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LOW MAGNITUDE EARTHQUAKES AND LANDSLIDE ACTIVITY: A CASE STUDY FROM ITALY

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Abstract. We report on a slump-earth flow occurred in Southern Apennines following a 3-day rainstorm in late 1993. Subsequently, the landslide underwent different phases of activity, and in particular, the reactivation phase in 1995, which apparently coincided with a series of minor earthquakes (local magnitude ~ 3) and seasonal rainfall events. We focus on one and a half year temporal-spatial variations in retrogressive evolution of the landslide and attempt to identify cause-effect relations between the main scarp failures and the occurrence of seismic and rainfall events. For this purpose, qualitative and quantitative correlations are sought between possible causative factors and landslide activity. The results show that: (1) the general retrogressive trend is neither directly correlated to the temporal seismic activity pattern, nor to the monthly or short term precipitation; instead, the trend appears to be influenced by groundwater level variations, which are related to a few month cumulative precipitation pattern; (2) the variations in retrogressive activity of the main scarp, with respect to the general trend, show a limited positive correlation with seismic energy and monthly precipitation pattern; (3) the relative influence of precipitation appears to be greater than that of seismic activity; the latter seems to give a contribution to instability only when the main scarp is already unstable. These results indicate that, in presence of other causative factors, low energy seismic activity can have a complementary role as destabilising agent; however, a rigorous quantification of its relative weight would require more detailed and longer term monitoring data provided by continuous *in situ* recording instrumentation.

Key words: landslide activity, low magnitude earthquake, Arias intensity, rainfall, groundwater level, correlation analysis.

Abstrakt. W artykule przedstawiono duży spływ ziemny w południowych Apeninach, który nastąpił pod koniec 1993 roku, po trzydniowym sztormie. Osuwisko przeszło następnie rozmaite fazy aktywności, a zwłaszcza fazę odnowienia w 1995 roku, powiązaną z serią niewielkich trzęsień ziemi o nasileniu ~3 oraz z okresowymi opadami. Zwrócono uwagę na półtoraroczne zmiany przestrzenne w ewolucji osuwiska oraz na próbę określenia związku przyczynowo-skutkowego pomiędzy podcięciem skarpy oraz wystąpieniem zjawisk sejsmicznych i opadów. W tym celu przebadano jakościowe i ilościowe związki pomiędzy prawdopodobnymi przyczynami a aktywnością osuwiska.
Otrzymano następujące wyniki: (1) rozwój nie jest związany bezpośrednio z okresową aktywnością sejsmiczną ani z opadami miesięcznymi lub krótkotrwałymi, natomiast prawdopodobnie jest związany ze zmianami poziomu wód gruntowych powodowanych kumulacją kilkumiesięcznych opadów; (2) zmiany ogólnego trendu zachowania się głównej skarpy wykazują związek z aktywnością sejsmiczną oraz z rozkładem miesięcznych opadów; (3) względny wpływ opadów wydaje się być większy od aktywności sejsmicznej, jakkolwiek ta ostatnia ma swój wkład w dalszą destabilizację już naruszonej skarpy. Wyniki te wskazują, że słabe wstrząsy sejsmiczne osłabiają stabilność stoków poddanych innym poważniejszym czynnikom. Dokładniejsze określenie tych relacji będzie jednak wymagać bardziej długotrwałych i dokładniejszych obserwacji przy użyciu instrumentów prowadzących zapisy na miejscu.

Słowa kluczowe: aktywność osuwiskowa, słabe trzęsienia ziemi, intensywność współczynnika Arias, opady atmosferyczne, poziom wód gruntowych, analiza korelacyjna.

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INTRODUCTION

Earthquakes of magnitude < 4.5 or modest amount precipitation generally do not trigger mass movements, but little is known to what extent these events can influence the evolution of landslide activity. The post-failure monitoring and field observations of a landslide in the upper Sele valley (Southern Italy) suggested that, in addition to the influence of rainfall events, there might be some temporal links between the occurrence of low energy earthquakes relatively close to the landslide area and the stages with increased rate of landslide movements.

Indeed, the upper Sele valley is characterised by frequent slope failures, which are usually triggered by rainfall and seismic shaking. Landsliding is favoured by the local geological and hydrogeological conditions (e.g. Agnesi *et al.*, 1983; Wasowski *et al.*, 2002).

From a geomorphological point of view, two different landscapes are recognised in the study area: one typical of the carbonate rock domains, and the other of the terrigenous materials (Fig. 1). The carbonate landscape occurs along the eastern and western margins of the valley, characterised by steep and at places subvertical slopes. Limestones and dolomitic limestones constitute the major aquifers as a result of their large volume and hydraulic conductivity enhanced by diffuse fracturing and karst processes. This area is locally affected by mass movements, which include rock falls, and topples.

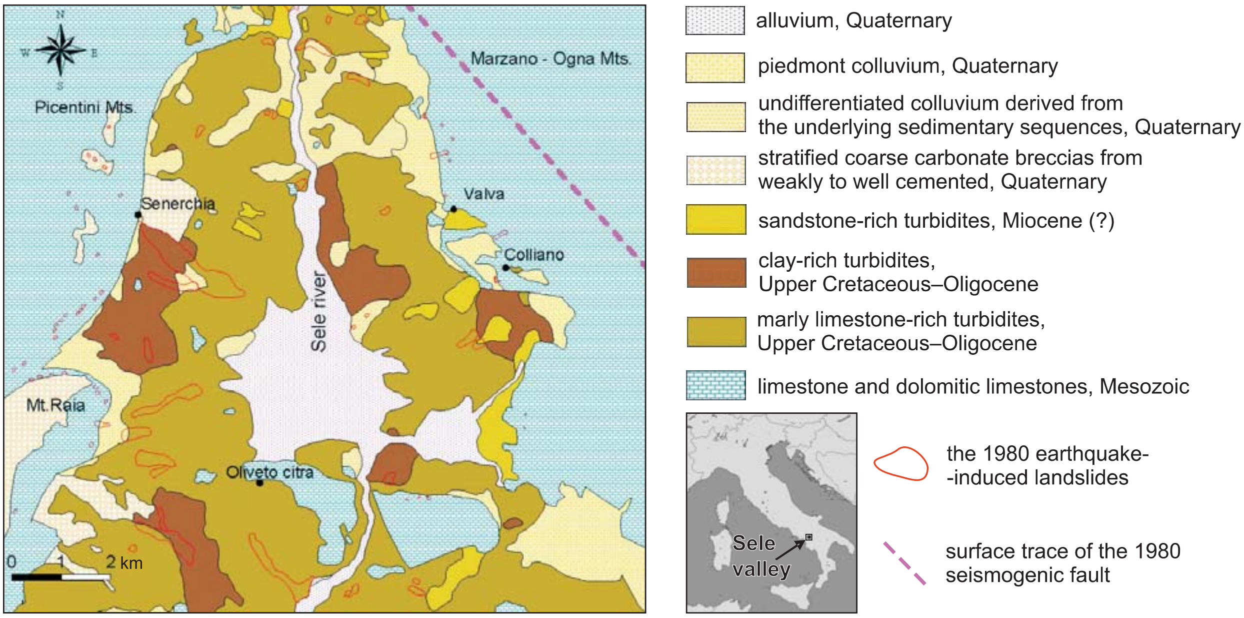

Fig. 1. Location of the study area and simplified lithological map of the Sele valley (from Wasowski *et al.*, 2002)

Landslide inventory data are from Agnesi *et al.*, 1983; note the town of Senerchia and other urban centres marked by black dots

Fig. 2. General view of the west side of the Sele valley near the town of Senerchia (centre of photo)

Violet and red arrows indicate, respectively, the Serra dell'Acquara landslide triggered by the 1980 earthquake and the main scarp area of the 1993 Acquara-Vadoncello landslide

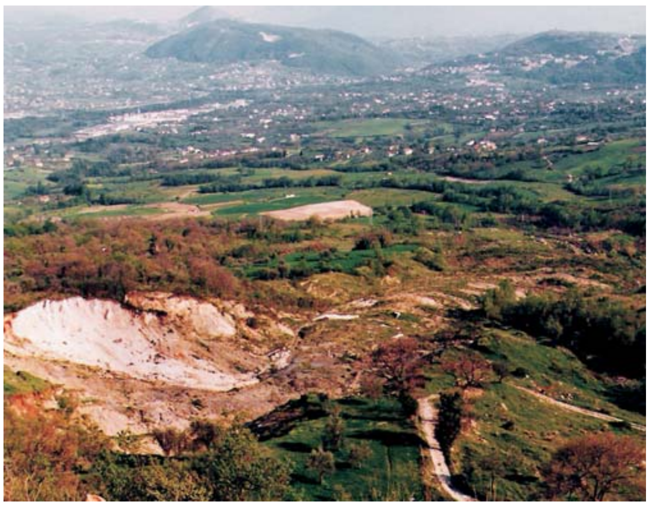

Fig. 3. Acquara-Vadoncello landslide reactivated by rainfall on 29 December 1993

Note steep morphology of the main scarp (lower left of photo)

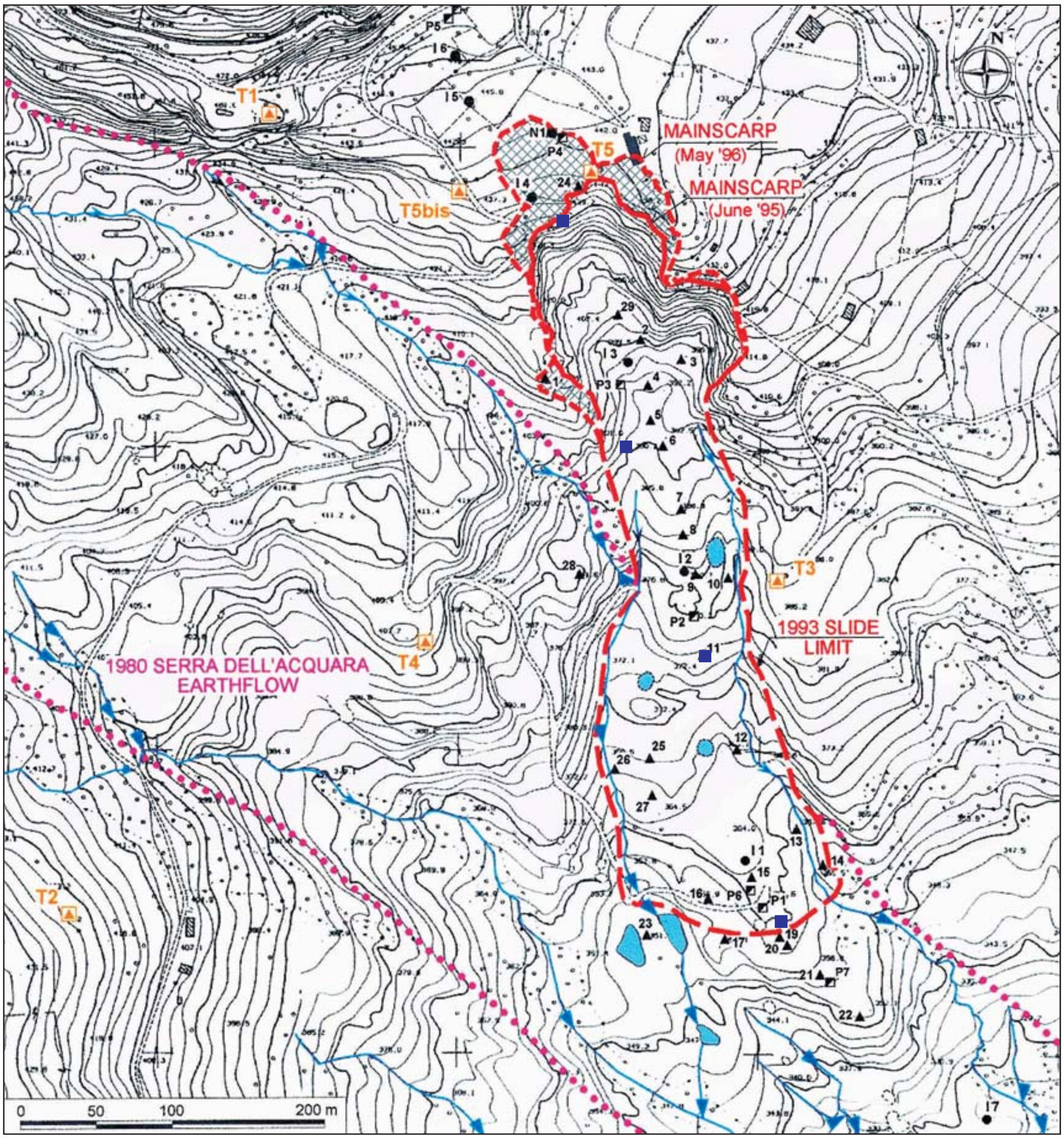

Fig. 4. Topographic map of the 1993 Acquara-Vadoncello landslide area

P1–P7 — piezometer boreholes, I1–I7 — inclinometer boreholes, T1–T5 bis — topographic control network, triangles — measurement points; piezometers P1–P4 discussed in text are highlighted in blue; note also the limits of the large 1980 earth flow (marked by violet dotted line) and local watercourses and landslide ponds shown in light blue (modified after Wasowski and Mazzeo, 1998)

The terrigenous landscape is characterised by low-medium acclivity slopes and by widespread landslide phenomena. The turbidite (flysch) deposits are in direct contact with carbonate rocks and several springs draining the carbonate aquifers are present along their margins.

In the upper Sele valley, the Irpinia earthquake (M 6.9) of November 23, 1980 (e.g. Carrara *et al.*, 1986) activated a large number of landslides. In particular, in the outskirts of the town of Senerchia, in a locality named "Serra dell' Acquara", a large landslide (2.5 km long, 500 m wide and up to 33 m thick) was triggered; it ceased its activity by 1981 (Fig. 2). Thirteen years later, on 29 December 1993, after a 3-day rainstorm, a 550 m long and up to 140 m wide landslide was reactivated on the left flank of the 1980 landslide (Fig. 3). Both 1980 and 1993 landslides occurred in the tectonically disturbed flysch succession made primarily of over consolidated mudstones, and secondarily of marlstones and limestones.

The Acquara-Vadoncello landslide caused the destruction of two rural roads and the collapse of a farmhouse. The post--failure evolution of the landslide posed additional hazard to the local infrastructures and was monitored through topographic surveys (Wasowski, Mazzeo, 1998), inclinometer and piezometer measurements (Wasowski, 1998), and geophysical investigations (Del Gaudio *et al.*, 2000a, b). In addition, data on precipitation and seismic activity were collected and analysed. In this work, we re-examine these different data sets in order to recognise possible causal relations between seismic events and mass movement activity.

MONITORING DATA, RAINFALL AND LANDSLIDE ACTIVITY

The 1993 mass movement can be classified as a slump--earth flow following Cruden and Varnes (1996). The main scarp-crown area is characterised by development of retrogressive slope failures that feed the earth flow (Fig. 4).

The monitoring of the retrogressive evolution started in the summer 1994 and revealed the irregularity of the recession process, both in time and space (Wasowski, 1996). The largest retrogression took place from June to September 1995 while the process slowed down starting from October 1995. The maximum (~74 m) and the minimum (~14 m) retrogressions were observed respectively along N and NW direction, while intermediate values were registered along the WNW and NE directions.

Four topographic measurement cycles of horizontal and vertical displacements were conducted on the earth flow. The measurements showed that the maximum displacement (~ 130 m) occurred between May and October 1995, and that during May 12–17, 1995 displacements of 4 m took place.

Rainfall is perhaps the most common triggering and causative factor of the land sliding. However, the relations between the post-failure activity of landslides and rainfall are by no means simple. In this case, a certain temporal link was observed between the landslide activity and the 5-day antecedent rainfall. In particular, Figure 5 shows that the reactivation on December 1993 and some other movements (e.g. those of 9 February and 12–17 May 1995) followed several rainy day periods.

However, temporal links were more clearly observed between landslide activity and longer-term rainfall. Figure 6 shows that the initial reactivation of the landslide in December 1993 occurred after a four-month rainy period. In addition, the displacements in spring–summer 1995 were preceded by first four rainy months of the year, which determined an increase in the groundwater level revealed by piezometer measurements (Figs. 7, 8).

The temporal record of landslide activity was also compared with the piezometer data. In particular, the data of the piezometers P2 (central part of earth flow) and P4 (crown — main scarp) show the link between the groundwater levels and landslide movements. The occurrence of movements detected by inclinometer measurements and of retrogressive failures follows the gradual increase in groundwater level in Casagrande cell C2 in P4 (Fig. 7). In the piezometer P2 (Fig. 8), the Casagrande piezometer cells, C1, and C2, were positioned respectively several meters below the slip surface and within the earth flow body. Between February and May 1995, the groundwater level in C2 showed the largest variations, while its level in C1 was practically constant. The increase in the piezometric level registered within the earth flow preceded deformations measured by inclinometers and the subsequent reactivation of the flow.

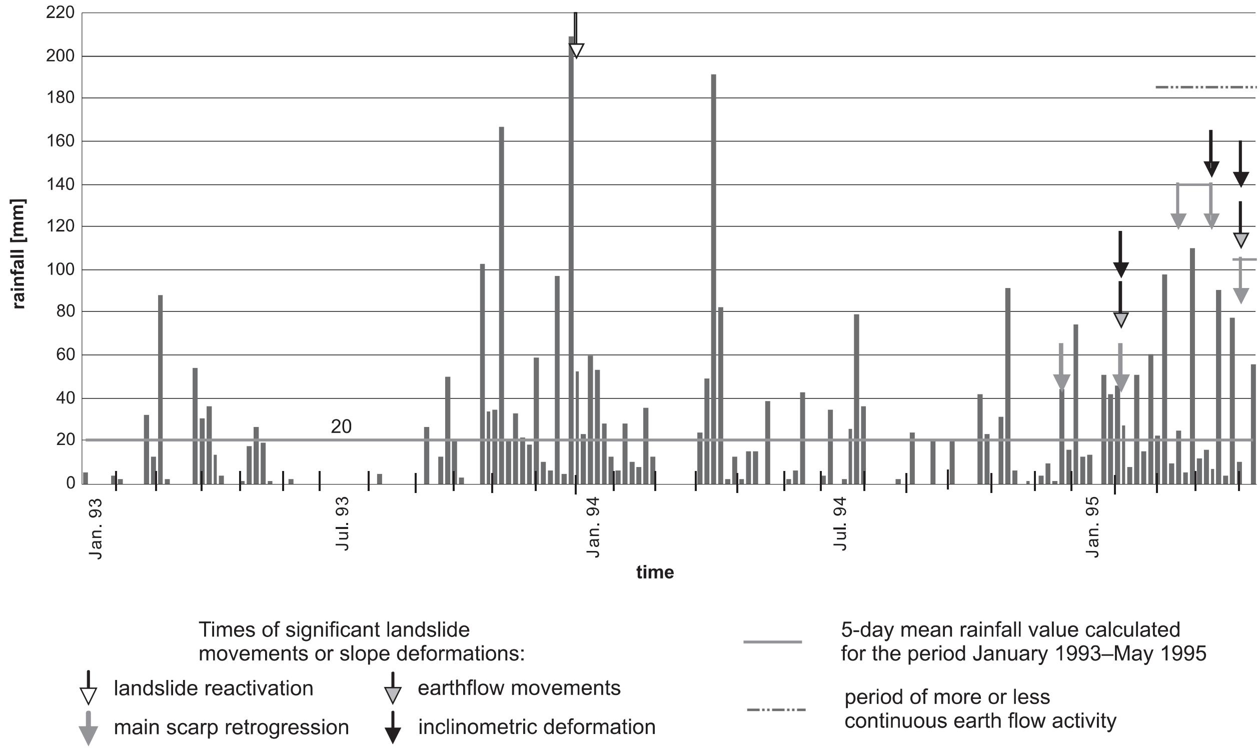

Fig. 5. Five-day cumulative rainfall at the Senerchia rain gauge and landslide activity

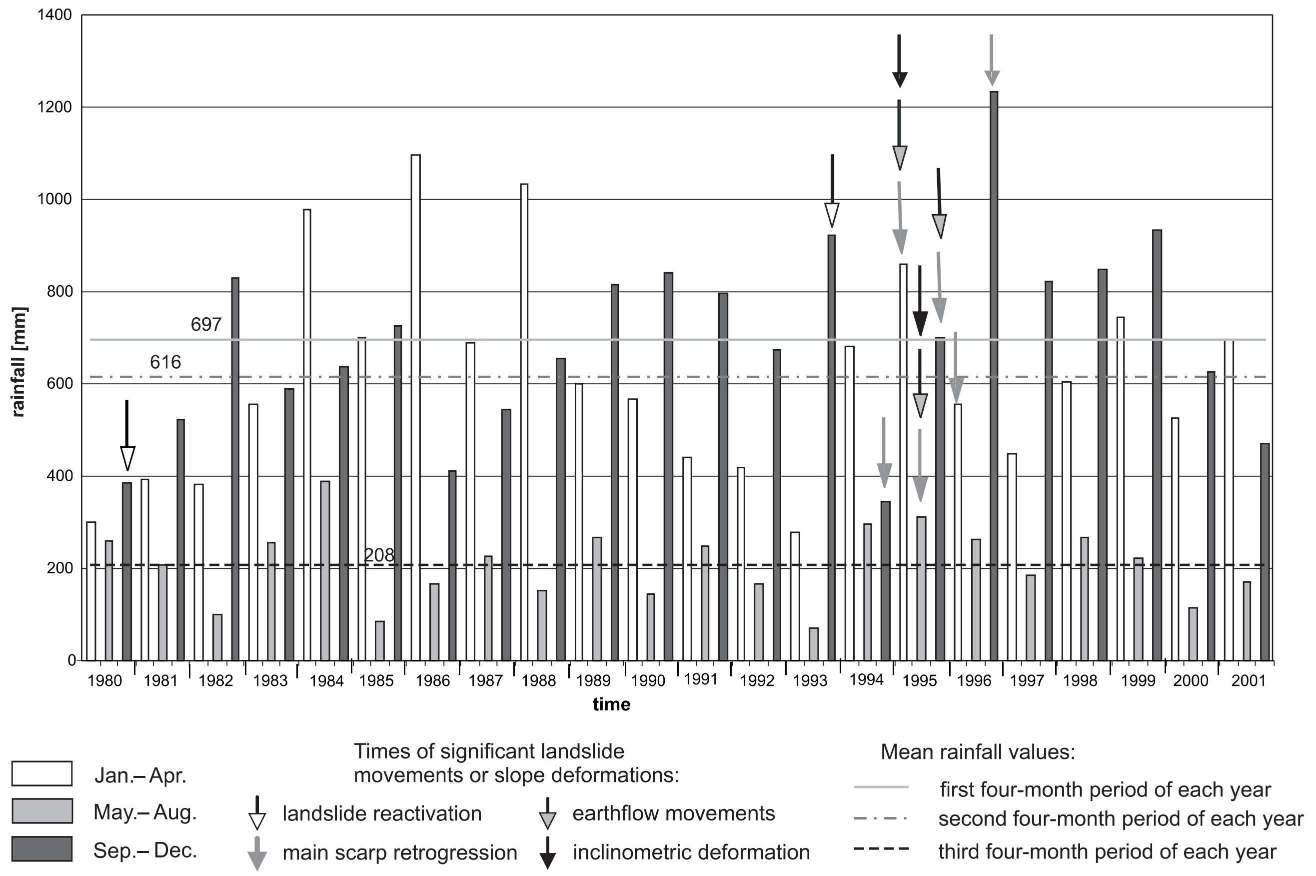

Fig. 6. Four-month cumulative rainfall at the Senerchia rain gauge and landslide activity

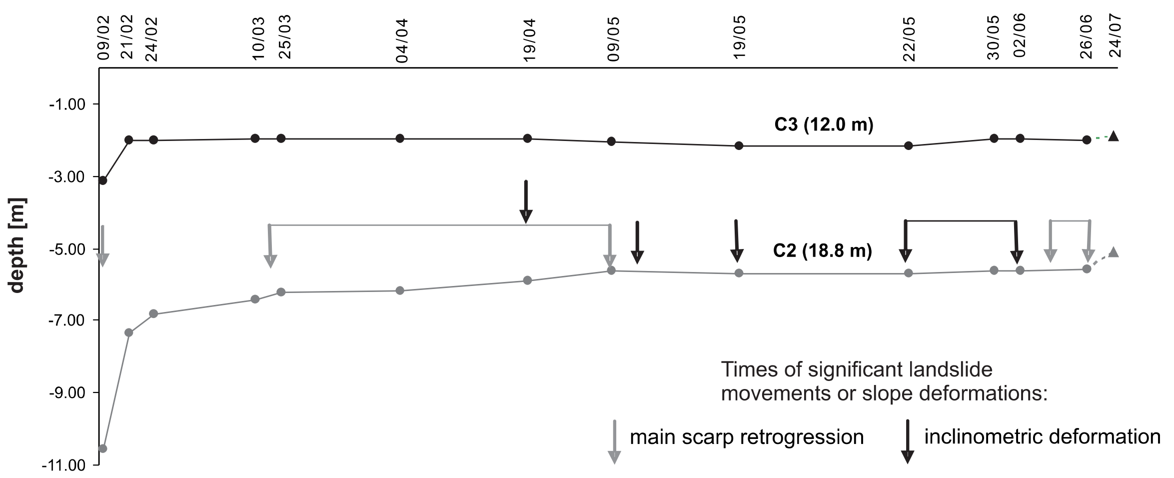

Fig. 7. Variation of piezometric levels in borehole P4 sited in the crown — main scarp area and landslide activity between February and July 1995

C2, C3 — Casagrande piezometer cells; for location see Figure 4

SEISMICITY AND LANDSLIDE ACTIVITY

Considering the high seismicity of the study area, we also examined possible relations between the intermittent movements of the Acquara-Vadoncello landslide, the local main scarp failures, and the small magnitude earthquake events registered during the monitoring period. Indeed, seismic shaking can contribute to the slope instability in different ways: directly as a triggering factor of co-seismic slope failures (as in case of rock falls produced by the mechanical action of the ground motion), or in-

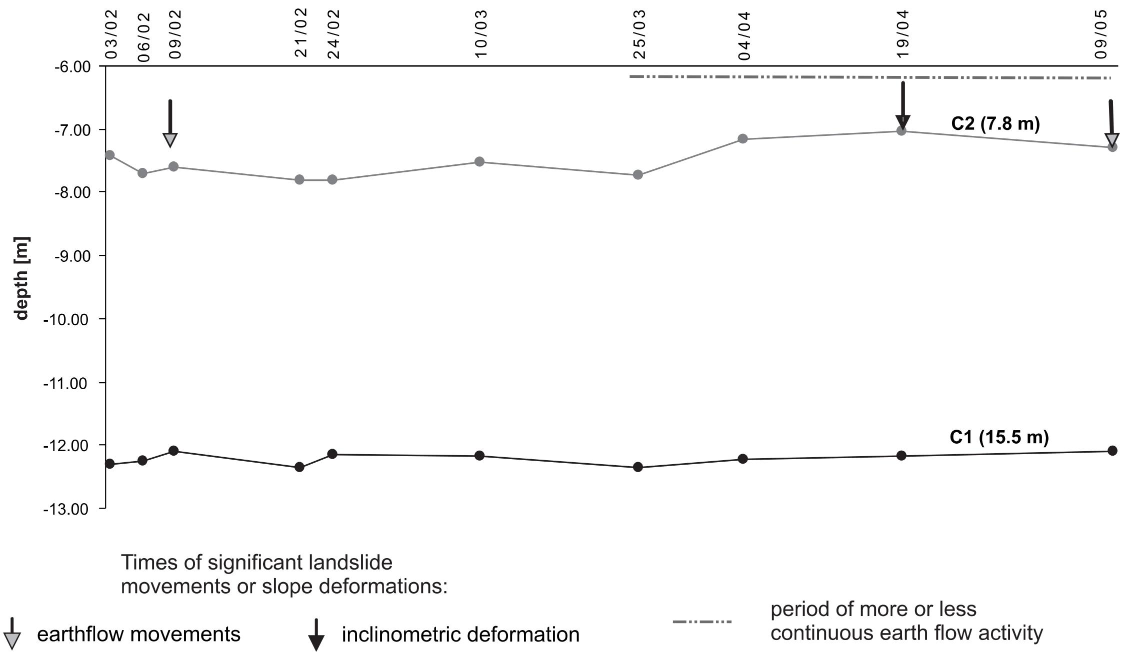

Fig. 8. Variation of piezometric levels in borehole P2 sited in central part of earth flow and landslide activity between February and May 1995

C1, C2 — Casagrande piezometer cells; for location see Figure 4

directly as a predisposing factor through the reduction of slope strength caused by the opening of cracks, the increase of permeability for fracturing or the increase of pore pressure induced by aquifer deformations. These variations may lower the safety factor and facilitate the triggering of mass movements shortly after the earthquake (e.g. Jibson *et al.*, 1994).

The study area has been characterised by a high concentration of seismic events (both historical and recent instrumentally recorded) distributed along the Apennine chain, within a short distance from Senerchia. In the last 300 years, about ten earthquakes have likely caused at Senerchia shaking of intensity equal or greater than VII MCS, and thus potentially capable of triggering landslides. However, only for the last of these events, the 23 November, 1980 earthquake, landslide activation (Serra dell'Acquara) was documented.

The role of low energy seismic shaking as a factor favouring slope failure is still uncertain (e.g. Keefer, 1984, 2002; Papadopoulos, Plessa, 2000). To evaluate the possible influ-

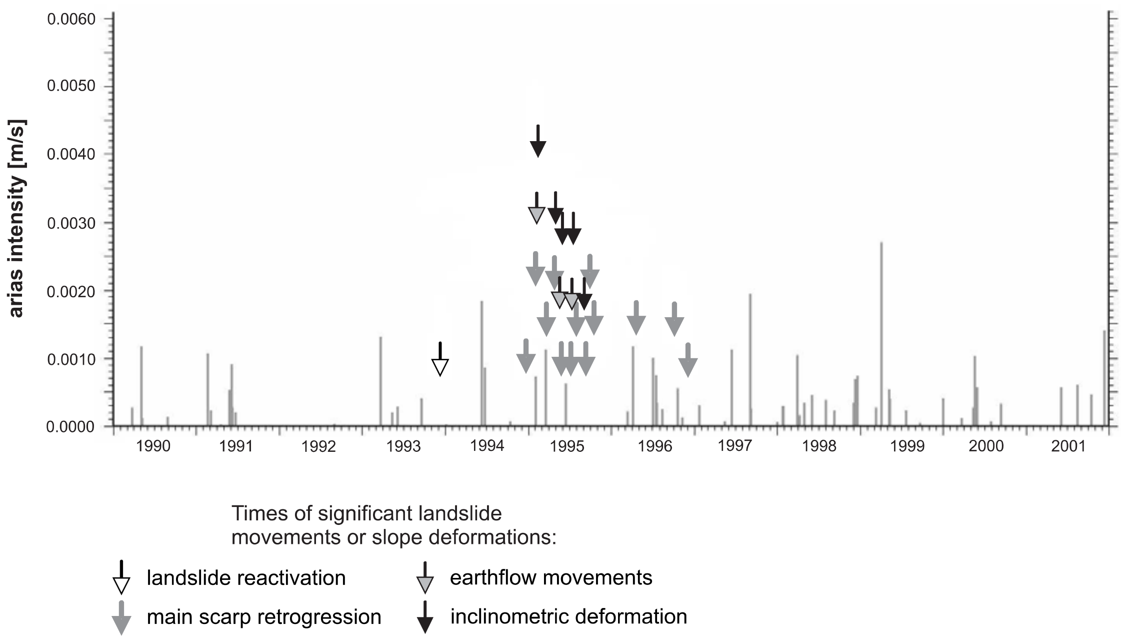

Fig. 9. Daily Arias intensity estimated for seismic events that affected the Senerchia area during the 1990–2001 period

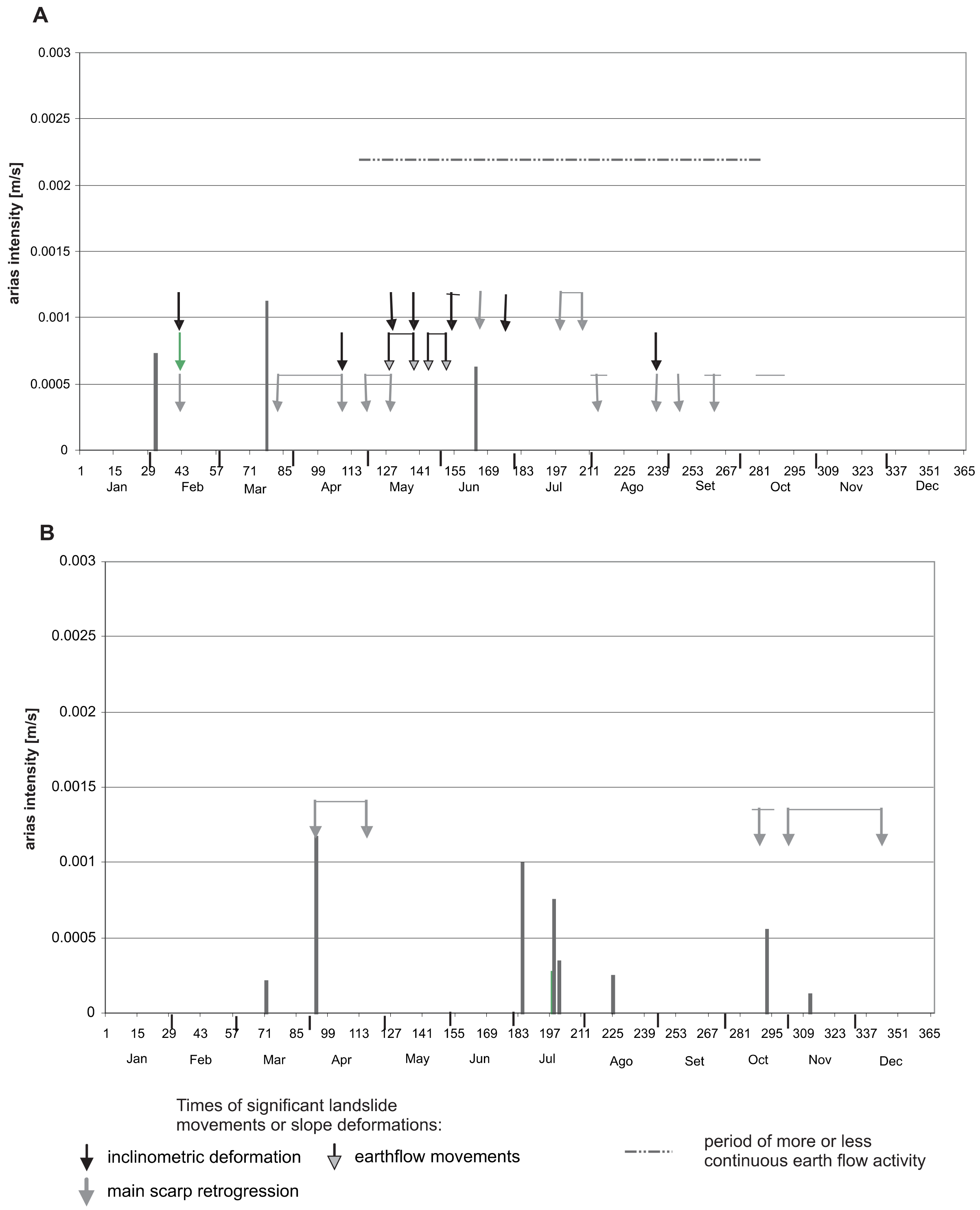

Fig. 10. Daily Arias intensity estimated for seismic events that affected the Senerchia area in 1995 (A) and 1996 (B)

ence of seismic activity on the evolution of the Acquara--Vadoncello landslide, earthquakes occurred from 1990 to 2001 and potentially felt in the study area with local intensity ≥ III MCS were extracted from the Italian database of the Istituto Nazionale di Geofisica e Vulcanologia (INGV). The intensity threshold was chosen in order to have a comprehensive list of events, i.e. omitting only those events for which an influence on slope instability can be excluded with a high confidence.

The seismic events were relocated with a standard code (Hypoellipse — Lahr, 1989) by means of a local velocity model, and magnitudes were recalculated based on the duration of recordings obtained by the stations of the Seismological Observatory of the University of Bari, in order to have a homogeneous source in the attribution of magnitude values. The shaking level caused at Senerchia was calculated in terms of Arias intensity (Arias, 1970), a parameter that has a better correlation with the destabilisation of slopes than macroseismic intensity (Harp, Wilson, 1995). The local Arias intensities of the selected events were estimated using the Sabetta and Pugliese (1996) attenuation relationship. The intensities obtained were in the order of 1–2 mm/s, at the most. This was much lower than the value 0.32 m/s, which, according to Keefer and Wilson (1989), is the minimum threshold for a triggering effect on coherent-type landslides as it is the case of the Acquara-Vadoncello landslide. Since the Arias intensity represents a measure of the energy transmitted by seismic waves to ground surface, the time distribution of this energy released daily was compared with the occurrence time of significant episodes of landslide activity, in order to recognise any possible relations (Fig. 9).

From a preliminary qualitative examination, no relation was found with reference to the first landslide activation in 1993, considering that no associated seismic activity was recorded in that period. However, an early 1995 phase of retrogressive landslide activity coincided with some weak seismic shocks (magnitude 3.3) located near the study area (Del Gaudio *et al.*, 2000a). For example, the seismic event on February 1, 1995 (magnitude 3.3 and localised about 15 km NE of Senerchia) caused an estimated value of Arias intensity of about 0.5 mm/s at Senerchia; this shock preceded local main scarp failures and the rise of the groundwater level between 3–9 February, 1995. On March 19, 1995, a seismic event of the similar magnitude occurred at a distance of ~10 km, and on the 13 June, 1995 seismic events (magnitude 3.2), localised about 15 km at SE of Senerchia, caused, respectively, about 1 and 0.5 mm/s of Arias intensity. In a few days, they were followed by falls occurred in the main scarp area (Fig 10A).

On April 3, 1996, a seismic event of the 3.7 magnitude was registered; it was localised about 20 km at SE of Senerchia. The estimated total daily Arias Intensity was similar to that of March 19, 1995, and also in this case the event was apparently followed by main scarp failures (Fig. 10B). On October 19, 1996, a seismic event of magnitude 3.4 occurred about 20 km at SE of Senerchia; Arias Intensity felt in the Acquara-Vadoncello landslide area was similar to that of February 1, 1995 event. In this case, a little landslide occurred on the main scarp about one week after the event (Fig. 10B). However, no recorded mass movement did follow some shocks of similar Arias intensity, occurred during 1996, particularly in July.

In summary, during the 1995–1996 period a series of local main scarp failures were observed to follow within days a few low magnitude seismic events, even if their Arias Intensity did not exceed values of similar events registered also before 1995, and after 1996. At the end of 1996, the landslide was practically stabilised and the successive seismic events did not influence the landslide activity, even if their Arias intensities were higher than those of the 1995 earthquakes.

QUANTITATIVE ANALYSIS

The temporal and spatial complexity of the observed landslide activity makes difficult the recognition of cause-effect relations on a purely qualitative basis. Therefore, we attempted a quantitative estimate of possible correlations between the landslide movements and rainfall and seismic events. In particular, considering that the amount of the main scarp retrogression was the slope failure parameter measured with more continuity, i.e. approximately with a monthly recurrence, we correlated this quantity with monthly cumulative values of rainfall and Arias intensity. The correlations were calculated using the following Bravais-Pearson coefficient correlation:

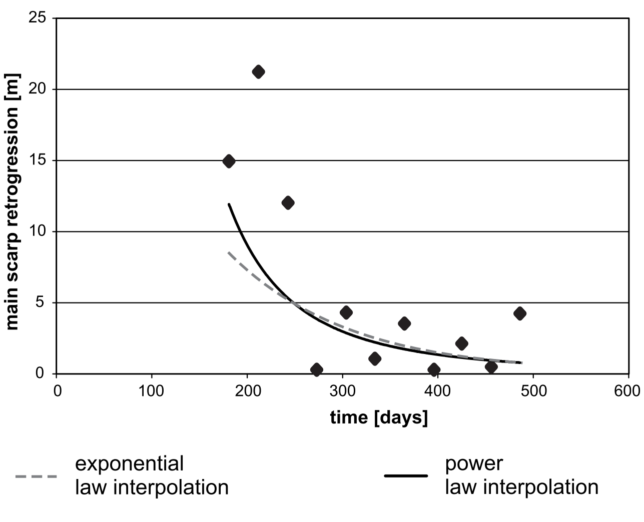

Fig. 11. Main scarp retrogression during June 1995–May 1996

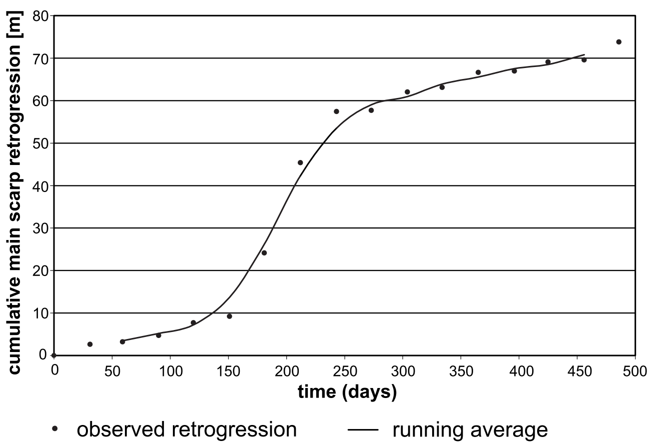

Fig. 12. Main scarp cumulative retrogression during the June 1995–May 1996 period, and moving average (continuous line) calculated on the three successive measurements

$$\phi_{xy} = \frac{\sum_{i=1}^{N}(x_i - \bar{x})\cdot(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{N}\left(x_i - \bar{x}\right)^2 \cdot \sum_{i=1}^{N}\left(y_i - \bar{y}\right)^2}}$$

where:

x — precipitation or Arias intensity,

y — retrogression values.

First results obtained for the period June 1995–May 1996 provided very low and negative correlations because (a) the main retrogressive episodes occurred in summer months characterised by very low precipitation, and (b) the maximum seismic energy release occurred towards the end of the considered period, when the landslide achieved a nearly stable condition.

To take into account the stabilisation effect, we tested two possible models of temporal evolution of the main scarp using exponential and power laws; the model parameters were obtained from a regression fit (Fig. 11). Since the destabilising actions are variable in time, it was assumed that they could produce oscillations around the stabilisation trend; therefore, we examined the correlation between the regression residuals and, separately, rainfall and Arias intensity values to reveal possible links between destabilising forces and deviations of main scarp evolution from the overall trend toward stability.

A weak positive correlation (34–37%) between seismic energy release and the main scarp retrogression was observed, whilst the correlation with rainfall was still very low and negative because of the displacements in the 1995 summer months. Since the short data series enhances the influence of the anomalous slope behaviour during the summer 1995, we extended the period of observation (January 1995–May 1996), even though this implied the use of data collected with more irregular time frequency. The general trend in this case was modelled using a moving average on cumulative movements and the correlation was calculated considering the residuals of main scarp cumulative retrogression with respect to this average (Fig. 12). The longer series of data reveals the increasing retrogression velocity in the spring 1995 period. In this case, there is a positive correlation with rainfall (40–50%) and no correlation with seismic energy release.

CONCLUSIONS

Results of the analysis show that the general retrogressive trend of the main scarp correlates directly neither with monthly seismic energy release nor with monthly rainfall. Instead, it appears to be influenced by the variations in the groundwater level (which depends on longer-term cumulative rainfall).

The short-term variations in the main scarp movements deviating from the general trend present a weak positive correlation (40–50%) with monthly precipitation. With regard to seismic activity, despite the low energy of the events (maximum magnitude 4.2), the seismic shaking showed an apparent positive correlation of 32–37% with main scarp retrogression, but only during the greatest landslide mobility phase. This suggests that low energy seismicity could influence the evolution of the main scarp failures during the high instability phases. We suspect that this may reflect some topographic amplification effects, which are to be expected in the case of the steep and convex main scarp — crown area morphology of the Acquara-Vadoncello landslide.

No correlation was observed between the low energy seismic activity and the earth flow activity. The monitoring and *in situ* controls showed that earth flow movements were favoured by the precipitation (particularly those concentrated during 5-days preceding the movement), by the rise of the groundwater level and by the progressive loading of the earth flow head by the local main scarp failures.

The outcomes of this work suggest that complex mass movements with characteristics similar to those of the Acquara-Vadoncello landslide are governed by the interaction of numerous destabilising factors (hydrogeological, geomorphologic, seismic and climatic). Their influence depends on the combination of several parameters whose weight can vary during the landslide evolution, and this makes difficult to highlight the role of a single factor, like weak seismicity, in slope evolution.

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