Karst processes and slope instability: some investigations in the carbonate Apennine of Campania (southern Italy)

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Abstract: Some investigations carried out in the Campania Region (southern Italy) are shown concerning instability phenomena, the development of which is strongly influenced by karst. The widespread presence of carbonate massifs close to important urban centres with dense road networks creates high-risk situations in many settings of this region.

Such phenomena can have very different dimensions, origin and geomorphological development, and can be traced back to the action of hypogean and epigean karst and to complex interactions with other erosional processes.

In particular, among the hypogean forms, we have analysed collapse sinkholes that have developed on carbonate slopes, especially along fault lines where there are aquifers and ascent of mineralized fluids, and which are sometimes connected to strong seismic events.

Among the forms connected to epikarst processes, the origin of pinnacles has been investigated. They are isolated rock pillars, whose origin depends on a particular interaction between the geostructural characteristics of the masses and the process of karstic dissolution.

Moreover, a wide variety of morphologies exist that are related to the interaction between epigean and hypogean karst and other typologies of erosional processes. Among these one group is represented by caves on carbonate slopes developed in cataclastic zones, where a slow karstic process leads to the formation of upwards caves, with dimensions of some decametres, and consequently to the high production of debris downhill. Similarly, this process has been observed along slopes set on talus. Finally, the complex combination of the karstic phenomenon with the erosional wave action forms both caves and natural rock arcs along the coasts.

Carbonate massifs in southern Italy, especially in Campania, are affected by karstic phenomena, both hypogean and epigean (Fig. 1). The numerous available studies on these areas have mainly a geomorphological and hydrogeological approach, while only a few deal with the relationships between karstic processes and slope stability, although several phenomena of instability can be found whose origin is strictly linked to karst.

Surveys started in some areas of the region have shown that karstic morphologies that appear to affect slope stability can be quickly grouped into three different categories. They can be mainly the result of hypogean and epigean karst or of interactions between karstic processes and other erosional agents (Fig. 2). In some cases such phenomena have damaged built-up areas and main roads, offering at the same time interesting scientific cues to their origin.

On the basis of these investigations, this paper is aimed at defining the various geological contexts affected by these problems.

In the first part we will focus on the engineering – geological aspects concerning the most significant karstic phenomenologies (sinkholes, pinnacles), pointing out the dangerous interaction often set up within built-up areas. Then, other less frequent phenomenologies are described; although they are little documented, in some particular settings they can cause serious damage to populated areas and road networks.

Karstic sinkholes and slope instability

It is generally acknowledged that a possible collapse of a sinkhole represents a serious problem for territory planning (Ford & Williams 1989), mainly because of the difficulty in predicting and localizing the event. This phenomenon has become so frequent in some areas of Florida (Sinclair & Stewart 1985) that the United States Geological Survey (USGS) carry out ongoing information campaigns for the inhabitants, who are trained to report, including through the Internet, any small amounts of soil deformation (www.sinkhole.org).

Recently, in Italy, the scientific community and public administration and local management agencies have become more aware of the frequent development of sinkholes (AA.VV. 2000, 2004). The sinkholes in Campania (Del Prete *et al.* 2004) can be distinguished (Nisio 2003; Sauro 2003; Waltham *et al.* 2005) into:

– *collapse sinkholes* of karstic origin, opening onto carbonate slopes;

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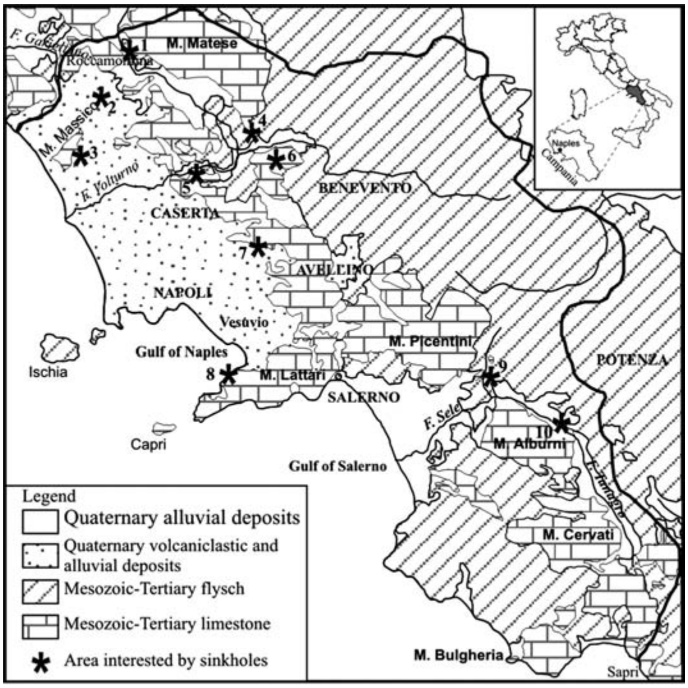

Fig. 1. Geological map of the Campania Region and the distribution of the main sinkhole areas: 1, Mastrati; 2, Vairano Lake; 3, Agro Falerno; 4, Telese; 5, Castelmorrone; 6, Solopaca; 7, Cancello; 8, Jala; 9, Contursi; and 10, Pertosa (after Del Prete *et al.* 2004, modified).

– *cover sinkholes*, wholly developing within detrital covers, lying at the base of carbonate massifs;
– *piping sinkholes*, developing in gravel, sand and silt deposits in the areas of alluvial plains.

In this work we will focus only on collapse sinkholes, which develop mainly along fault lines where there are aquifers or upward movement of mineralized fluids together with hyperkarst phenomena. In some cases there is evidence of their formation in conjunction with strong seismic events. Some examples can be seen on the mountains of Avella, along the coastline between Vico Equense and Castellammare (Nota D'Elogio 1979), and near the thermal springs of Telese and Contursi. The presence of mineralized aquifers in these areas seems to confirm, as suggested by various authors (Corniello & De Riso 1986; Forti & Perna 1986; Forti 1991, 2002; Corniello *et al.* 1999), the existence of a close connection between the origin of sinkholes, hyperkarst phenomena and, most probably, recent tectonic activity. It has been observed that sinkholes can develop in two different contexts: (a) deeply karstic areas with wide underground caves (collapse of cave); and (b) much fractured limestone and dolomite bedrock.

Collapse of cave

In the areas where carbonate massifs are characterized by slightly fractured formations with wide caves very close to the surface, collapse sinkholes are more likely to develop owing to the collapse of the cave vaults (Fig. 3). Basically, as also observed by other authors (Lolcama *et al.* 2002; Beccarisi *et al.* 2003; Delle Rose *et al.* 2004), the process starts with the formation of an embryonic cave connected to a karstic base level. Subsequently, the evolving dissolution process leads to a constant widening of the cave, also fostered by partial collapses of the vault and the walls. Thus, the cave tends to widen upwards and, if an underground stream is present, also at the base owing to erosion and dissolution processes. Such a constant widening of the cave also affects the geomechanic characteristics of the bedrock. The thinning of the vault near the surface and the increasing tangential stress affecting the vault rock at the same time can cause a sudden collapse with consequent formation of a collapse sinkhole.

When these phenomena take place near urban centres and main road networks they evidently represent a serious risk factor.

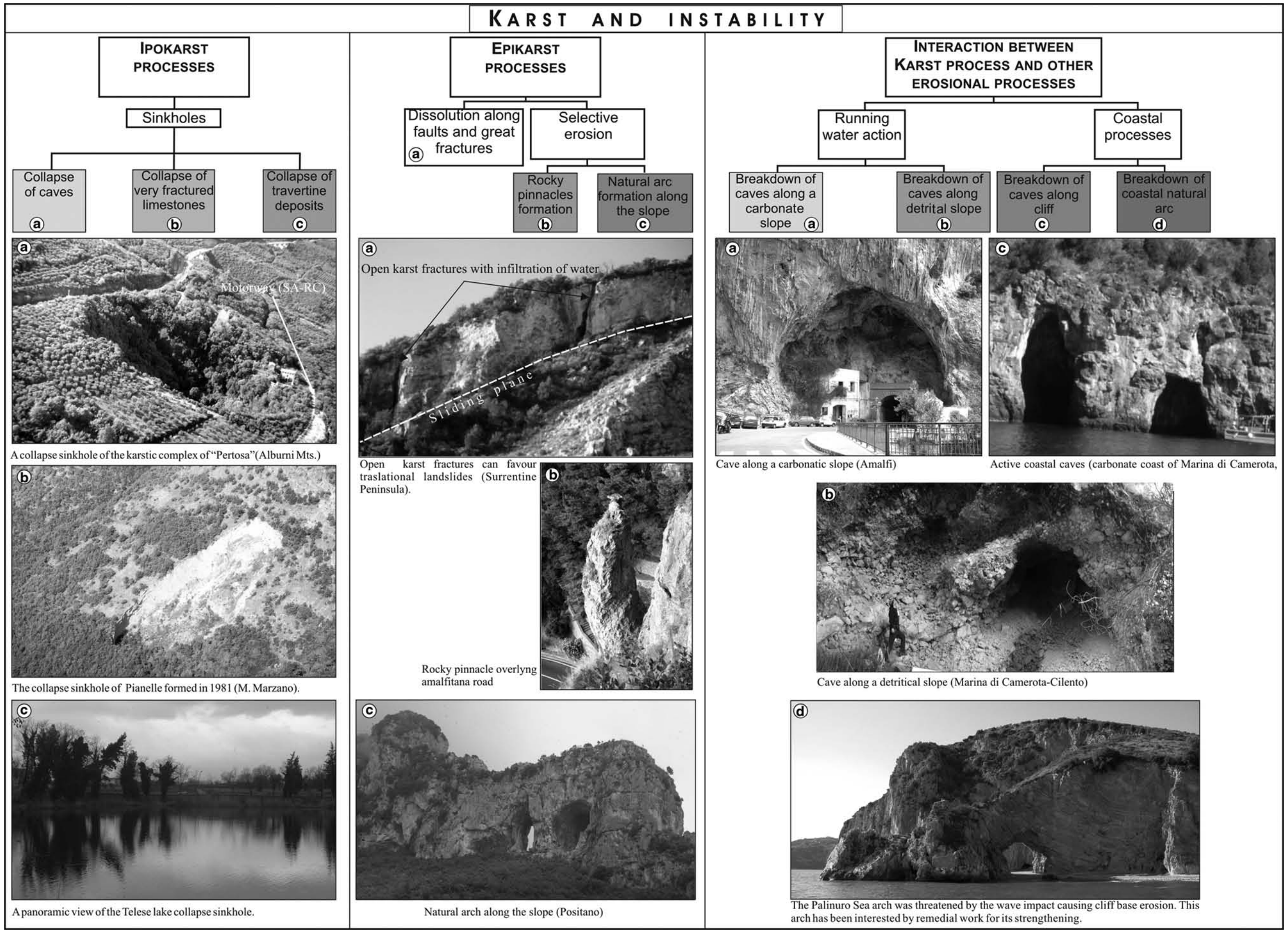

Fig. 2. The different types of karstic morphologies that can affect slope stability.

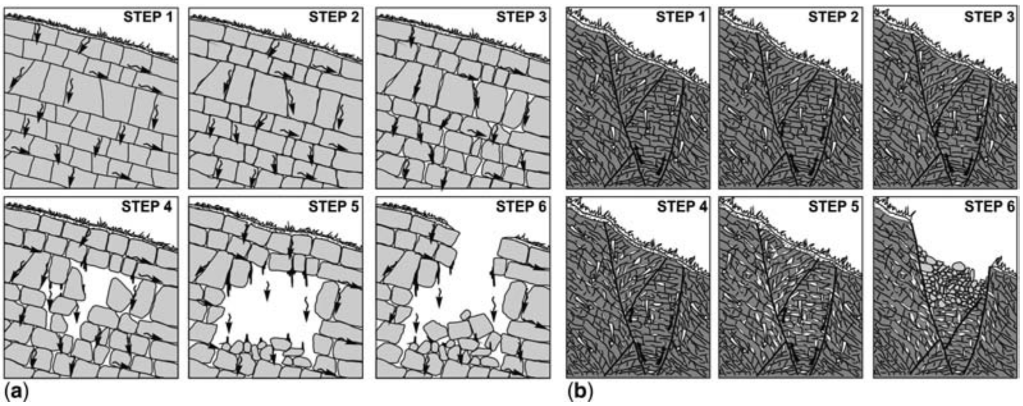

Fig. 3. Schematic representation of the various periods of a collapse sinkhole formation. (**a**) Collapse of a cave and (**b**) highly fractured limestones.

An example occurs in the historical centre of the village of Maddaloni near Caserta, where, under the houses close to the ancient medieval castle, a wide cave (50 m long, 17 m wide and 7 m high) has recently been discovered (Fig. 4). The thickness between the cave vault and the topographic surface is less than 3 m, and the constant water infiltration due to leaks in the underground pipelines contribute to accelerating the phenomenon of karstic dissolution of the rock, which is already in an instable condition.

Another example is represented by two collapse sinkholes in Pertosa at the base of the Alburni Mountains; when the sinking occurred is not yet known, but they are likely to have opened up in connection with one of the several karst systems developing along the basal aquifer of the massif. In this case the plan of the Salerno–Reggio Calabria motorway, which runs just a few metres from the sinkholes, has not taken into consideration either the sinkhole presence or the possibility of further sinking phenomena.

Collapse of deeply fractured limestones

Collapse phenomena can occur in highly fractured and karstic carbonatic massifs (Maffei *et al.* 2005), without necessarily the presence of a wide cave (Fig. 3).

In these cases, chemical dissolution leads to the formation of several small cavities in the bedrock, ranging in size from a few centimetres to some decimetres. When their frequency becomes particularly high, compared to the whole volume of the rock, tangential resistance can be overcome and cause the formation of a sinkhole on the surface.

Similar cases are represented by the Hill of Cancello sinkhole on Avella's mountains and by the Jala doline in the Sorrentine Peninsula (Fig. 5a). In the former case the excavation front of a stone quarry exposes the base of the sinkhole, and shows the presence of deeply fractured limestone. Similarly, the presence of deeply fractured and karstic limestone at the Jala sinkhole has been confirmed by surface geological surveys and drillings.

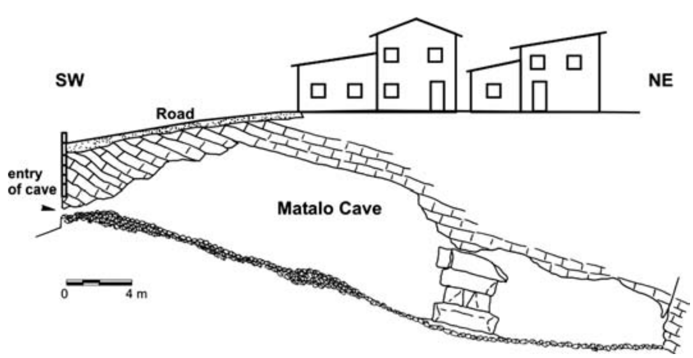

Fig. 4. An example of sinkhole risk: historical centre of the Maddaloni village.

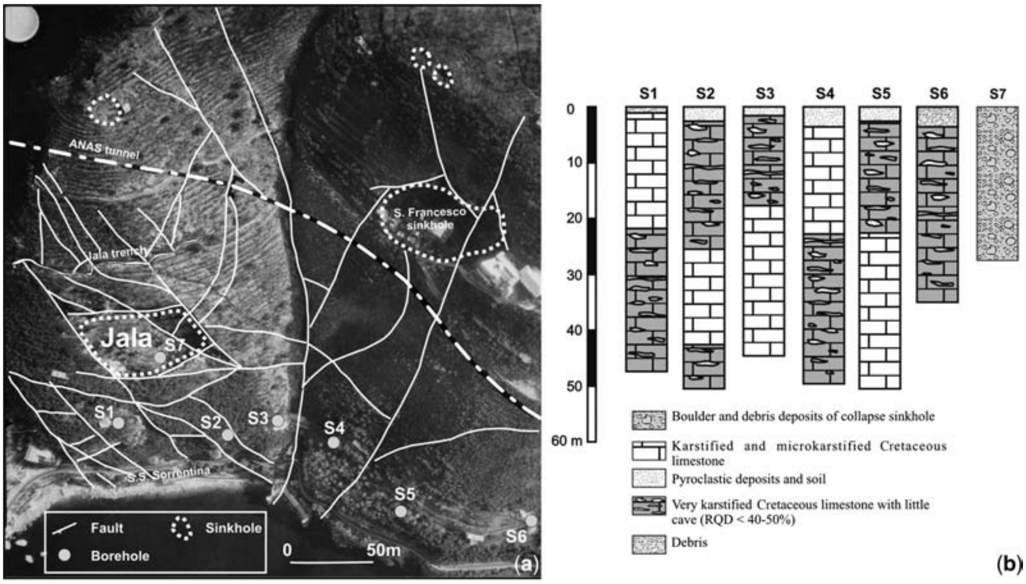

Fig. 5. (**a**) Aerial view of the 'Jala' sinkhole (Surrentine Peninsula), probably formed in the 18th century and (**b**) boreholes carried out in this area.

These have met much tectonized and karstic bedrocks with several micro-caves, filled in some cases with sand and characterized by very low Rock Quality Designation (RQD) values (<40–50%; Fig. 5b).

In this case the described morphologies have a negative impact on main road networks. In Vico Equense the presence of sinkholes caused several problems during the excavation of some tunnels because of the deeply fractured state of the karstified bedrock (Budetta *et al.* 1996; Santo & Tuccimei 1997).

Rocky pinnacle formation and slope instability

In the Campania Region, on the deeply fractured Triassic–Jurassic dolomite and limestone slopes, the numerous karstic morphologies are represented by pinnacles. They are concentrated in rock masses with low inclined bedding, having intersected highly inclined joint sets, some of which are parallel to the slope. The main erosive agent in their formation is water, which when penetrating through the joints works with a constant dissolution and

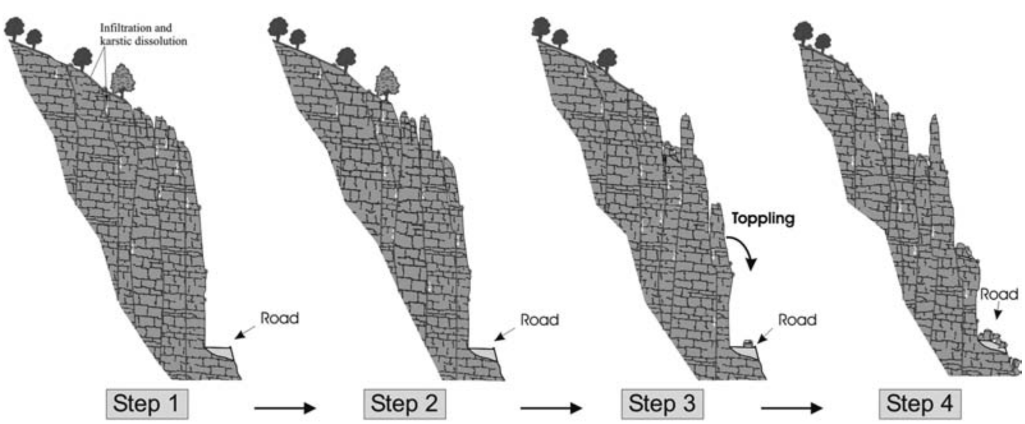

Fig. 6. Schematic representation of the various periods of the rocky pinnacle formation.

disgregation process on the masses; karst can be accompanied by effects of thermoclastic and crioclastic phenomena and of gravity. Pinnacles very often show a condition of instable balance, overlying very busy roads and creating highly risky situations.

Figures 6 and 7 show pinnacle formation schematically over time. It is evident how a slope characterized by vertical joint sets (step 1) leads through selective erosion to the formation of prismatic structures (step 2), which, with a progressive dissolution and erosion process, form unstable pinnacle structures (step 3) possibly leading to topple failures (step 4). Owing to their high, narrow form, pinnacles are inherently unstable and when adjacent to busy roads can create a hazardous situation.

In order to better understand the discontinuities pattern, failure typology and concerned volumes of the pinnacles, detailed geostructural surveys have been carried out on a sample area along Amalfi's coast, where such phenomenologies are very common (Fig. 8a).

The orientation of faults, joints and beddings has been drawn on pole plots (Schmidt equal-area stereographic projection), so that the cyclographics representative of each of the three main discontinuity sets can be found (Fig. 8b). Sets K1 and K2 transversally cut the slope, while the K3 set shows a dip direction opposite to the slope and a dip angle of 78°. The bedding appears to be generally low dipping in relation to the slope gradient, but with a very low inclination (<10°).

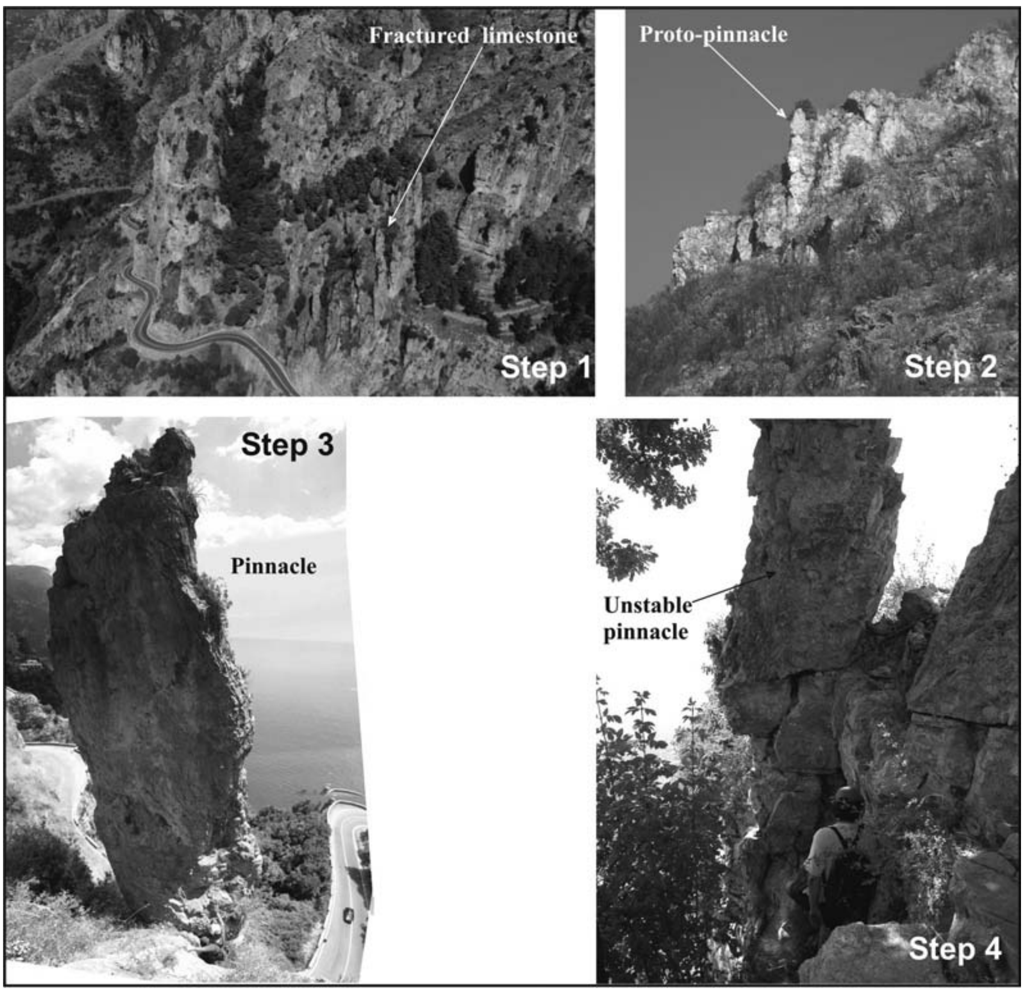

Fig. 7. Examples of rocky pinnacles along the main road between Amalfi and Positano.

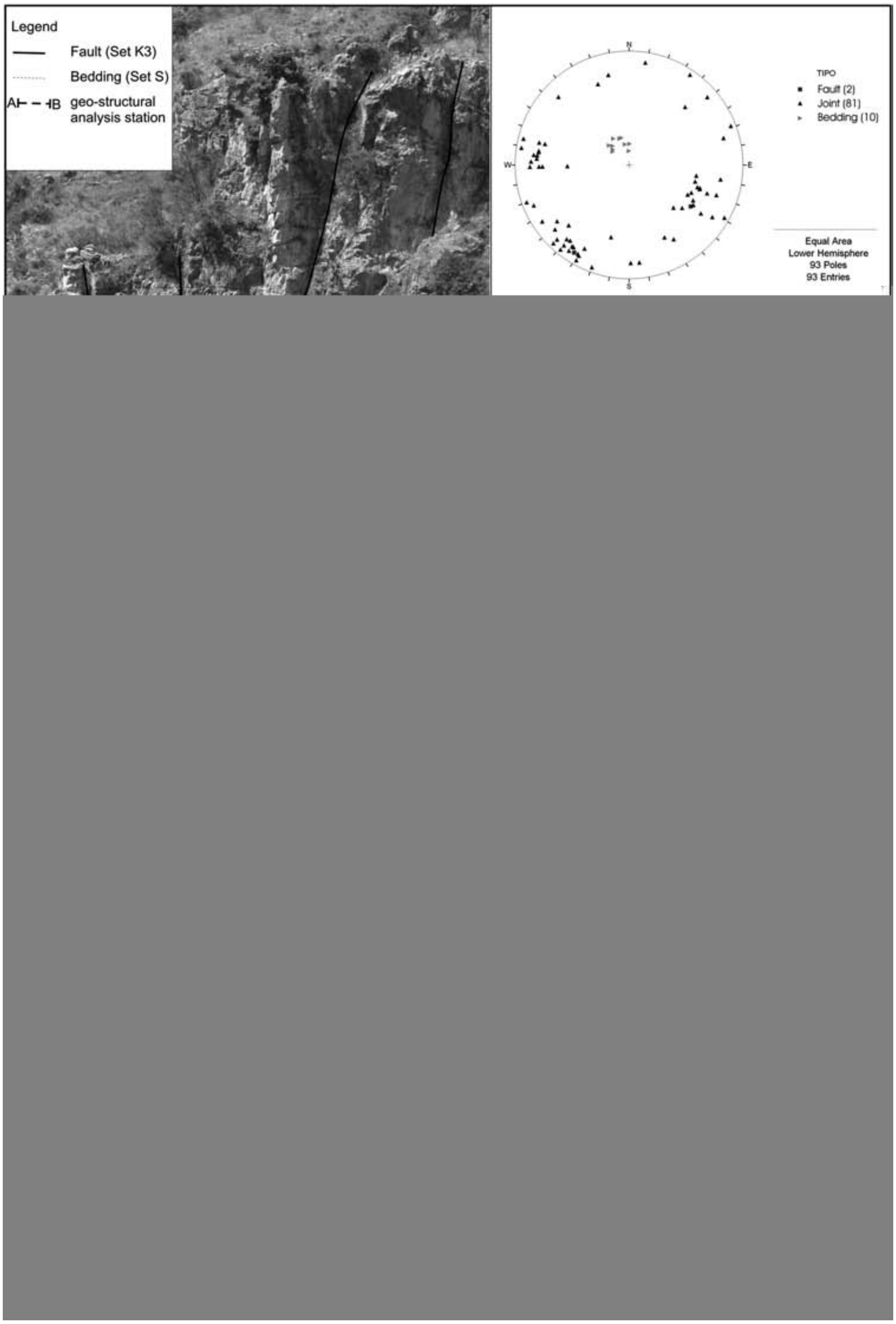

Fig. 8. (**a**) Geostructural surveys on a sample area along the Amalfi coast; (**b**) pole plot, rosette plot, Schmidt contour plot, mean poles/planes displayed for set K1, K2, K3 and bedding S; (**c**) stereonet overlay for assessment of worst-case discontinuity sets; and (**d**) other field observations of rock conditions.

Table 1. *Geomechanical values of the parameters affecting the rock masses*

Compressive strength (MPa)	Discontinuities								
	Mean spacing (mm)	RQD (%)	Length (m)	Separation (mm)	Roughness (JRC)	Infilling	Roughness profile	Groundwater	Weathering
20	60–200 Close	70	<1 Very low	2.5–10 Moderately wide	4–8; 8–12 Slightly rough to polished	Compacted clay material and calcite	Slightly undulating	None	Slightly weathered

RQD, Rock Quality Designation; JRC, Joint Roughness Coefficient.

The orientation of the discontinuity sets in relation to the slope gradient has been assessed to test the existence of degrees of looseness as a possible cause of failure (Fig. 8c) (Moon *et al.* 2001). The result attained shows a high tendency towards toppling failure.

Toppling failure is fostered by the presence of discontinuity planes at a high gradient within the rock mass, often represented by open discontinuities in the K3 set. The cyclographic of this set shows a dip direction opposite to the slope and a strike close to the slope gradient. Moreover, the masses thus isolated upwards are transversally faulted by at least another two discontinuity sets (K1 and K2), which thus isolate vertical rock prisms. These can undergo a toppling phenomenon around a rotation point connected to the stratification planes.

The field survey has also defined other parameters needed for a geomechanical rock mass assessment (Table 1, Fig. 8D) (ISRM 1978).

The geostructural analysis on the pinnacles has shown a high possibility of the occurrence of toppling failures involving volumes in the range from a few to several m^3.

Other phenomena

In addition to the cases just dealt with, in Campania there are other karstic phenomena both epigean and hypogean that are likely to favour landslide occurrence. Since historical documentation of these phenomena is lacking, we will only refer briefly to them and focus on their origin and geomorphological evolution.

Breakdown of caves along carbonate slope

In the areas of the Lattari Mountains and Cilento numerous karstic caves along slope have been surveyed. They develop on deeply fractured dolomitic limestone slopes affected by low-angle fault sets with dip direction against the slope.

Along cataclastic lines, representing the weakest points of the rock masses, there are the conditions for the formation of a ‘proto-cave’, that can evolve over time in response to slow karstic processes brought about by a local groundwater circulation that runs along the contact line between highly fractured zones and less affected ones. The karstic process results in the widening of joints and the occurrence of breakdown processes; the fallen blocks may be easily removed along the talus and transported outside the cave (Fig. 9). The particular joints set patterns, therefore, allow local superficial groundwater circulation and at the same time the removal of fallen material. In this way a progressive widening of a small cave can be slowly attained, sometimes with

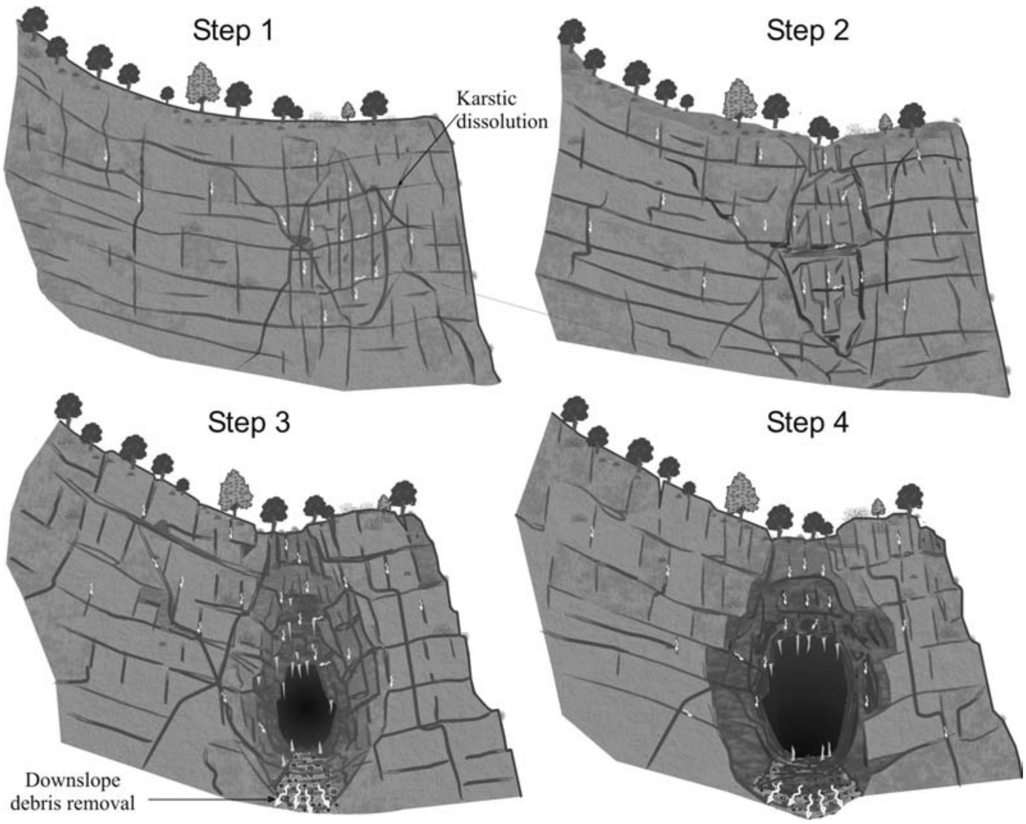

Fig. 9. Schematic representation of the various periods of a cave formation along a highly fractured carbonatic slope.

the formation of remarkably large caves that can reach vault heights of 30–40 m (Fig. 10).

Sometimes a further development of the cave upwards can lead to thinning, and thus instability, of the vault, with consequent sudden phenomena of breakdown involving the whole cave or part of it. In many cases, in fact at the base of the slopes with these cave typologies, large blocks up to several m^3 and talus can be found. In addition, on the slope surface we can find clear evidence of old caves that have fallen down because of the presence of wide hollows, still preserving relicts of stalactites and speleothems formed in a hypogean environment.

An example of a collapse involving a large cave along slope is the Amalfi landslide of 1899 (Budetta *et al.* 1994); Figure 11 shows evidence of a cave, today no longer visible, that existed on the slope before the landslide; collapse of this cave was most probably the main cause of the landslide that caused numerous casualties.

This historically documented event is not the only one, as several similar situations have been found on the slopes of Amalfi's coast and Mount Bulgheria in Cilento, some of them very close to built-up areas or overlying arterial roads. These phenomena can cause highly risky situations, so they should be studied in a more detailed way.

Breakdown of caves along a detrital slope

The foothills of carbonate massifs are characterized by the presence of highly dipping debris, with a thickness ranging from a few to several metres. When the talus is cut at the base of the slope, either for natural (faults, stream and sea erosion) or anthropogenical (road cuts, etc.) reasons, they can cause, because of karstic phenomena, some particular typologies of landslides. These have already damaged the road network at many sites.

Case histories have shown that within some talus, or at the contact between talus and limestone bedrock, a variation in the permeability can result in the local presence of groundwater. This might set

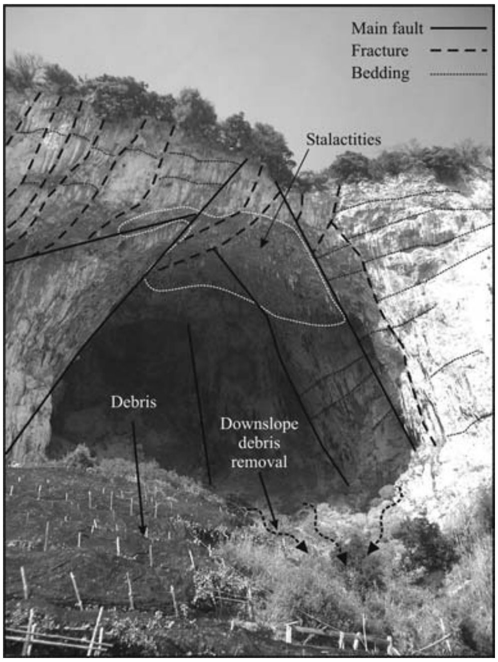

Fig. 10. The large cave of Saraceno, partially collapsed (Praiano).

off a slow karstic process affecting the debris. The formation of voids along the bedding is likely to be thus attained, which in time can collapse or initiate translational sliding of the talus material above.

The initial step (Fig. 12) is characterized by a voidless talus slope, on which we can find small crowns of rock falls. In this phase the slope is mainly susceptible to collapse of single clasts that roll down the hillslope and can cause damage only when of considerable size. The slow action of dissolution (step 2) creates a small void at an embryonic stage (proto-cave). The progressive collapse of talus, produced by the combined effect of karstic dissolution and gravity, slowly widens the cave towards the inside of the slope and upwards.

The ongoing development of caves leads to step 3, that is to the formation of bedding voids that can be as much as 30–40 m^3 wide (Fig. 13). The last phase (step 4) is that of the collapse of the cave vault, with the following rolling of blocks, or translational sliding along the contact with the limestone bedrock.

These types of landslides are strongly influenced by a slow karstic dissolution process and have caused problems on road networks. For example, the roads near Amalfi and Marina di Camerota are frequently closed to traffic because of these events.

Dissolution along large fractures

In some carbonate massifs the karstic effect along faults or tectonic fractures can slowly widen the width of surface discontinuities to create open fractures that can be some tens of metres long and more than 1 m wide. These might favour the start of rock falls.

The karstic process can occur through water rilling along fractures walls, through condensation phenomena and, most of all, through humus filling, which makes running waters more aggressive. In many cases of down-slope bedding slopes, numerous open joints occur; these show isolated large blocks of rock that foster landslides processes.

This is the case of Bikini's landslides that affect the Sorrento coastline. Limestone with fractures and karstic processes, and the presence of a marly interbed, have caused numerous translational slides that have affected the arterial road on several occasions.

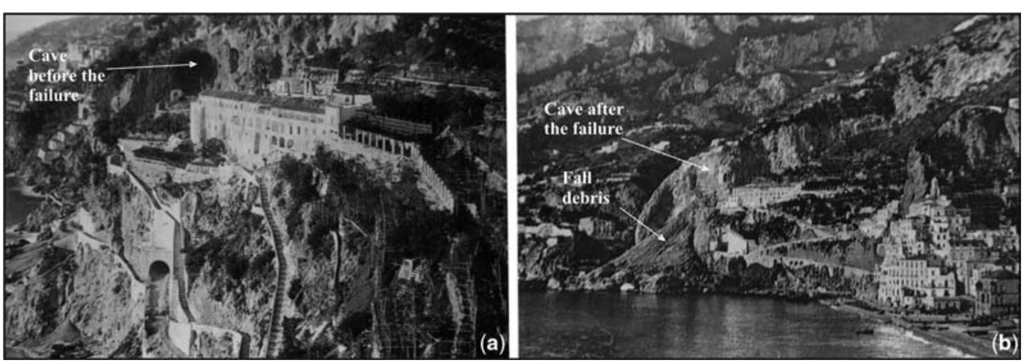

Fig. 11. The 'Cappuccini' landslide occurred in 1899 in Amalfi village. In (**a**) before the event the presence of a cave is evident in the future crown zone (**b**).

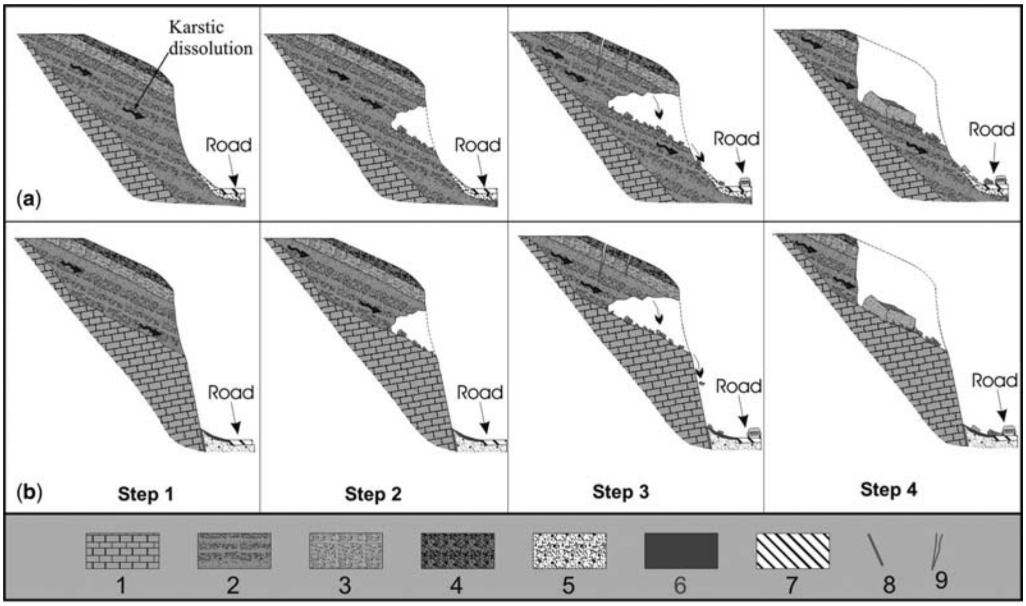

Fig. 12. Phases of cave evolution (**a**) along a talus slope and (**b**) along the contact between inclined talus and limestone: 1, carbonate bedrock; 2, incoherent or partially incoherent debris; 3, coherent debris; 4, soil; 5, talus; 6, fall deposits and soil; 7, anthropic deposits; 8, fault; and 9, fracture.

In other cases, large open joints can cause rock fall and toppling, as in the case of Mount Catiello in Positano. This rock fall occurred on 4th January 2002, and analysis of aerial photographs taken before the landslide show a wide and extended joint that isolated a rock dihedron (about 100 m high) from the surrounding rock. The failure occurred on the open joint, which is still evident (Fig. 14); it is about 2 m wide, and shows evidence of a long karstic phase (at least 2000 years BP) because of filling with reworked pyroclastic deposits and silt.

The rockfall of Mount Catiello can possibly be attributed to the effect of ice forming in the joint-filling materials. Low temperatures, much below average (−10 °C with respect to the average temperature of 10–12 °C), were recorded during the time preceding the failure (Budetta *et al.* 2002).

Collapse of caves along cliffs and natural arc formations

Along the limestone coasts of Campania we can find hundreds of karstic caves formed by the combination of karstic phenomena and erosional wave action. They are often of considerable size with planimetric developments of hundreds of metres, and are sometimes up to 20–30 m high. They originated through the dissolution and erosion of deeply fractured areas that were worked by the sea, especially when sea level was higher than present during the Middle Pleistocene and Tyrrhenian ages (Ford & Williams 1989; Esposito *et al.* 2003).

In many cases the origin of caves was favoured by the mixing of sea water and the groundwater along the coast, as occurred at Mount Bulgheria in Cilento and near Vico Equense on Sorrentine Peninsula (Fig. 15).

In some cases the progressive evolution of a cave that originates along a rock spur can extend to the opposite side, thus forming a natural arc whose origin is strongly influenced by karstic phenomena and erosional wave action. These often are very fractured and can result in rock falls when they collapse. The 'Palinuro arc' is such an example (Budetta & Santo 2000).

It has to be pointed out that many of these caves, which are heavily populated by tourists during the summer season, can be considered to be unstable.

Conclusions

The carbonate massifs of Campania show many cases of instability phenomena that can be linked

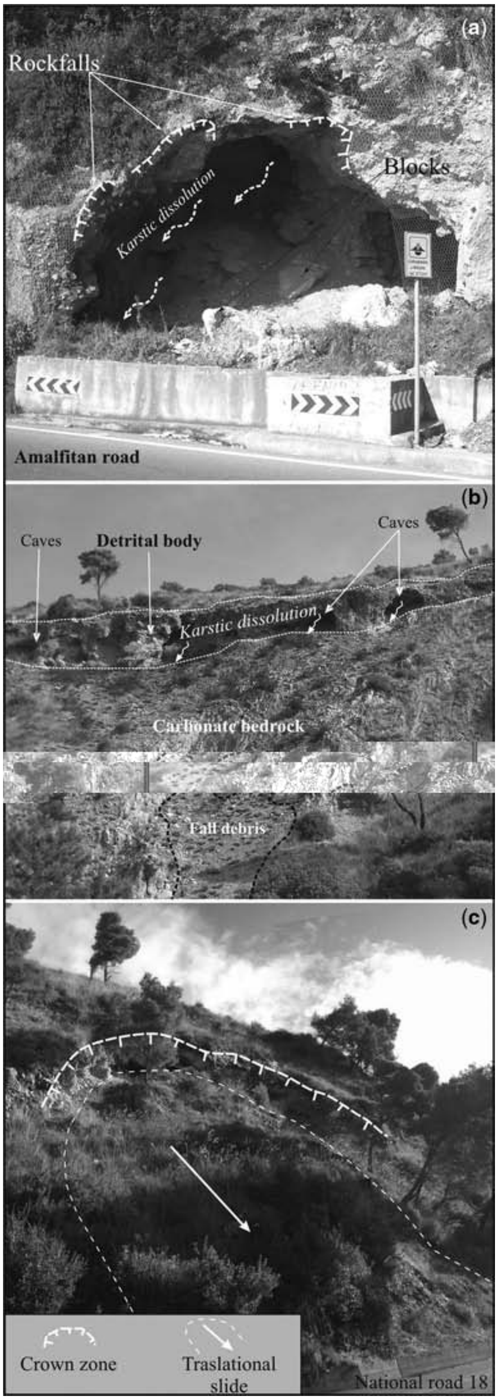

Fig. 13. Karstic dissolution and landslides along a detrital slope: (**a**) rock falls on the 'Amalfitana' road; (**b**) caves in instable conditions along the contact between inclined detritical body and limestone bedrock; and (**c**) translational slide on the National Road 18.

to karstic processes. It is evident that the determining factors are often different and concomitant, but the effect of karstic dissolution is fundamental in the processes of joint widening, clastic movement, increase of the voids and the reduction of cohesive strength. In particular, landslide types and associated fracture patterns can have very different patterns of development and can involve volumes ranging from dm^3 to hundreds of thousands of m^3.

As regards sinkholes, only recently have they been taken more into consideration for stability assessment in some regions of Italy (AA.VV. 2000), as up until a few years ago these phenomena were neglected or confused with other morphologies. In Campania, even though many cases of sinkholes are located within urban areas that are at high risk (for example, in the Sorrentine Peninsula or in Telese village), this problem is not considered seriously enough by the local management agencies. In fact, the variety of processes and geological settings of these areas, and the difficulty in the identification of subsurface karst processes, makes the identification of the possible causes of the sinkhole very difficult and, therefore, the production of detailed stability maps for the prediction of sinkholes more complex.

Moreover, the gradual subsidence that can be originated from bedrock dissolution must be considered only as a long-term management strategy. For this reason, to better define the areas at risk, it is important to gain a detailed knowledge of the hydrogeological and geomorphological history, the rate of karst dissolution of bedrock, and the likely changes in groundwater circulation that may initiate or vary the dissolution processes.

A detailed survey of rock pinnacles indicates that they occur frequently on dolomite slopes and can create hazardous situations when located close to a road network. Their fracture pattern is quite simple, so in many cases mitigation should be straightforward.

Structural detailed analyses and monitoring campaigns should be carried out on the vaults of large bedding voids, sea caves and natural arcs. In these cases sudden collapse could result in large failures. A knowledge of the joint patterns of the vaults in these caves, especially when in heavily urbanized areas as for example on Amalfi's coast, is fundamental to preventing hazardous situations. In other cases, karst has also led to limestone deposits; they are most frequently small in size (some dm^3), but when they are overlie arterial roads can still cause highly hazardous situations. The carbonate contexts of Campania karst plays an important role in local slope stability and can be one of the factors that must be considered in landslides hazard assessment.

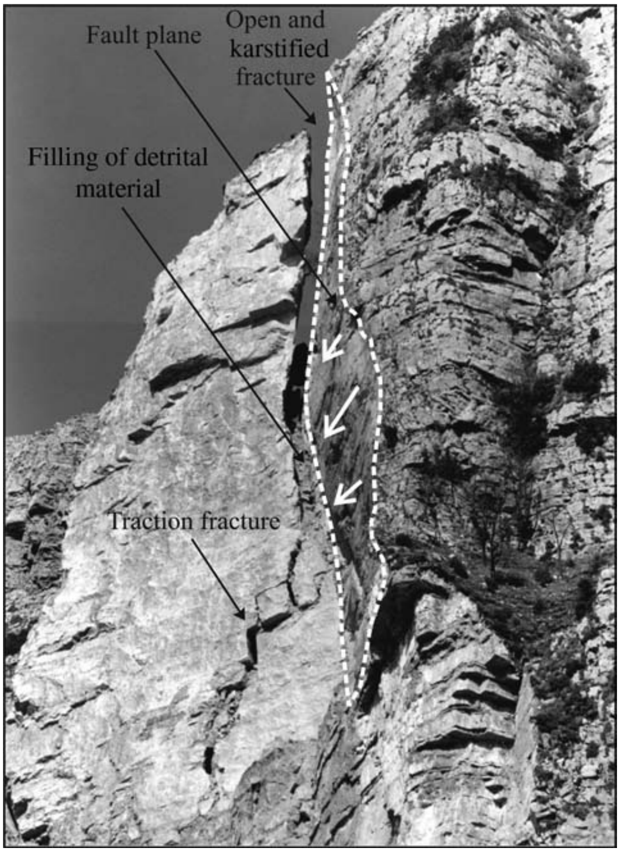

Fig. 14. Example of an open karst fracture that caused a large rock fall (Catiello Mt, near Positano village).

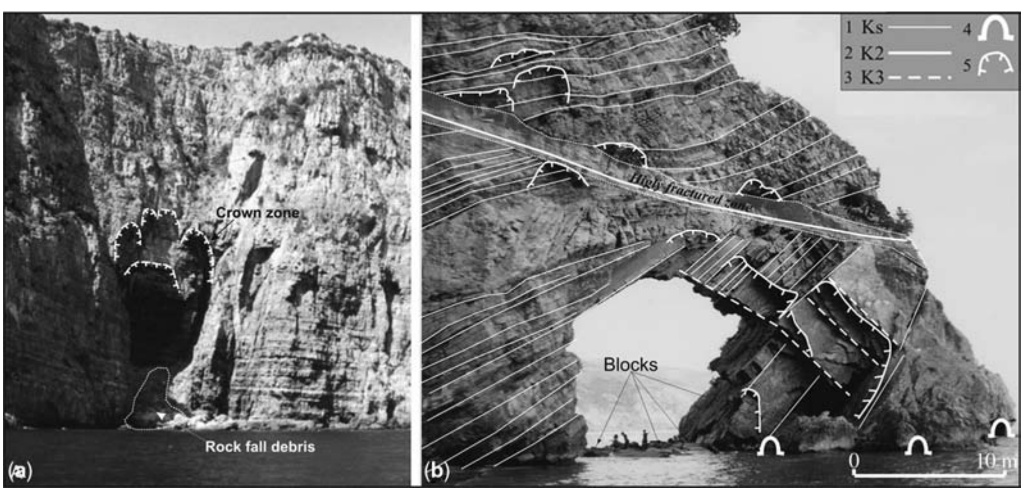

Fig. 15. Wave action can produce the breakdown of karstic coastal caves forming little bays and a promontory. (**a**) A partially collapsed coastal caves (carbonate coast of Marina di Camerota); (**b**) Palinuro arc: 1, bedding; 2, 3, discontinuity sets; 4, coastal caves; 5, rock fall (after Budetta & Santo 2000, modified).

Studies aimed at territory planning and proper planning of mitigation to reduce landslide risks have to take into consideration karst phenomena and the role they have in the development of some particular morphologies and the setting off of different landslide types.

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