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Aspects of landslide activity in the Mercantour Massif and the French Riviera, southeastern France

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Abstract

Landslides pose serious hazards in the Mercantour Massif and the French Riviera in southeastern France. The context for landslide development is a particularly favourable one, both in terms of the geomorphic and structural setting of this Alpine region, and of the climatic, hydrologic and seismic factors that trigger such failures. High mountain relief and steep slopes constitute a very favourable setting for failures affecting massive basement rocks and a very heterogeneous sedimentary cover whose resistance has been weakened by weathering, tectonic stresses, and cambering due to gravity. Among trigger factors, the most important appears to be the precipitation regime. Rainfalls are commonly concentrated into short high-intensity downpours or into bursts of sustained falls over periods of several days, leading to soil saturation and lubrication of potential failure planes. Snowmelt also contributes to these lubrication processes. Earthquakes affecting this region are also a potentially important landslide trigger. However, while a lot of work has been done on the relationship between extreme climatic events and landslide activity, much less is known of the trigger effects of earthquakes.

Both the background factors that promote landslide development and the factors that trigger such failures are discussed within a time frame of landslide development. Progressive changes in soil strength due to weathering, rock cambering and shattering processes lead to long-term reduction in resistance. Superimposed on these progressive changes are episodic triggerings related to rainfall and snowmelt episodes or earthquakes. Landslides may occur as shallow, low-volume "one-time" events or may be part of a progressive long-term failure. The former generally affect unconsolidated or clay-rich sedimentary rocks, especially on the coastal hillslopes of the French Riviera. A notable exception of a major, voluminous "one-time" event was the submarine landslide of the Var Delta in 1979. This landslide, like numerous other smaller subaerial landslides onland, was largely a result of human activities. This landslide occurred following extensive modification of the Var Delta and, notably, reclamation of the steep, fine-grained delta front. Deforestation, quarrying, urbanisation and road network developments are various ways in which human activity has destabilized the coastal hillslopes, favouring the development of numerous shallow landslides following each episode of heavy rainfall.

Progressive landslides on the upper hillslopes of the Mercantour Massif have developed over long time spans (order of 10^1 to 10^5 yrs) and have involved more complex interactions between lithological controls, slope characteristics and trigger factors. The Collelongue and Bois de Malbosc landslides have evolved into now stable failures buttressed by resistant migmatitic diorites or amphibolites. The more voluminous and well monitored Clapière landslide is a relatively simple

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rotational landslide of the toe-failure type. This active landslide poses a serious threat to inhabitants and infrastructure in the Tinée Valley. The importance of continued field monitoring, modelling and mapping of landslides and their hazards is emphasised.

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1. Introduction

Landslides sometimes constitute a serious threat to life and property in mountainous areas and on steep coasts. In inland settings, hazards include debris runout, valley damming, sometimes involving inundation upstream of the dam, and eventual dambursting. In coastal areas, landslides may lead to loss of valuable property, while submarine failures may generate destructive tidal waves. Landslide activity and the hazards such mass movements generate have become a cause for serious concern in the Alpes-Maritimes Department of southeastern France (Fig. 1). This area forms the maritime rim of the French Alps. High relief, sharp topographic contrasts, and a wide variety of crystalline and sedimentary rock types, more or less deformed by tectonic and gravity effects, give rise to a wide variety of slope failures, from minor rockfalls ranging in volume from a few cubic metres, to mass movements involving several million cubic metres of material. The hydrological, meteorological and seismic characteristics of this region are particularly favourable to landslide triggering. Rainstorms and sustained episodes of high-intensity rainfall, heavy and rapid snowmelt, torrential activity and earthquakes constitute the dominant triggers of landslides in this area. Over the last century, massive urbanisation of the French Riviera seaboard and, in recent years, economic development of the hinterland, have led to human exacerbation of landslide activity while creating the potential for greater threat to life and more substantial damage to property.

The aim of this paper is to review various aspects of landslide activity on this lithologically heterogeneous high-relief setting. The aspects discussed include the setting and trigger factors of landslides. These are discussed within a temporal framework of landslide development. Examples of landslides, especially major progressive and now stable landslides, illustrate this time frame. The role of human activity in landslide development and perspectives for a better understanding of landslides and their hazards are also briefly examined.

2. Geomorphic and geologic context

2.1. Topography

The strong topographic contrasts of the Alpine setting of the study area are particularly favourable to landslide activity. The Mercantour Massif and the French Riviera are cut by steep-sided, narrow valleys and canyons. The multitude of interfluve crests, high, steep, poorly vegetated valley walls and rock cliffs constitute a high-energy setting particularly subject to gravitational effects. With inclinations greater than 30° on some of the upper slopes of the Mercantour, the equilibrium threshold is very close to the friction angle under dry soil conditions.

Steepness is also characteristic of the Riviera margin, on which over 90% of the present population of the Alpes-Maritimes Department resides. Rocky coasts account for over 54% of the shoreline (Anthony, 1994). The shelf, often non-existent along stretches of bold cliffed coasts, is, where present, generally narrow (< 5 km-wide) and dissected by numerous canyons and ravines that are commonly the seaward extensions of short, steep valleys on land. Much of the incision of valleys and submarine canyons in this area occurred during phases of glacio-eustatic sea-level fall during the Quaternary (Savoye and Piper, 1993).

2.2. Lithology

The Mercantour Massif consists of granitic, and especially gneissic, basement rocks (Fig. 2), Permian sandstones and schists, a varied series of overlying limestones, comprising hard "Tithonian" limestones of Upper Jurassic age, thick Cretaceous limestones and Middle Eocene Nummulitic limestones, as well as several hundred metres of Annot Sandstones. An

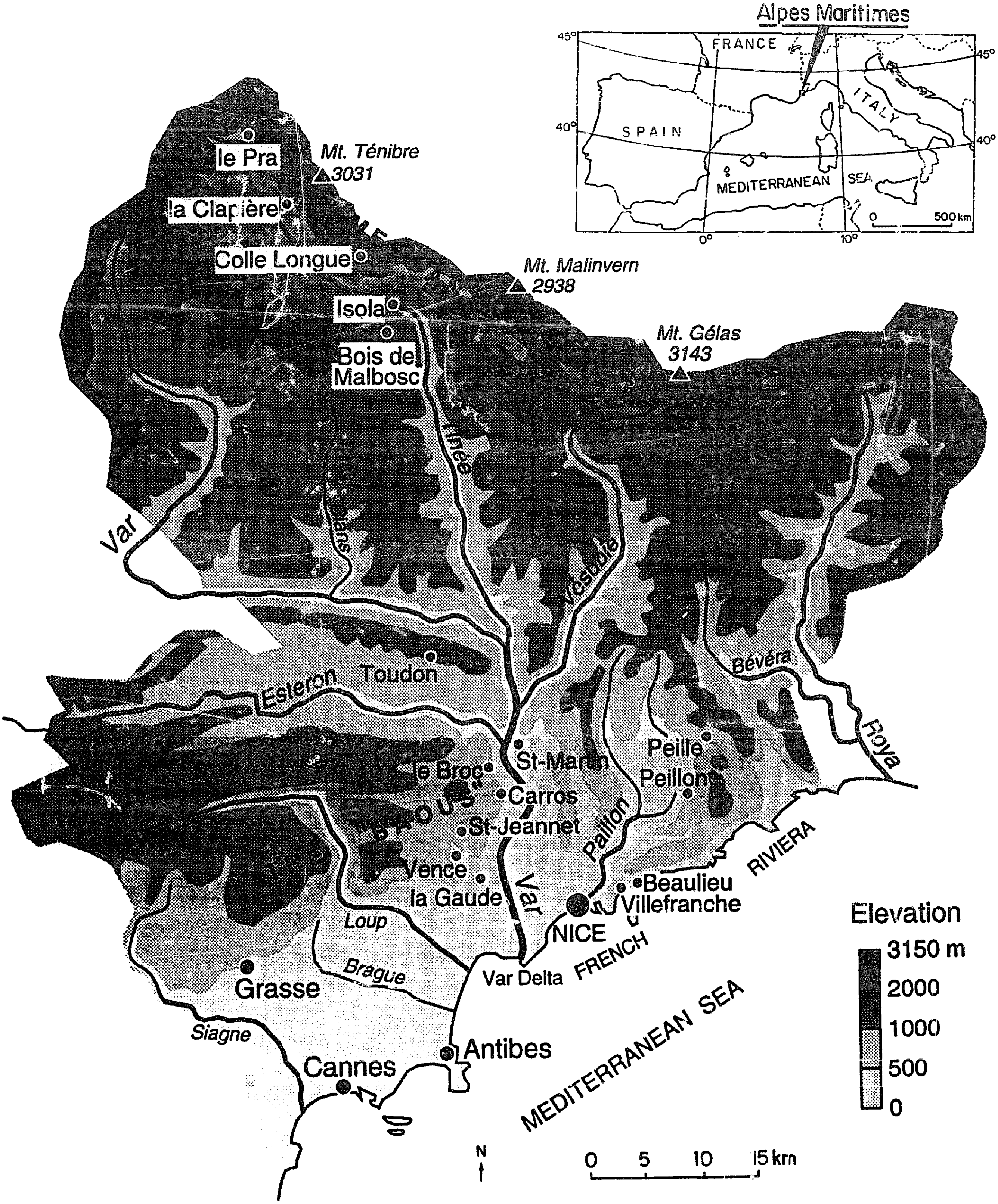

Fig. 1. The Mercantour Massif and French Riviera in the Alpes-Maritimes Department, southeastern France.

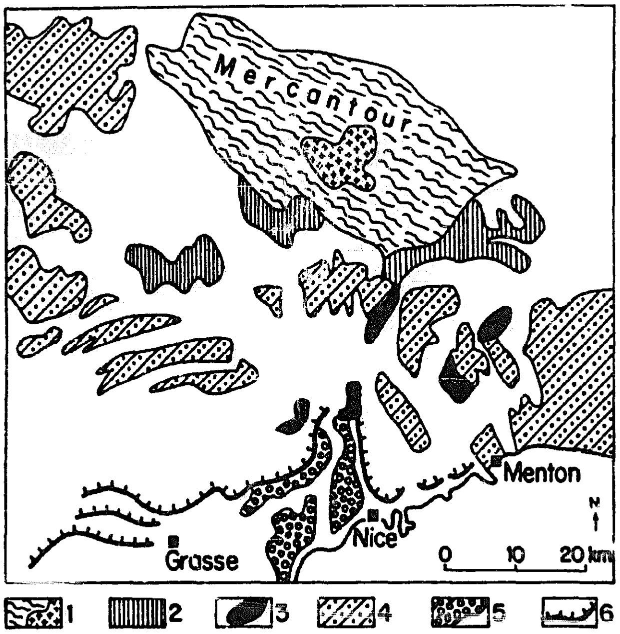

Fig. 2. Simplified geological sketch of the Alpes-Maritimes Department. 1. Metamorphic and granitic basement. 2. Permo–Triassic sandstones and schists. 3. Limestones and marls (gypsum). 4. Annot sandstones and flyschs. 5. Neogene conglomerates. 6. Frontal thrust of the Alps.

essential characteristic of these massive rocks is that their discontinuities are either subvertical foliations and schistosities related to Hercynian, and to a lesser extent, Alpine tectonic movements, or stratification planes.

In addition to the resistant rock types enumerated above, the Mercantour Massif and the French Riviera exhibit vast areas of soft sedimentary rocks. Rock types include plastic and soluble gypsum, volcaniclastics and conglomerates. Evaporites are often capped and abutted on by limestone or sandstone plateaux. Slopes are mantled by superficial formations and/or Quaternary deposits such as colluvium, scree and moraines. Such loose material is generally prone to gully erosion, but also occasionally to landslides and debris flows. Much of the continental shelf and especially the continental slope is covered by a blanket of mud deposited in Holocene times (Savoye and Piper, 1993).

2.3. Tectonics

The tectonic framework, characterised by intensive deformation of both the basement and the sedimentary cover during the Hercynian and Alpine orogenesis, acts via three different mechanisms: foliations and fractures, residual and neotectonic stresses, and earthquakes.

Hercynian foliations and fractures have affected both the basement and the overlying sedimentary cover. Faults and joints of various types related to different tectonic phases have resulted in fragmentation of the rock masses. Foliations have also been affected by deformations while rock benches have cambered under the effects of gravity. In the sedimentary cover, salt mobility, notably in areas rich in evaporites (Julian and Nicod. 1990), has resulted in diapirism, swelling of upfolds and intrusion along strike faults. These features, together with the fracture networks have favoured permeability and rock weathering. Permeability is a primary factor in the activity of some rockslides (Julian, 1991). Slopes occurring on the flanks of folds commonly coincide with dip directions and are, as a result, markedly unstable, and subject to failures, especially when the toes of such dip slopes are laterally undermined by erosion.

The residual tectonic stresses favour failures of hillslopes bounding massive rocks. Such stresses have been intensified by compression due to active neotectonics. Ai and Miao (1987) have shown that such compression is also liable to directly generate failures. Finally, earthquakes in epicentral zones and along active faults have also played a major role in generating structural weaknesses and failures. The potential role of earthquakes as a trigger factor of mass movements is discussed in the next section.

3. Trigger factors

Landslide triggering depends on several complex and interrelated variables, such as episodes of heavy rainfall, cumulative precipitation prior to failures, snowmelt, changes in groundwater characteristics, and in pore fluid pressure and shearing resistance due to a variety of factors such as sediment loading and compaction, changes in slope geometry and seismic activity. In the study area, the main potential trigger factors are episodes of heavy precipitation, with earthquakes playing an apparently subordinate but, as yet, rather poorly documented role.

3.1. Precipitation

The Alpes-Maritimes Department is characterised by a typical North Mediterranean rainfall regime, with snow becoming increasingly important at elevations exceeding 1300–1400 m. As far as landslide activity is concerned, the most noteworthy features of this precipitation regime are interannual irregularity, concentration of falls in time, and common occurrence of high-intensity downpours (Julian and Anthony, 1993). Another important aspect is the episodic occurrence of heavy rainfalls over periods lasting several days. As commonly occurs in coastal mountain belts, the outer seaward-exposed areas are the rainiest. In the Paillon catchment (Fig. 1) for instance, the following orders of magnitude have been observed over different durations:

- downpours of up to 150 mm, and even more in the core area, in a few hours;
- 24 h rainfalls of over 100 mm recorded seven times in Peillon between 1951 and 1960, and over 150 mm on two occasions;
- rains lasting several days commonly exceeding 300 mm, and sometimes attaining close to 500 mm, as between October 10–16, 1979, when heavy rains and heavy river discharge contributed

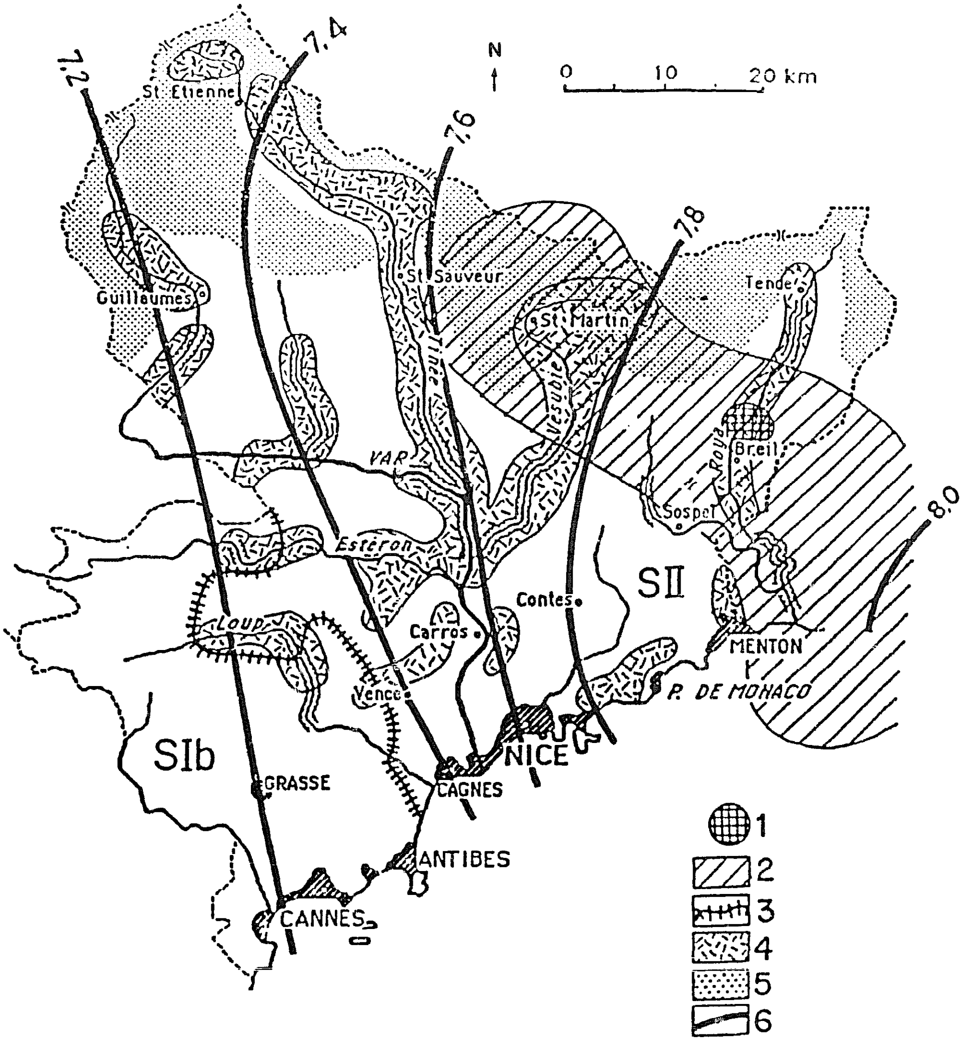

Fig. 3. Seismic zoning and instabilities in the Alpes-Maritimes Department (modified after Dadou et al., 1984). 1. Location of the earthquake epicentres of a recent crisis (1983–1984) in the Roya Valley. 2 Highest expected magnitudes (≥ VII) over a time span < 50 yr. 3. Limit between zones of potentially moderate (SII) and potentially low seismicity (SIb). 4. Areas with a high density of landslides. 5. High mountains with a strong snow avalanche hazard. 6. 200 yr seismic hazard (magnitudes ranging from 7.2 to 8). Stipples represent densely populated coastal belt.

in triggering the submarine Var Delta landslide, discussed later.

Rains and snowmelt waters have either a direct triggering effect or an accelerating effect on the movement rate of on-going landslides. The best example of the accelerating effect is that of the thoroughly monitored Clapière landslide (Follacci, 1987; Julian, 1991; CETE MEDITERRANEE, 1993), in which heavy rainfall and snowmelt result, with a small time lag, in direct acceleration of some of the surface components of this landslide.

3.2. Earthquakes

The Mercantour Massif and the French Riviera coast are located on a passive plate margin that has been reactivated during the Quaternary through convergence between the African and the European plates (Mascle and Réhault, 1991). Neotectonic stresses result in moderate but spatially variable seismicity. Hazard levels deduced from a study of past and present seismicity give a rather sketchy but useful picture of the threats posed by earthquakes (Fig. 3). These show a 100 yr risk of having an earthquake of magnitude VII–VIII east of Nice and a 200 yr risk of the same magnitude over the entire Nice Arc area, and a 1000 yr risk of magnitude above IX east of a line running from the mouth of the Roya River to St. Martin in the Vesubie Valley (Fig. 1), and VIII to IX further west.

In reality, past links between earthquakes and landslides in the study area are rather tenuous and often sketchy (e.g., Vogt, 1979). Potentially, earthquakes could have a dramatic accelerating and amplifying effect on on-going landslides, notably that of Clapière. Earthquakes are also considered as the most important potential trigger of submarine landslides affecting the underconsolidated muds of the continental slope in this area (Mulder et al., 1993).

4. The time frame of landslide development

The role of the background geologic and geomorphic factors and the trigger factors discussed above may be envisaged within a time frame of landslide development such as that proposed by Finlayson and Statham (1980). A version of their model adapted to the study area is shown in Fig. 4. Progressive failures and consequent landslides occur when the disturbing forces are more efficient than those of slope failure resistance. Various stages may be identified within this schematic time frame (Fig. 4).

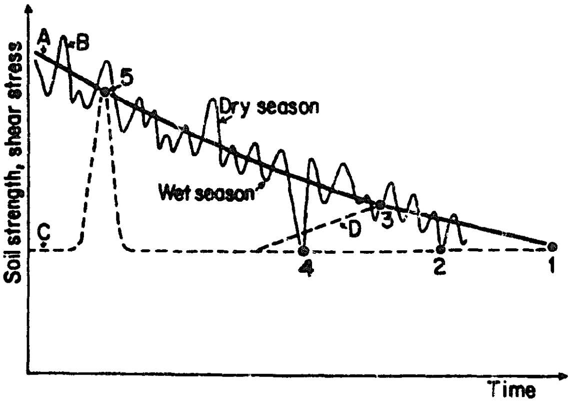

Fig. 4. Model showing the time frame of landslide development and the punctual role of certain trigger factors in the study area (adapted from Finlayson and Statham, 1980). Points 1 to 5 correspond to instances where shear strength is equal to shear stress, leading to failure (see text for explanation). A = long-term changes in soil strength due to weathering and rock shattering by tectonic stresses. B = Short-term oscillations in strength due to porewater pressure changes that depend on rainfall episodes and snowmelt as well as on massive man-made sedimentary loading of poorly consolidated coastal deposits. C = Critical shear stress level below which failure occurs. D = Progressive increase in shear stress due to slope steeping by basal erosion for instance, or to sedimentary loading of upper slopes.

On a long-term (order of 10^4 to 10^6 yrs) basis, a progressive reduction in resistance occurs until the failure threshold is reached (point 1 in Fig. 4). This reduction in resistance is commonly due to weathering. However, in zones with young fold belts such as the study area, where residual tectonic stresses persist, compressive movements and complementary tensile effects have led to fracturing and crushing, transforming massive, hard rocks into piles of loose fragments.

Over moderate to long time spans (10^2 to 10^4 yrs), slope steepening, due to valley incision for instance, or to erosion at the base of hillslopes, may lead to an increase in shear stress up to the point of failure (point 3 in Fig. 4). Valley scouring, essentially due to glacio-eustatic drops in sea level during the Quaternary, enhances vertical stresses and enables the formation of new extensional joints, thus facilitating the dislocation of massive rocks by gravity movements. Similar slope steepening may also occur in the submarine realm, as fine-grained sediment fallout progressively blankets the continental slope or prograding delta fronts. Such steepening may occur over short to long time scales, depending on sediment input. Short-term slope steepening may occur on delta fronts subject to massive sedimentation of poorly compacted fine- to coarse-grained sediments. Submarine landslides off the French Riviera coast have, in the past, essentially affected the Var Delta (Fig. 1). Such instabilities also effect the poorly consolidated to underconsolidated muds that mantle large areas of the continental slope (Mulder et al., 1993).

The effects of long-term rock weathering and fracturing are translated into much shorter term landslide activity by seasonal oscillations of the soil water balance and by rainfall episodes of high intensity. In areas rich in unconsolidated or poorly consolidated sediments, especially clayey or gypsum-rich deposits, such shorter-term events may be directly responsible for lowering resistance and leading to failures. Heavy rainfalls and/or snowmelt are liable to lead to strong increases in pore water pressure, triggering failures whenever water saturation levels exceed the corresponding Atterberg limits. Such failures are denoted by points 2 and 4 in Fig. 4. We have assessed (Julian and Anthony, 1993) several existing models relating rainfall intensity (e.g., Caine, 1980; Gostelow, 1991), antecedent rainfall (Campbell, 1975; Govi and Sorzana, 1980, Meneroud, 1983), and cumulative precipitation (Meneroud, 1983; Crozier, 1986) to landslide triggering thresholds in the study area. Our results show that such models are indeed effective indicators of the climatic thresholds beyond which subaerial failures are generated. Fig. 5 depicts, for instance, a typical relationship between rainfall and a landslide that occurred in Menton (Fig. 2) in 1959.

At any instant, a sudden increase in shear stress may be due to vibrations caused by an earthquake (point 5), and in historic and modern times, to vibrations caused by human activities such as quarry blasting or consolidation works. The sharp increase in shear stress may be due either directly to tremors and vibrations, or, indirectly, to sediment loading and increase in pore water pressure. Moreover, earthquake vibrations whose intensity varies, depending on topographic position (both underground and on the surface), may become amplified up to two or three times on a hilltop relative to the foot of the hill. A "catapult" effect inducing ultragravity falls may be thus created, the amplification being capable of attaining from 0.15 to 0.35g on hill sites such as those of Nice (Bard et al., 1984, 1987).

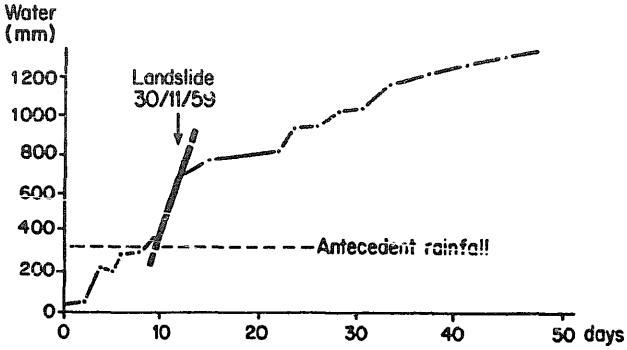

Fig. 5. Example of a rainfall/landslide crisis in Menton (Fig. 2) in 1959.

5. Examples of landslide activity at various spatial and temporal scales

In the Mercantour Massif and the French Riviera, as in other high-relief settings subject to landslides, the joint effects of long-term weathering, erosion and structural deformation act in the background to lower rock resistance, while climatic, hydrological and seismic factors, acting instantaneously or over relatively short time spans, serve as triggers. The local geomorphic setting and the activity of certain trigger factors, notably groundwater, may also strongly reflect the influence of man. At any given time, landslides may be defined as "first-time" or progressive failures. The former may either be "one-time" events or may evolve into complex "progressive" landslides with long time spans of activity. Although "one-time" slides may be occasionally voluminous, in the study area most landslides of this type are generally shallow failures involving relatively small volumes of commonly unconsolidated material. Such failures are frequent following episodes of intense rainfall (Carrega, 1983; Julian and Anthony, 1993). In the coastal hills around Nice, roadside landslides locally attain a spacing of one every 100 m following heavy rains. We will focus our attention essentially on progressive landslides, as their study provides scope for understanding the complex mechanisms underlying failures and landslide activity over time. Potentially, such slides are also the most hazardous to life and property in the study area.

5.1. Examples of progressive landslides

Whether associated with unconsonsolidated rock formations, as in the Beaulieu landslide (Bergeaud et al., 1959) or with bedrock formations as in the cases of Pra and Clapière (Fig. 1) (Follacci, 1987; Follacci

Fig. 6. Photograph of the steep west wall of the Upper Tinée Valley upstream of St. Etienne (October, 1994). The upper slopes are cut into the basement while the sedimentary cover outcrops on the lower slopes.

et al., 1988), the major mass movements in the study area developed over a fairly long period. These landslides are best developed in valley slopes in the Mercantour Massif, notably the Upper Tinée Valley (Fig. 6), a deep glacier-gouged valley where the high relief contrasts and long periods of slow deformation have acted on massive basement rocks. Mountain sides and valley walls of the Tinée generally exhibit three slope segments: a basal segment, which commonly descends below the valley floor under alluvial and glacial fill, and whose average slopes exceed 50°, a middle segment with slopes of 30 to 35° and an upper spur segment with average slopes of 20°.

The landslides affecting the Upper Tinée Valley pose the thorny problem of the response of the steep valley walls to two, apparently opposite, but complementary long-term shearing stresses. On the one hand, horizontal residual or neotectonic stresses are greater than vertical stresses, and lead to deformation of rocks from the bases of slopes to hillcrests. On the other hand, deep valley scouring tends to suppress horizontal stresses normal to the valley wall while making way for the dominance of vertical stresses, enabling the formation of new extensional joints; in this case, the dislocation of the massive rocks is enhanced by gravity movements. In considering such stresses, the models proposed by Ai and Miao (1987) and Huang et al. (1990), based on photoelastic and numerical simulations, show that the maximum horizontal compression occurs at the base of slopes. The failure will first affect this basal portion, which may be considered as a high "geostress" area, and then propagates progressively upslope in response to a stress inversion, tensile stresses dominating and leading to the formation of a fracture. This slow "building up stage" is followed by a stage of "fracture expansion", followed by a "bursting stage". The instability behaviour of the rock mass thus affected is controlled by morphological factors and material properties. The whole process of landslide initiation may come to a standstill in response to changes in the environmental factors responsible for such failures. The Upper Tinée Valley is interesting, because the horizontal stress (North 20–40° East) is almost

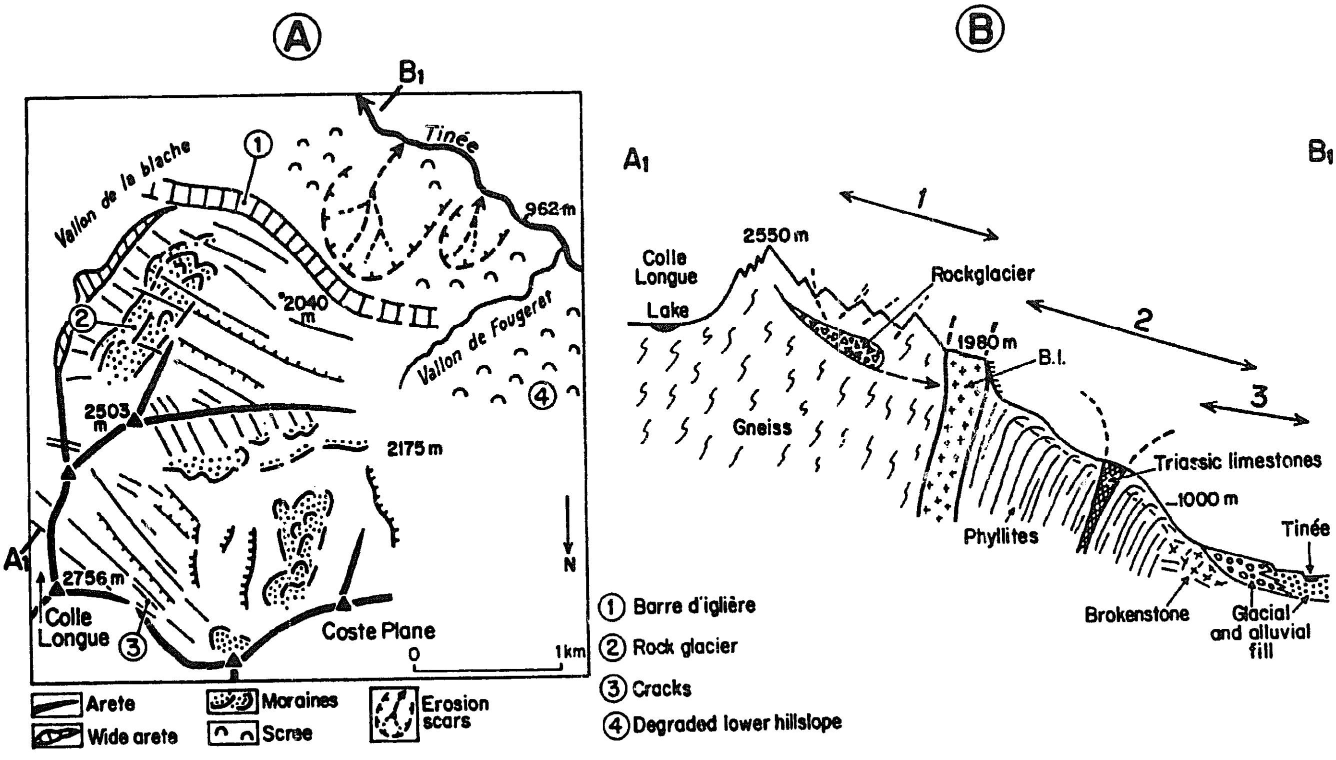

Fig. 7. The ancient Collelongue landslide in the Tinée Valley. (A) Interpretation of an aerial photo coverage (for better visualisation, the sketch has been inverted). (B) Cross section (A′–B′): 1. Rocksteps, ridges and furrows. 2. Slope subject to cambering of rock benches. 3. Lower slope highly dissected by erosion. BI. Scarp formed by the resistant migmatites of the Barre d'Iglière which has buttressed the landslide.

orthogonal to the valley direction. Fractures on the ridges and upper hillslopes, formerly attributed to gravity processes (Follacci et al., 1984), may in fact be due also to tensile effects due to upward stress propagation. The parallelism of the foliations with the valley, and cambering of the heads of metamorphic rock benches, by more than 50 m in Clapière, and their common warping valleyward, are important elements in understanding these mechanisms. Tensile effects and active gravitational forces seem to be the most important forces on these hillslopes whose drop exceeds 1000 m in the case of Malbosc, and is close to 2000 m in Clapière. The best examples of the effects of such long term tectonic and gravity effects are seen in the landslides of Collelongue, Clapière and Malbosc (Fig. 1).

5.1.1. The Collelongue landslide

The area of hillslope affected by this failure comprises two segments separated by a rock bar of resistant migmatitic diorite, the Barre d'Iglière (Fig. 7). In the upper segment, glaciers fed by two enormous juxtaposed cirques have cut up the flank of the Mercantour dome into an alveolar feature between 2000 m and the 2756 m high Collelongue Peak. The photointerpretation sketch shown in Fig. 6 highlights the pronounced dissection of the hillslopes and the rockglaciers located within the cirques. A series of open cracks, expressing deeper-seated fractures, run along the rock mass, affecting moraines and scree. The general impression from aerial photo-interpretation and field observation of this slide is that the hillslope has subsided in situ. An overall gravity deformation can be envisaged but such an effect must have generated, in turn, a compression of the rock masses against the Barre d'Iglière. Below this rock scarp, cambering, fracturing and weathering of the less resistant phyllites have resulted in a highly degraded slope dissected by active torrential catchments and subject to differential mass movements. The Collelongue landslide is presently stable. The sheared rockglacier affected by this failure is Late-Glacial (from 15,000 to 10,000 yr B.P.) in age. However, eventual failure of the Barre d'Iglière could lead to a voluminous landslide involving displacement of the shattered and weathered gneiss upslope of this bar.

5.1.2. Bois de Malbosc landslide

A second example of long-term neotectonic, weathering and gravity effects on hillslope failures in the study area is that of Bois de Malbosc landslide (Fig. 1). These effects are highlighted by deep weathering and pronounced cambering of the foliated augen gneiss, and by numerous dislocations of rock benches, escarpments, furrows and pseudo-

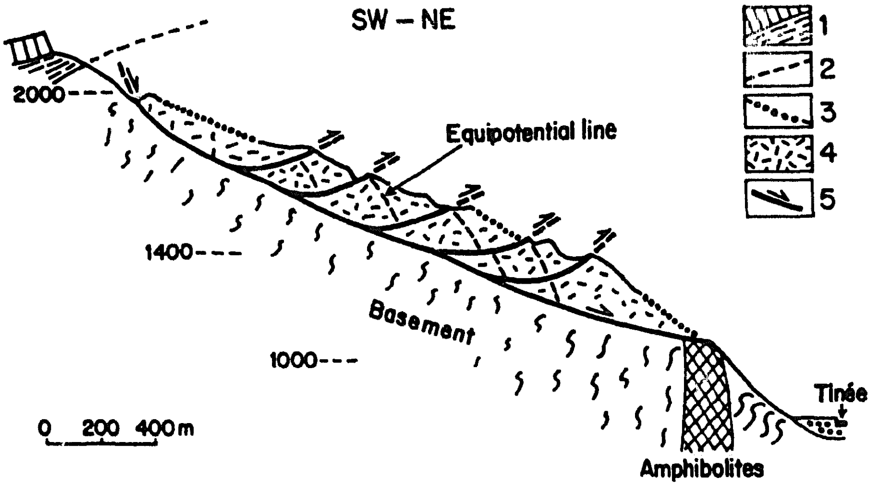

Fig. 8. Longitudinal section and envisaged failure mechanism of the now stable Bois de Malbosc rockslide in the Tinée Valley. 1. Sedimentary cover (Jurassic limestones and marls). 2. Unconformity. 3. Scree. 4. Loose material. 5. Slip surface. The failed rock mass, weakened by cambering and fractures, probably comprises a system of superposed slides with a single sliding plane from which bifurcate reverse faults. These are considered as reflecting compression, and define convex-downslope equipotentials. A resistant band of amphibolites has served to buttress the toe of the hillslope.

dolines. Dislocations are expressed on aerial photographs by the elbow courses they impose on small torrents within the longitudinal furrows. The long-term pattern of development of this mass movement is schematised in Fig. 8. This sketch depicts a system of once active superposed slides, apparently with a single sliding plane from which bifurcate reverse faults due to compression. An alternative model that may be envisaged is that of a system of retrogressive movements starting from the base and leading to the formation of dip-slip faults, each delimiting a slice of slide. As in the Collelongue slide, this movement is blocked downslope by a massive barrier of resistant amphibolites. The Bois de Malbosc landslide appears to be a now stabilized failure buttressed by these amphibolites. This is attested by the stability of the substratum and by the well developed forest cover perched close to 200 m above the present bed of the Tinée.

5.1.3. Clapière landslide

The Clapière landslide (Fig. 9) is one of the most thoroughly studied existing landslides in the world (Follacci et al., 1988: Julian, 1991; Sousa and Voight, 1992). It differs from the other two landslides in that it is active and even presents a very serious hazard. It is also the most imposing of the three, with a height of over 800 m, an area of 80 ha and an estimated volume of 50 million m^3. The landslide has affected foliated gneiss. The base of the failure is a simple circular plane. As for its origin, one may suppose that a major gravity effect, comparable to that deduced for Collelongue landslide, led to a failure that may have been initially buttressed by the Iglière migmatite. The severe stress imposed on this rock bar weakened its resistance, leading to transformation of the failure from a rock mass creep or "Sackung" into a well defined landslide, the "burst" heralded by the formation of several disten-

Fig. 9. Photograph of Clapière landslide (October, 1994). Tensile features are visible at the top of the failure, while compression at the base has resulted in the formation of scree.

sional fractures whose throw exceeds 60 m. Failure of fragments of the Iglière bar has fed rockfalls that form brokenstone accumulations downslope. A study of the structural properties of this movement (Follacci et al., 1988) suggests that neotectonic compression may have played an important role as in the case of Collelongue landslide. Such compression has affected alignments of valley, slopes and crests by inducing stress at the base of the hillslope, such stress propagating upwards to induce tensile effects towards the most elevated parts of the failure.

The Clapière landslide is much more recent than the other two. It has been active for the past 50 years at least, but seems to have undergone accelerated displacement since 1977 (Follacci, 1987). Slide rates average around 3 m/yr. Peak slope velocities of up to 27 mm/day occur in late spring and are related to increased groundwater pressure related to heavy rains and snowmelt (Sousa and Voight, 1992).

6. The role of human activity

Human modifications of the local topography, the hydrological and groundwater regime, and the vegetation cover play an increasingly important role in generating failures in the study area. Apart from massive urbanisation of the coastal fringe, human activities include road works, quarry blasting, consolidation works and reclamation works in the coastal zone. The abundance of small shallow first-time or recurrent landslides along roads in the study area is due in part to modifications of slope and vegetation.

The most important landslide resulting largely from human effects was that of the Var Delta, which occurred in 1979, and which probably involved a total volume of up to 400 million m^3 (Gennesseaux et al., 1980). This landslide resulted in several casualties, led to the downslope evacuation of port installations (Fig. 10) and generated a tidal wave. Over the

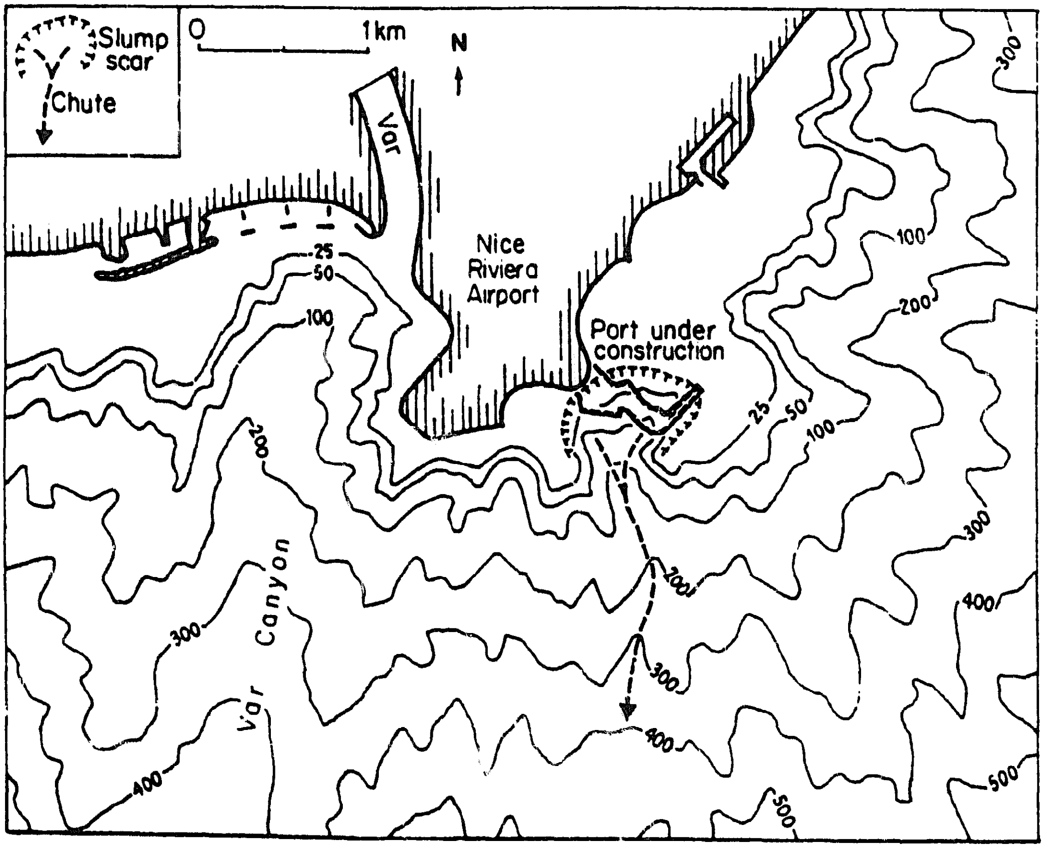

Fig. 10. The reclaimed Var delta-plain and upper delta-front, showing the steep nearshore bathymetry (in metres) and collapsed port installations (adapted from Leuridan et al., 1988). Inset highlights the two major visible morphologic elements following this landslide: the slump scar representing retreat of the head of the submarine slide, and the narrow chute along which turbidity currents evacuated downslope the slumped material, including the port.

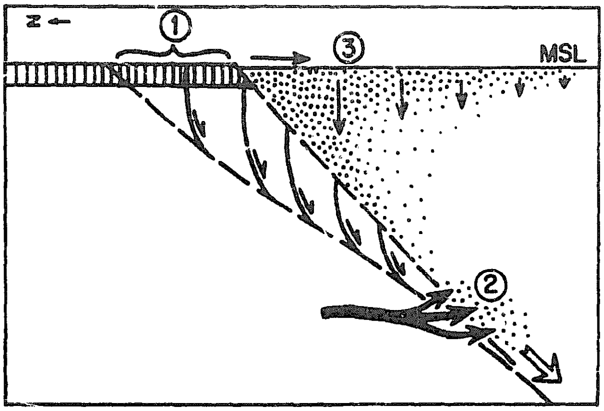

Fig. 11. The three joint trigger mechanisms we believe to have been involved in the Var Delta landslide. Circled numbers: 1. Progressive fill loading and steepening of the upper delta-front slope. 2. Enhanced seaward submarine outflow of the confined Var delta-plain aquifer, leading to undermining of the lower delta-front slope. 3. Heavy turbid discharge and deposition of an unstable blanket of muds on the steep delta-front, possibly leading to the generation of a turbidity current. MSL = Mean sea level.

last century, much of the subaerial Var delta plain and the upper muddy delta front have been reclaimed. These transformations no doubt resulted in a steepening of the upper delta-front plain angle, eventually bringing it to the limiting slope inclination, referred to as the "angle of yield" (Nemec, 1990), providing the premises for the landslide. Much of the fill consisted in reclaiming, up to 300 m offshore, the inner nearshore delta-front plain to depths of 25 m. Three factors that probably jointly triggered this landslide are schematised in Fig. 11. These are slope steepening by reclamation fill up to the angle of yield, scouring of the basal slopes of the muddy delta front by massive submarine outflow seepage from a confined delta aquifer fed by very heavy rains and high river discharge during the week prior to the failure, and heavy sediment fallout from turbidity plumes of the Var River.

Earthquakes are considered by Mulder et al. (1993) as the most important potential trigger of submarine landslides on the French Riviera. Although no earthquake activity was involved in the catastrophic landslide of the Var Delta, this hazard must be kept in mind as far as coastal and nearshore management practices are concerned in this area. Historical data on earthquakes in 1564, 1818 and 1887 show evidence for the generation of tidal waves that were most probably due to submarine landslides off the Var Delta.

Various other examples of human-induced exacerbation of mass movements due to road works or to the obstruction of narrow valleys in the Mercantour Massif have been documented. These have sometimes led to massive damage and loss of life as in the Tinée Valley in 1926 and 1948.

7. Landslide monitoring and prognosis

Landslide hazards are exacerbated by the rapid rate of urbanisation of the Alpes-Maritimes Department. In this context, hazard assessment and mitigation call for careful collection of data and mapping of instabilities. In France, maps showing zoning as a function of slope instabilities, such as "Zermos" or CRAM maps, elaborated for each department, have constituted more than a step in the right direction. Beyond this mapping stage, research needs to be directed towards a better understanding of the mechanisms and triggers through modelling and field monitoring of earthquakes, decisive rainfall events, groundwater state, destabilizing erosional events, and in the coastal zone, particularly illustrated by the case of the Var Delta failure, reclamation fill operations. It is only by "crossing" the various categories of data that an acceptable level of efficiency in prediction and forecast will be attained.

8. Conclusion

The high relief, sharp topographic contrasts and wide variety of crystalline and sedimentary rock types, more or less deformed by tectonic and gravity effects, give rise to a wide variety of landslides and terrain instabilities in the Mercantour Massif and the French Riviera. In addition to this morpho-structural setting, this region is subject to important rainfall crises that constitute the dominant landslide trigger factor. Although this area is prone to earthquakes, the role of such seismic movements in triggering landslides still needs to be properly assessed. Evaluation of hazard levels related to various potential magnitudes suggests that serious attention should be paid to this factor.

The effects of long-term tectonic, weathering and gravity effects are lowering of rock resistance, thus paving the way for landslides triggered by climatic or seismic factors acting instantaneously or over very short time scales. Landslides in the study area may be shallow, non-recurrent or "one-time" events. Major, progressive landslides, exemplified by the well studied case of Clapière and the lesser known, presently stable cases of Collelongue and Bois de Malbosc in the Upper Tinée Valley, developed over relatively long time spans and may show varying rates of displacement over time.

In the last century, urbanisation of the French Riviera seaboard and economic development of the mountainous hinterland have resulted in exacerbation of landslide activity. Assessment of the potential hazards of landslides in the years to come should be carried out through thorough field studies, modelling and mapping of existing landslides, and monitoring of "sensitive" spots liable to slope failure.

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