proper symbols (fig.1).

– In the second place, by means of different colours, distinction is made, between three levels of hazard for formations that result potentially subject to landslides because of their lithological features, as it was stated by our research; in fact, we have found a concentration of landslide phenomena in some formations (in particular, basal

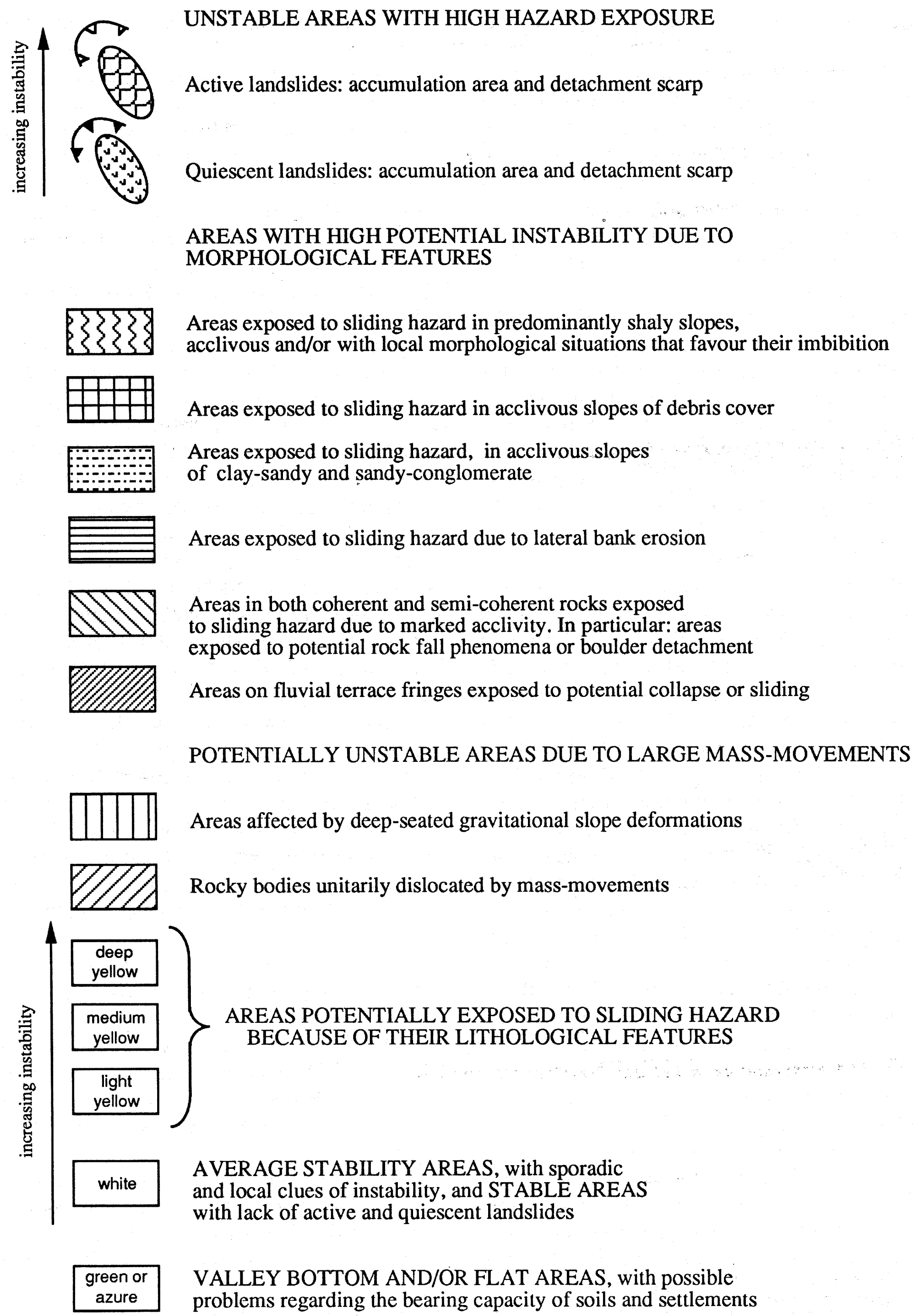

Fig.1. Legend of the slope stability map.

shaly complexes of Ligurian Units s.l., calcareous-marly flysch, «Scaglia rossa» shales, lacustrine clays). In order to establish such division in classes of hazard, for each formation we take into consideration the extension of the outcrop surface and of the unstable surface; later on, we relate and work out these data statistically, in order to obtain an areal index of slope stability, indicated as *I* (see below); its value just enables us to subdivide the formations into three classes of lithological hazard and represents an estimate of the probability that a landslide occurs in apparently stable areas.

– In the third place, zones that, because of their morphological and hydrogeological features, are prone to instability are emphasized by means of coloured over-symbols; such zones may happen to fall on areas that, from a lithological point of view, do not in general present problems of instability and thus they call to attention a local situation, or they may otherwise fall in yellow-coloured areas according to the several classes of potential instability due to their lithological features and so they may markedly worsen the evaluation of overall stability.

We shall not enter into the distinctions made of the hazard factors stemming from the geomorphological analysis, because such distinctions may be modified as a function of reality and features of the various regions. At this point of research, in order to maintain a good readability and promote their use outside of the scientific scope, we have chosen not to overload the cartographic documents with the distinction of the type of landslide phenomenon.

In particular, on the slope stability maps distinction is made for:

1) *Unstable areas with high-hazard exposure*

They include: «active landslides», where signs of recent or still-in-action movements have been found, sometimes testified by accumulations not yet modified by exogenous agents; «quiescent landslides», namely those areas which, although presenting typical landslide features, are by now modified in their morphological configuration, in such a way that in some cases a new drainage has been established. These areas result to be extensively represented, in number and surface, in comparison to «active» landslides and sometimes they are bequeathed from climatic situations different from the present ones. However, these zones, which appear in morphological equilibrium, have been included in the high-hazard exposure class because in many cases new movements have taken place, especially in coincidence with anthropic interventions, extreme meteorological events and earthquakes.

2) *Areas with high potential instability due to morphological features*

This classification has been applied to areas which, although not in movement now, present a coincidence of elements of predominantly morphological nature, besides a lithological and hydrological one; that leads to a reasonable evaluation of their proneness to instability and mass-movement. Among these areas, a few types have particularly been singled out:

– areas of predominant shaly nature, situated on steep slopes and/or with morphological situations favouring their imbibition;

– areas located on steep slopes of a clay-sandy and sandy-conglomerate nature;

– areas situated in steep slopes of debris cover;

– areas situated in coherent and semicoherent rocks but exposed to instability, due to their marked steepness; particularly, they are exposed to rockfall or boulder detachment phenomena;

– areas on the fringe of fluvial terraces;

– areas exposed to instability, due to lateral bank erosion.

3) *Potentially unstable areas, due to large mass movements*(2)

– areas affected by deep-seated gravitational slope deformation;

– rocky bodies unitarily dislocated by mass-movements.

4) *Areas potentially exposed to instability, due to their lithological features*

Lithology, among the factors affecting the stability of a slope, represents a very important parameter as it constantly conditions the intensity and degree of slope instability in a region. Thus, in working out cartography, the instability features have been considered for all the geological formations outcropping in every single cartographic element; where possible, further distinctions within some formations have been evaluated, based mostly on the state and degree of alteration of the rocky complex, having in view the influence these elements may have on the local conditions of slope stability.

In order to evaluate more precisely the degree of influence of lithology upon the instability of a geological formation, measurements have been taken of the planimetrical outcrop surface of that formation and the planimetrical extension of active and quiescent landslides that rest on it(3). Then, the overall surface of landslides is compared to the outcrop surface of that formation, curtailed of the areas liable to local morphological influences, whether favourable (terraces, flat areas) or unfavourable in terms of stability (bank erosion, areas exposed to rock falls, etc.). So, we obtain an areal stability index I (I = Ratio between *Overall extension of landslides of a formation* and *Outcrop surface of that formation*), by which the territory is subdivided into some classes of potential instability.

The classes we utilize correspond to the following intervals of the slope stability index I (they are distinguished on the maps by means of a reference colour):

$0.1 < I < 0.2$ (light yellow)

$0.2 < I < 0.3$ (medium yellow)

$I > 0.3$ (deep yellow)

If $I < 0.1$, the formation is considered stable and its colour is white.

The conditions of lithological instability may result worsened by further factors that influence stability, such as the acclivity degree, hydrological conditions etc.

In these cases, as can be seen on the map, the specific figure is superimposed over the basic colour, thus pointing out the presence of destabilizing morphologic factors.

5) *Areas of average stability and stable areas*

They have sporadic and local clues of instability or absence of active and quiescent landslides. These areas, which appear blank on the slope stability map, represent low-hazard zones; nevertheless, the possibility that they may evolve in a negative sense is not to be ruled out, when the factors that warrant the natural slope equilibrium run out; for instance, because of anthropic interventions.

6) *Valley bottoms and flat areas*

These areas are not prone to landslide phenomena, because of the lack of steepness; typical examples are represented by alluvial planes, plateaus of fluvial terraces, etc.

4. Conclusions

At the present time, the detailed survey of so vast territories, whose related maps have been mostly published, gives a great knowledge about landslide characteristics in the quoted regions, and particularly in the most socially important areas.

As several formations with different lithological features outcrop in the regions at issue, we may put out synthetic considerations about the frequency, distribution and typology of instabilities, on the base of Varnes' classification (Varnes, 1978), as modified by Carrara *et al.* (1987).

In lithologies where shales or clays prevail, landslides are more widespread, with frequent events of rotational slide, flow, and slide-flow. In more competent formations, like the limestones of the Tuscan Succession, the calcareous-marly flysch and the sandstones, the frequency of instability is remarkably reduced: landslides of traslational, rotational and roto-translational types, of medium/small extension, often prevail, although wider movements, sometimes of a grandiose size, are not lacking; rotational movements occur because of the state of severe tectonic crushing of the bedrock, connected to the complex tectonic evolution of the quoted regions.

In the presence of a remarkable relief energy as well as of marked differences in height and, often, of particular geological-structural conditions, these more competent lithologies may react against the destabilizing efforts, by developing cut-surfaces restricted to slope summits as well as plastic deformations in the lower part; in such cases, those phenomena known as «deep-seated gravitational slope deformations» occur.

In correspondence with the more competent formations, the thickness and extension of debris cover increase; the debris tends to accumulate mostly in slope concavities or at their base; such covers are often affected by solifluction phenomena or translational slide over the substratum, by more or less rapid flows, rotational slides and slide-flows. Sometimes the debris appears cemented and may reach very high angles of rest: as a consequence, it may get involved into falls.

Results and considerations exposed above lead us to consider the slope stability map as an «alarm-map» of a synthetic type: beside the active and quiescent landslides, prominence has been given to areas having a sliding tendency, where the hazard is pointed out by a colour (instability due to lithological features); to this a further symbol can be added, showing above all the influence of the acclivity factor.

In conclusion, the cartographic solution adopted, for the above explained reasons, enables us to define, in relatively short time and with sufficient reliability, the landslides and the zones more exposed to landslide hazard. The resulting cartography is both exhaustive and easily readable and may constitute a document of particular usefulness in studies connected with earthquake hazard and in territorial planning as well. These maps will be the foundation of future researches about relations between landslides and earthquakes in the quoted regions.

F. Buti, F. Caredio, M. Curci, G. Mazzanti, G. Pellegrino, M. Redini cooperated with the activity of the Research Unit.

([1]) Among the most important earthquakes that occurred in Garfagnana/Lunigiana, we single out the one which took place on 7 September 1920 (degree X MCS). On that occasion, the mobilization of instability phenomena was recognized. We also recollect, among others, the following earthquakes (Postpischl, 1985): 11 April 1837 (degree IX MCS); 15 May 1481, 6 March 1740, 23 July 1746 and 21 January 1767 (degree VIII MCS); 10 October 1939 and 15 October 1939 (VII MCS); degree VI MCS tremors were recorded on 7 June 1980 too, on 23 January 1985 (which even caused a «seismic alarm») and on 10 February 1987. We want also to quote the studies on seismicity included in the volume «Progetto Terremoto in Garfagnana e Lunigiana» (Earthquake in Garfagnana and Lunigiana Project) (CNR-Regione Toscana, 1986).

([2]) The role played by deep-seated gravitational slope deformations in influencing the surface mass-movements of slopes is well known, as well as the possibility that they may, in certain cases, evolve towards collapse through grandiose landslides. «Rocky bodies unitarily dislocated by mass-movements» have been distinguished from ordinary landslides because of their particular morphological features and stability, by which they could be mistaken for the rock substratum.

([3]) An outcrop is considered in the statistics only if its area is vast enough (0.5 square kilometres at least, in the authors' opinion and for the geological and geomorphological reality of the regions surveyed) and homogeneous in the instability distribution; in this way, the calculation is more reliable and the results may be extended to other areas with similar characteristics.

REFERENCES

AMADESI, E., G. VIANELLO, F. BONFATTI, R. PIGNONE and D. PRETI (1977): *Guida alla realizzazione di una carta della stabilità dei versanti*, Reg. Emilia Romagna (Ed. Pitagora).

AMADESI, E. and G. VIANELLO (1978): Nuova guida alla realizzazione di una carta della stabilità dei versanti, *Mem. Soc. Geol. It.*, **19**, 53-60.

BOSI, C. (1978): Considerazioni e proposte metodologiche sulla elaborazione di carte della stabilità, *Geol. Appl. Idrogeol.*, **13**, 245-281.

CARRARA, A., B. D'ELIA and E. SEMENZA (1987): Classificazione e nomenclatura dei fenomeni franosi, *Geol. Appl. Idrogeol.*, **20** (2), 1985, 223-243.

C.N.R. - Regione Toscana (1986): Progetto terremoto in Garfagnana e Lunigiana (Ed. La Mandragora, Firenze).

DALLAN, L., R. NARDI, A. PUCCINELLI, G. D'AMATO AVANZI and M. TRIVELLINI (1991): Valutazione del rischio da frana in Garfagnana e nella Media Valle del Serchio (Lucca). 3) Carta geologica e carta della franosità degli elementi «Sillano», «Corfino», «Fosciandora» e «Coreglia» (scala 1:10.000), *Boll. Soc. Geol. It.*, **110**, 245-272.

D'AMATO AVANZI, G. and A. PUCCINELLI (1988): Geologia e franosità del territorio di Aulla (MS), *Boll. Mus. St. Nat. Lunig.*, **6-7** (1986-1987), 21-27.

LUCINI, P. (1969): Metodo grafico per la valutazione della franosità, *Mem. e Note Ist. Geol. Appl. Univ. Napoli*, Vol. **11**.

NARDI, R. (1985): *Valutazione del rischio da frana in Garfagnana e nella Media Valle del Serchio (Lucca)* (Pacini Fazzi Ed., Lucca), pp. 1-17.

NARDI, R. (1988): Considerazioni sul rischio da frana in Lunigiana, *Boll. Mus. St. Nat. Lunig.*, **6-7** (1986-1987), 75-78.

NARDI, R., A. PUCCINELLI and M. VERANI (1981): *Carta geologica e geomorfologica con indicazioni di stabilità della Provincia di Pistoia alla scala 1:25.000* (Tip. S.EL.CA., Firenze).

NARDI, R., A. PUCCINELLI, C. DI PASSIO, E. HOST and D. MORINI (1986a): Pericolosità indotta. Carta della franosità: l'esempio della valle del Serchio tra Pieve Fosciana e Camporgiano (Lucca), in *Progetto terremoto in Garfagnana e Lunigiana*, C.N.R.- Regione Toscana (Ed. La Mandragora, Firenze), pp. 75-80.

NARDI, R., A. POCHINI, A. PUCCINELLI, G. D'AMATO AVANZI and M. TRIVELLINI (1986b): Valutazione del rischio da frana in Garfagnana e nella Media Valle del Serchio (Lucca). 1) Carta geologica e carta della franosità degli elementi «Gragnana», «Piazza al Serchio», «Casciana» e «Ceserana» (scala 1:10.000), *Boll. Soc. Geol. It.*, **104** (1985), 585-600.

NARDI, R., A. PUCCINELLI, G. D'AMATO AVANZI and M. TRIVELLINI (1987): Valutazione del rischio da frana in Garfagnana e nella Media Valle del Serchio (Lucca). 2) Carta geologica e carta della franosità degli elementi «Sillico», «Castelnuovo Garfagnana», «Cascio», «Castelvecchio Pascoli», «Gallicano», «Barga», «Fornaci di Barga» e «Ghivizzano» (scala 1:10.000), *Boll. Soc. Geol. It.*, **106**, 819-832.

NARDI, R., A. PUCCINELLI and G. D'AMATO AVANZI (1990a): *Carta della franosità della Lunigiana (Massa Carrara). Elemento «Barbarasco» (scala 1:10.000)* (Tip. S.EL.CA., Firenze).

NARDI, R., A. PUCCINELLI and G. D'AMATO AVANZI and A. BISERNA (1990b): *Carta della franosità della Lunigiana (Massa Carrara). Elemento «Aulla» (scala 1:10.000)* (Tip. S.EL.CA., Firenze).

NARDI, R., A. PUCCINELLI and G. D'AMATO AVANZI and F. CAREDIO (1990c): *Carta della franosità della Lunigiana (Massa Carrara). Elemento «Podenzana» (scala 1:10.000)* (Tip. S.EL.CA., Firenze).

NARDI, R., A. PUCCINELLI and G. D'AMATO AVANZI and G. PELLEGRINO (1990d): *Carta della franosità della Lunigiana (Massa Carrara). Elemento «Terrarossa» (scala 1:10.000)* (Tip. S.EL.CA., Firenze).

PANIZZA, M. (1973): Proposta di legenda per carte della stabilità geomorfologica, *Boll. Soc. Geol. It.*, **92**, 303-306.

PAPANI G. and C. TELLINI (1973): Metodo elementare per elaborare uniformemente carte della stabilità potenziale dei terreni. Studio della parte media della Val Tresinaro, Ateneo Parmense, *Acta Nat.*, **9**, 153-179.

POSTPISCHL, D. (Editor) (1985): *Catalogo dei terremoti italiani dall'anno 1000 al 1980* (C.N.R. - Prog. Fin. Geodin., Bologna).

VARNES D.J. (1978): Slope movement types and processes, in *Landslides analysis and control*, edited by R. SCHUSTER and R.J. KRIZEK, Transportation Research Board, Special Rept., **176**, Nat. Acad. of Sciences, pp. 11-33.