9.2 Hazards resulting from mass movements

The nature and causes of mass movements and resultant hazards

Mass movements can be classified in a number of ways. The main ones include speed of movement and the amount of water present. In addition, it is possible to distinguish between different types of movement, such as falls, flows, slides and slumps. (See Topic 3, Section 3.3.)

The likelihood of a slope failing can be expressed by its safety factor. This is the relative strength or resistance of the slope, compared with the force that is trying to move it. The most important factors that determine movement are gravity, slope angle and pore pressure (Figures 9.20 and 9.21).

Figure 9.20 Landslide near Zermatt, Switzerland

Figure 9.21 Landslip on a slope in Oxford, UK

Gravity has two effects. First, it acts to move the material downslope (a slide component). Second, it acts to stick the particle to the slope (a stick component). The downslope movement is proportional to the weight of the particle and slope angle. Water lubricates particles and in some cases fills the spaces between the particles. This forces them apart under pressure. Pore pressure will greatly increase the ability of the material to move. This factor is of particular importance in movements of wet material on low-angle slopes (Table 9.9).

Table 9.9 Increasing stress and decreasing resistance

Factor	Examples
Factors contributing to increased shear stress	
Removal of lateral support through undercutting or slope steepening	Erosion by rivers and glaciers, wave action, faulting, previous rockfalls or slides
Removal of underlying support	Undercutting by rivers and waves, subsurface solution, loss of strength by exposure of sediments
Loading of slope	Weight of water, vegetation, accumulation of debris
Lateral pressure	Water in cracks, freezing in cracks, swelling, pressure release
Transient stresses	Earthquakes, movement of trees in wind
Factors contributing to reduced shear strength	
Weathering effects	Disintegration of granular rocks, hydration of clay minerals, solution of cementing minerals in rock or soil
Changes in pore-water	Saturation, softening of material pressure
Changes of structure	Creation of fissures in clays, remoulding of sands and clays
Organic effects	Burrowing of animals, decay of roots

Landslides are a common natural event in unstable, steep areas (Figure 9.22). Landslides may lead to loss of life; disruption of transport and communications; and damage to property and infrastructure. The annual repair cost for roads in the Caribbean is estimated to be US$15 million.

Figure 9.22 Mam Tor landslide, Derbyshire, UK

Tropical storm activity may trigger landslides. In Jamaica in 2001, tropical storm Michelle triggered a number of debris flows, many 2–3 kilometres in length. Similarly, tropical storm Mitch (1998) caused a mudflow 20 kilometres long and 2–3 kilometres wide, which killed more than 1500 people in the town of Posoltega in Nicaragua and surrounding villages.

The two main forces that trigger landslides in the Caribbean are:

- seismic activity
- heavy rainfall.

Jamaica is subject to frequent landslides. In the Blue Mountains, over 80 per cent of the slopes are greater than 2°. The area is also geologically young and heavily fractured, and the bedrock is deeply weathered, making it unstable. The largest historic landslide in the region occurred on Judgement Cliff, eastern Jamaica, where an estimated 80 million m^3 of material was moved.

Human activities can increase the risk of landslides, for example by:

- **increasing the slope angle**, for instance cutting through high ground – slope instability increases with increased slope angle
- **placing extra weight on a slope**, for instance new buildings – this adds to the stress on a slope
- **removing vegetation** – roots may bind the soil together and interception by leaves may reduce rainfall compaction
- **exposing rock joints and bedding planes**, which may increase the speed of weathering.

There have been various attempts to manage the landslide risk. A number of landslide hazard maps have been produced for the region. Methods to combat the landslide hazard are largely labour intensive and include:

- **building restraining structures** such as walls, piles, buttresses and gabions – these may hold back minor landslides
- **excavating and filling steep slopes** to produce gentler slopes – this can reduce the impact of gravity on a slope
- **draining slopes** to reduce the build-up of water – this decreases water pressure in the soil
- **watershed management**, for example afforestation and agroforestry ('farming the forest') – this increases interception and reduces overland flow.

However, many settlements are located on unsuitable land because no-one else wants that land. Relocation following a disaster can also occur. For example, at Mayeyes near Ponce in Puerto Rico, the site was cleared following a landslide. Similarly, the Preston Lands landslide in 1986 in Jamaica resulted in the local community being relocated.

Section 9.2 Activities

1 Suggest why hazards due to mass movement are common throughout many parts of the Caribbean.
2 How can human activity increase the risk of landslides?

Impacts on lives and property

Landslides

Case Study: Landslides in Puerto Rico

Approximately 70–80 per cent of Puerto Rico is hilly or mountainous (Figure 9.23). Average annual precipitation in Puerto Rico ranges from less than 1000 millimetres along the southern coast to more than 4000 millimetres in the rainforest of the Sierra de Luquillo in the north-eastern part of the island. Rain in Puerto Rico falls throughout the year, but about twice as much rain falls each month from May to October – the tropical storm season – as falls from November to April. In October 1985, a tropical wave, which later developed into tropical storm Isabel, struck the south-central coast of Puerto Rico, and produced extreme rainfall.

Figure 9.23 Puerto Rico – relief

Puerto Rico can be divided into three distinct physiographic provinces: Upland, Northern Karst and Coastal Plains. The Upland province includes three major mountain ranges and is covered by dense tropical vegetation. Slopes as steep as 45° are common. The Northern Karst province includes most of north-central and north-western Puerto Rico north of the Upland province. The Coastal Plains province is a discontinuous, gently sloping area. Puerto Rico's major cities are built primarily in the Coastal Plain province, although population growth has pushed development onto adjacent slopes of the Upland and Northern Karst provinces. Some 60 per cent of the 3.35 million population lives in the four largest cities – San Juan, Ponce, Mayaguez, and Arecibo – which are located primarily on flat or gently sloping coastal areas. However, continuing growth of these urban centres is pushing development onto surrounding steep slopes.

All major types of landslide occur in Puerto Rico. Most of the Upland province and the Northern Karst province, on account of their high relief, steep slopes and abundant rainfall, have continuing landslide problems. The drier south-western part normally experiences landslides only during exceptionally heavy rainfall.

Debris slides and debris flows – rapid downslope sliding or flowing of disrupted surface rock and soil – are particularly hazardous because they happen with little or no warning. Rock falls are common on very steep natural slopes and especially on the numerous steep road cuttings on the island.

A major tropical storm in October 1985 triggered thousands of debris flows as well as a disastrous rock slide that destroyed the Mameyes district of Ponce, killing at least 129 people. The Mameyes landslide was the worst ever landslide experienced in Puerto Rico. More than 100 homes were destroyed, and about as many were later condemned and removed because of continuing risk from landslides.

The greatest cost to public works in Puerto Rico is road maintenance. The frequency of serious storms suggests that a long-term average of perhaps five fatalities per year could occur, tens of houses be destroyed or made unfit to live in and hundreds be damaged by landslides each year.

Section 9.2 Activities

1 Suggest why Puerto Rico is so vulnerable to landslides.
2 How could the threat of landslides be reduced?

Case Study: China's landslide, 2010

China experienced its deadliest landslide in decades in 2010. At least 700 people died in north-western Gansu province when an avalanche of mud and rock engulfed the small town of Zhouqu. Zhouqu town is in a valley. Heavy rain quickly ran off the steep, barren hills, triggering mudslides and swelling the river. Landslides levelled an area about 5 kilometres long and 500 metres wide, and more than 300 houses collapsed.

Officials have warned for years that heavy tree-felling and rapid hydro development were making the mountain area around Zhouqu vulnerable to landslips. One government report in 2009 called the Bailong River a 'high-occurrence disaster zone for landslides'.

The landslide created a loose earth dam. Water levels behind the barrier fell slightly after controlled explosions created a channel to funnel off some of the water.

The landslide was the worst to hit China in 60 years, and was the most deadly single incident in a year of heavy flooding that killed nearly 1500 people.

Mudslides

Case Study: Human causes – the Italian mudslides, 1998

In May 1998, mudslides swept through towns and villages in Campania, killing nearly 300 people. Hardest hit was Sarno, a town of 35 000 people (Figure 9.24). In the two weeks before the mudslide, up to a year's rainfall had fallen. Geologically, the area is unstable – it has active volcanoes, such as Etna and Vesuvius, many mountains and scores of fast-flowing rivers. Following the mudslide, a state of emergency was declared in the Campania region, and up to £18 million was allocated for repairing the damage. Campania is one of Italy's most vulnerable regions – since 1892, scientists have recorded at least 1173 serious landslides in Campania and Calabria. Since 1945, landslides and floods have caused an average of seven deaths every month (Table 9.10).

Figure 9.24 Sarno, Italy

Table 9.10 Floods and landslides in Italy since 1950

Year	Region	Event	Deaths
1951	Calabria	Floods	100
1951	Polesine, Veneto	Floods	89
1954	Salerno, Campania	Floods	297
1963	Longarone, Veneto	Landslide, floods	1800
1966	Florence, Tuscany	Floods	35
1985	Val di Stava, Trentino	Landslide, floods	269
1987	Valtelina, Lombardy	Floods, landslide	53
1994	Alessandria, Piedmont	Floods	68
1996	Versilia, Tuscany	Floods, landslide	14
1998	Sarno and Siano, Campania	Mudslide, floods	285

However, the disaster was only partially natural – much of it was down to human error. The River Sarno had dwindled to a trickle of water and part of the river bed had been cemented over. The clay soils of the surrounding mountains had been rendered dangerously loose by forest fires and deforestation. Houses had been built up hillsides identified as landslide zones, while Italy's sudden entry into the industrial age in the 1960s led to the uncontrolled building of houses and roads, and deforestation. Nowhere was this more evident than in

Campania. Over 20 per cent of the houses in Sarno were built without permission. Most are shoddily built over a 2 metre-thick layer of lava formed by the eruption of Vesuvius in 79 CE. Heavy rain can make this lava liquid, and up to 900 million tonnes of material are washed down in this way every year. Much of the region's fragility is, therefore, due to mass construction, poor infrastructure and poor planning.

It is likely that similar landslides will be experienced in Spain, Portugal, Greece and Turkey as these countries are developed. All across southern Europe, the natural means by which excess rainfall can be absorbed harmlessly are being destroyed. First, the land is cleared for development (even land that may have been designated as green-belt land). The easiest way to clear the vegetation is to set it on fire. The growing incidence of forest fires around the Mediterranean is not coincidental. Many are started deliberately by developers to ensure that the area loses its natural beauty. One of the side-effects of fire is to loosen the underlying soil.

Throughout southern Europe, the easiest way for an individual to add an extension or build a house is not to submit plans for approval but just to go ahead. In Sicily, up to 20 000 holiday homes have been built on beaches, cliffs and wetlands, in defiance of planning regulations. In Italy, 217 000 houses have been built without permission, and without proper drainage or foundations. Many stand close to an apparently dry river bed that can become a torrent during a storm. One Campanian town, Villaggio Coppola di Castelvolturno, with a population of 15 000 inhabitants, was created entirely without authorisation.

Section 9.2 Activities

1. What are the natural reasons why Italy is at risk from mudslides?
2. What human factors have increased the risk of mudslides in the region?
3. Why is the threat of mudslides increasing throughout the Mediterranean region?

Case Study: The Venezuelan mudslides

The Venezuelan mudslides of 1999 were the worst disaster to hit the country for almost 200 years (Figure 9.25). The first two weeks of December saw an unusually high amount of rainfall in Venezuela. Precipitation was 40–50 per cent above normal in most of the eastern Caribbean during 1999. On 15 and 16 December, the slopes of the 2000 metre Mt Avila began to pour forth avalanches of rock and mud, burying large parts of a 300 kilometre stretch of the central coast. The rains triggered a series of mudslides, landslides and flash floods that claimed the lives of between 10 000 and 50 000 people in the narrow strip of land between the mountains and the Caribbean Sea. Over 150 000 people were left homeless by landslides and floods in the states of Vargas and Miranda.

Figure 9.25 Venezuela

Hardest hit was the state of Vargas. Countless mountainside slum dwellings were either buried in the mudslide or swept out to sea. Most of the dead were buried in mudslides that were 8–10 metres deep. The true number of casualties may never be known. The mudslides also destroyed roads, bridges and factories, buried crops in the fields, destroyed telecommunications and also ruined Venezuela's tourist industry for the immediate future. The international airport of Caracas was temporarily closed and the coastal highway was destroyed or closed in many places. Flash floods damaged hundreds of containers at the seaport in Maiquetía. Hazardous materials in some containers were leaked into the ground and into the sea. Flash-flood damage halted operations at the Maiquetía seaport and hampered efforts to bring in emergency supplies immediately after the disaster. Economic damage was estimated at over US$3 billion.

The disaster was not just related to heavy rainfall. The government blamed corrupt politicians from previous governments and planners who had allowed shanty towns to grow up in steep valleys surrounding the coast and the capital, Caracas.

The immediate response was a search-and-rescue operation to find any survivors in the mudflows, landslides and buildings that had been damaged or destroyed. Few survivors were found after the first few days. The other short-term response was to provide emergency relief – accommodation, water purification tablets, food and medicines to those in need. The relief operation was severely hindered by the poor state of the infrastructure, which made operations difficult.

Ironically, the government had already been planning to redistribute part of Venezuela's population away from the overcrowded coast to the interior. Up to 70 per cent of Venezuela's population live in this small area.

Government plans for rebuilding

The Venezuela government announced a plan to restore Venezuela's northern coastal region by rebuilding thousands of homes there, expanding the country's main airport and constructing canals that can direct rivers away from communities.

The plan includes building 40 000 new homes in the hard-hit state of Vargas. The resort towns of Macuto and Camuri Chico were restored as tourist destinations and $100 million will be spent to expand Venezuela's main international airport. The country's main seaport, also in Vargas, was 'modernised'.

The towns that were utterly devastated by the disaster, where most structures were swept out to sea, were not rebuilt. Instead, these towns, including the coastal community of Carmen de Uria (Figure 9.26), were turned into parks, bathing resorts and other outdoor facilities.

Figure 9.26 Landslide at Carmen de Uria

In 2005, floods and mudslides brought on by heavy rains in the northern and central coast of Venezuela caused 14 deaths. Some 18 000 people were affected, while 2840 houses were damaged and a further 363 destroyed. In many cases, those that were affected in the 1999 mudslides were also affected in 2005.

Section 9.2 Activities

1 What were the causes of the Venezuelan mudslides?
2 Why were the impacts so great?

Table 9.11 Examples of hazards in mountainous areas

Hazards	Disaster event
Rockslides	Elm, Swiss Alps, 1881 Vaiont Dam, Italian Alps, 1963
Mud and debris flows	European Alps, 1987 Huanuco Province, Peru, 1989
Debris torrents	Coast Range, British Colombia 1983–84 Rio Colorado, Chile, 1987
Avalanches	Hakkari, Turkey, 1989 Western Iran, 1990
Earthquake-triggered mass movements	Campagna, Italy, 1980 Mt Ontake, Japan, 1984
Vulcanism-triggered mass movements	Mt St Helens, USA, 1980 Nevado del Ruiz, Colombia, 1985
Weather-triggered mass movements from volcanoes	Mt Kelut, Indonesia, 1966 Mt Semeru, Java, 1981
Natural dams and dam-break floods	
Landslide dams	Indus Gorge, Western Himalayas, 1841 Ecuadorean Andes, 1987 Sichuan earthquake, 2008
Glacier dams	'Ape Lake', British Colombia, 1984
Moraine dams	Khumbu, Nepal, Himalaya, 1985
Avalanche dams	Santa River, Peruvian Andes, 1962
Vegetation dams	New Guinea Highlands, 1970
Artificial dam failures	Buffalo Creek, Appalachians, USA, 1972 Shanxi Province, China, 1989

Table 9.11 summarises some of the hazards that are experienced in mountainous areas around the world.

Avalanches

Avalanches are mass movements of snow and ice. Newly fallen snow may fall off older snow, especially in winter, while in spring partially thawed snow moves, often triggered by skiing. Avalanches occur frequently on steep slopes over 22°, especially on north-facing slopes where the lack of Sun inhibits the stabilisation of the snow. They are also very fast. Average speeds in an avalanche are 40–60 kilometres per hour, but speeds of up to 200 kilometres per hour have been recorded in Japan.

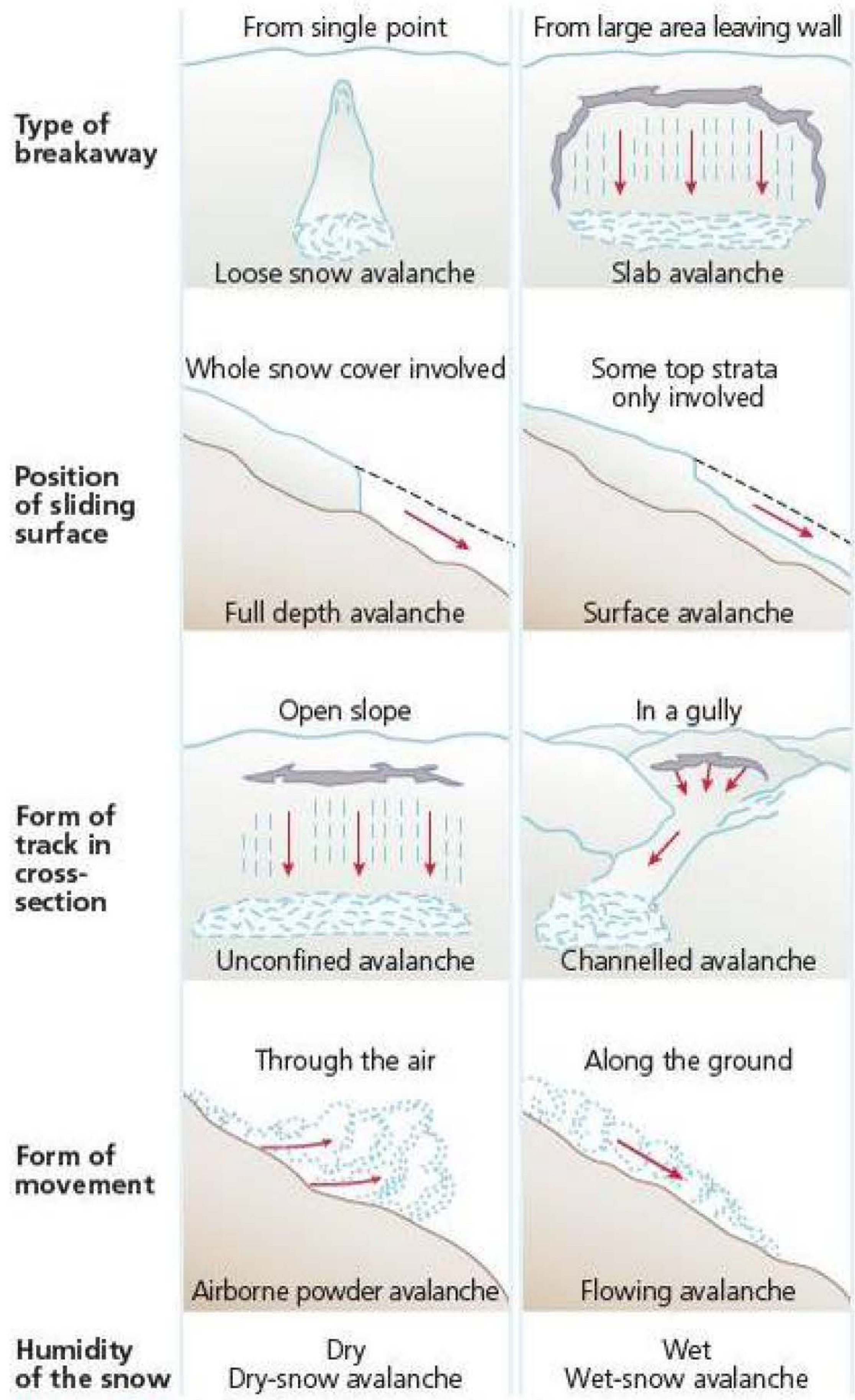

Figure 9.27 A classification of avalanches

Avalanches are classified in a number of ways (Figure 9.27). At first, a distinction was made between airborne powder-snow avalanches and ground-hugging avalanches. Later classifications have included:

- **the type of breakaway** – from a point formed with loose snow, or from an area formed of a slab
- **position of the sliding surface** – the whole snow cover or just the surface
- **water content** – **dry** or **wet avalanches**
- **the form of the avalanche** – whether it is channelled in cross-section or open.

Although avalanches cannot be prevented, it is possible to reduce their impact (Figures 9.28 and 9.29). So why do avalanches occur? The underlying processes in an avalanche are similar to those in a landslide. Snow gets its strength from the interlocking of snow crystals and cohesion caused by electrostatic bonding of snow crystals. The snow remains in place as long as its strength is greater than the stress exerted by its weight and the slope angle.

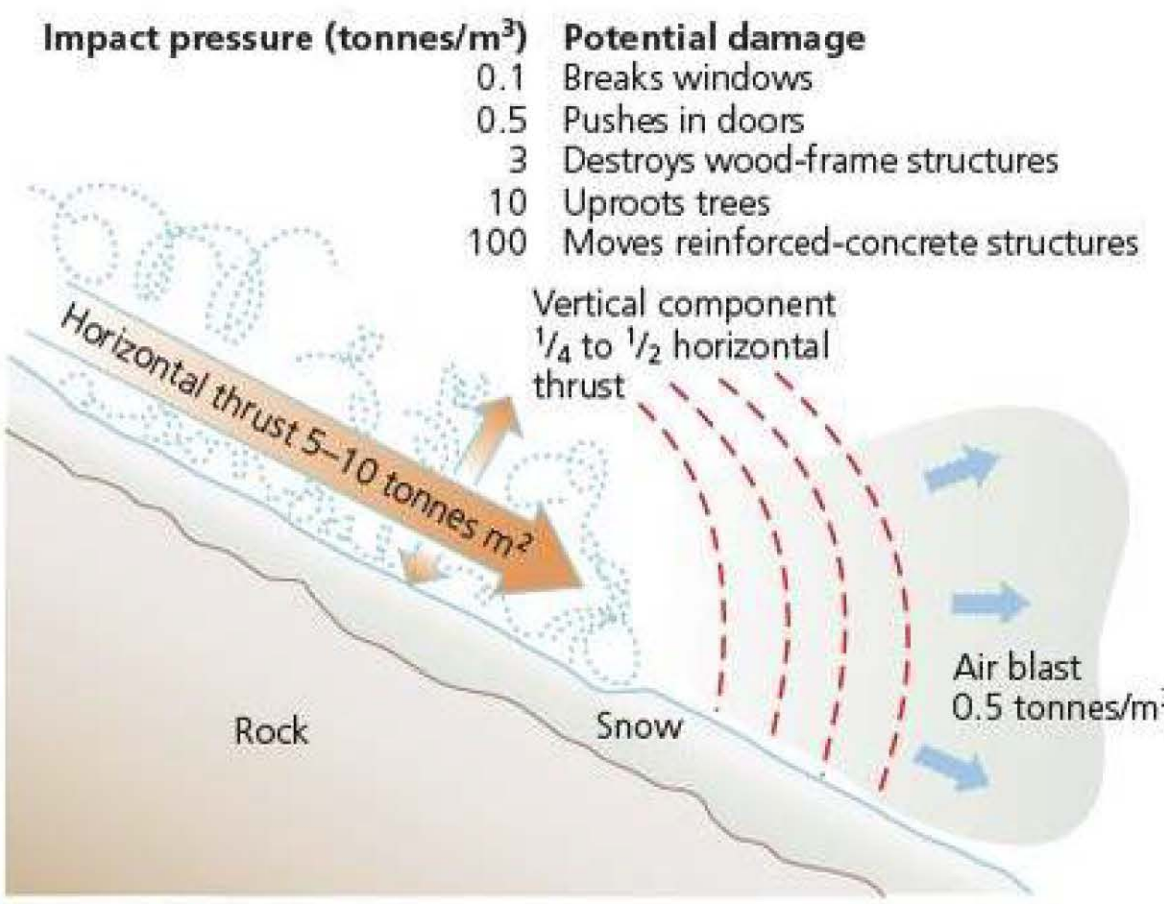

Figure 9.28 Avalanche impact

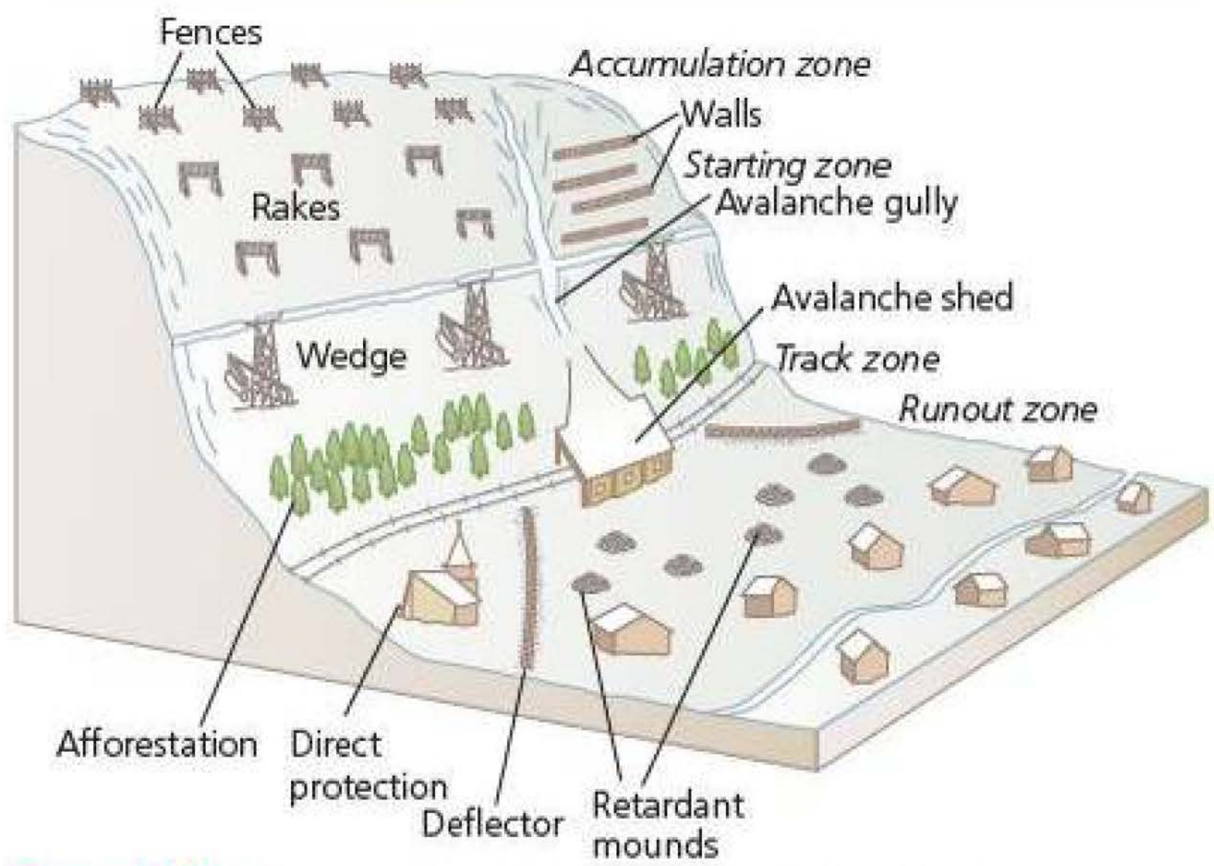

Figure 9.29 Measures to reduce the impact of avalanches

The process is complicated by the way in which snow crystals constantly change. Changes in overlying pressure, compaction by freshly fallen snow, temperature changes and the movement of meltwater through the snow cause the crystal structure of the snow to change. It may become unstable and move downslope as an avalanche.

Loose avalanches, comprising fresh snow, usually occur soon after a snowfall. By contrast, slab avalanches occur at a later date, when the snow has developed some cohesion. The latter are usually much larger than loose avalanches and cause more destruction. They are often started by a sudden rise in temperature that causes melting. The meltwater lubricates the slab, and makes it unstable. Many of the avalanches occur in spring (Table 9.12) when the snowpack is large and temperatures are rising. There is also a relationship between the number of avalanches and altitude (Table 9.13).

Table 9.12 Occurrence of avalanches in the French Alps

December	10%
January	22%
February	32%
March	23%
April	13%

Table 9.13 Avalanches and altitude in the Swiss Alps

Altitude (m)	No. of avalanches	% of total
Above 3000	326	3
2500–3000	2210	24
2000–2499	3806	41
1500–1999	2632	28
Below 1500	394	4

Section 9.2 Activities

1 Suggest reasons why avalanches are clustered in the months January to March. Give details on at least **two** reasons.

2 Table 9.13 shows the distribution of avalanches with altitude in Switzerland. The tree-line is at about 1500 metres and the snow line is at 3000 metres. Describe the distribution of avalanches with altitude. How do you explain this pattern?

Case Study: The European avalanches of 1999

The avalanches that killed 75 people in the Alps in February 1999 were the worst in the area for nearly 100 years. Moreover, they occurred in an area that was thought to be fairly safe. In addition, precautionary measures had been taken, such as an enormous avalanche wall to defend the village of Taconnaz, and a second wall to stop the Taconnaz glacier advancing onto the motorway that runs into the mouth of the Mt Blanc tunnel. However, the villages of Montroc and Le Tour, located at the head of the Chamonix Valley, had no such defences.

The avalanche that swept through the Chamonix Valley killed 11 people and destroyed 18 chalets (Figure 9.30). Rescue work was hampered by the low temperatures (–7 °C), which caused the snow to compact and made digging almost impossible. The avalanche was about 150 metres wide, 6 metres high and travelled at a speed of up to 90 kilometres per hour. It crossed a stream and even travelled uphill for some 40 metres. Residents were shocked, since they had not experienced an avalanche so powerful, so low in the mountains and certainly not one capable of moving uphill.

Nothing could have been done to prevent the avalanche. Avalanche warnings had been given the day before, as the region had experienced up to 2 metres of snow in just three days. However, buildings in Montroc were not considered to be at risk. In fact, they were classified as being in the 'white zone', almost completely free of danger. By contrast, in the avalanche danger zones no new buildings have been developed for many decades. Avalanche monitoring is so well established and elaborate that it had caused villagers and tourists in the 'safe' zone to think that they really were safe. In Montroc, the experience was the equivalent of the eruption of an extinct volcano – the last time the snow above Montroc had caused an avalanche was in 1908.

Meteorologists have suggested that disruption of weather patterns resulting from global warming will lead to increased snowfalls in the Alps that are heavier and later in the season. This would mean that the conventional wisdom regarding avalanche 'safe' zones would need to be re-evaluated.

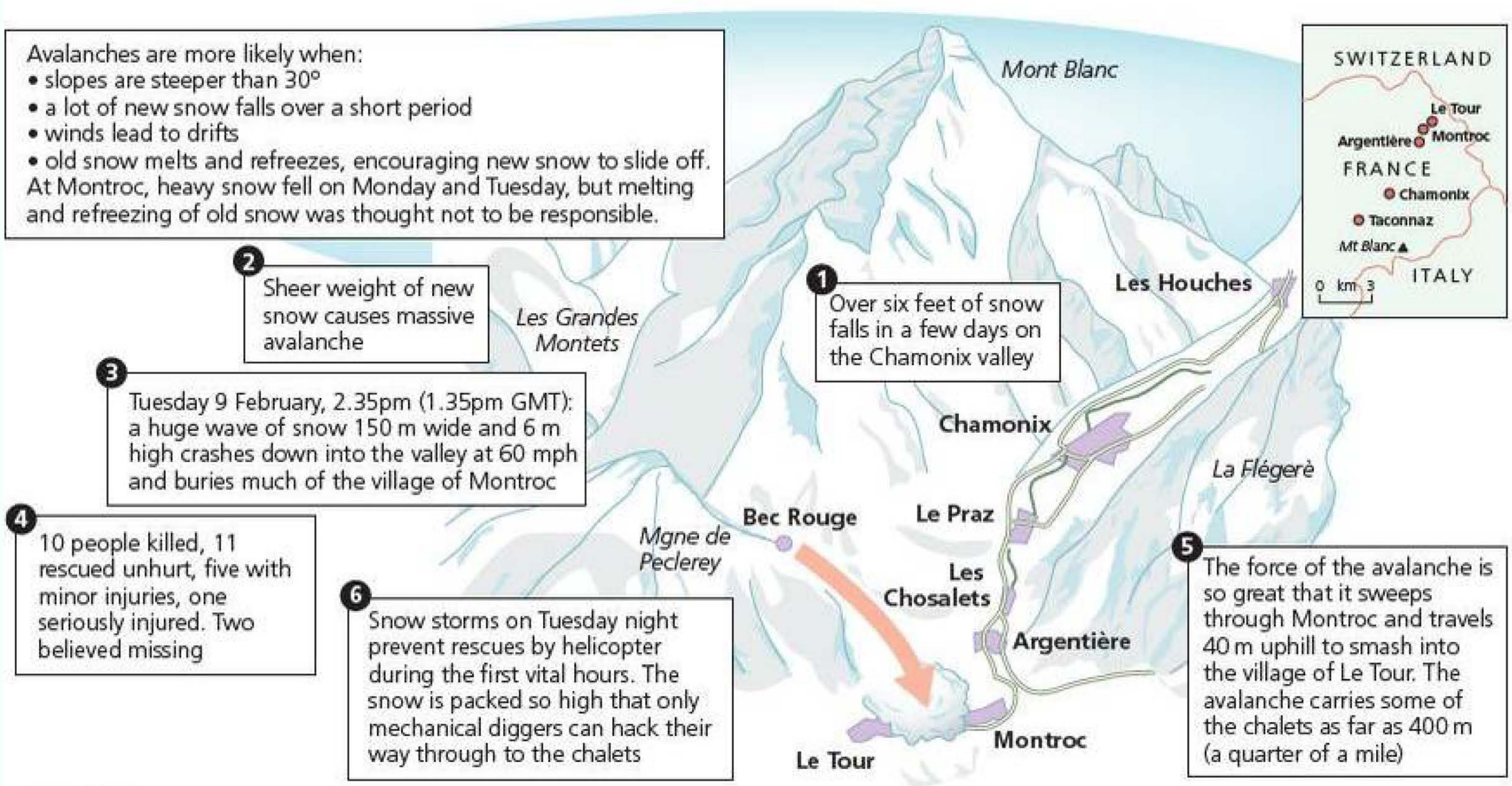

Figure 9.30 Causes and consequences of the Montroc–Le Tour avalanche

Snowslides 2009–10

In December 2009 and January 2010, dozens of people were caught in the path of avalanches. The increase in snowslide activity sent ominous rumblings through the communities of Europe's Alpine resorts. Residents live in fear of seeing a repeat of early 1999 (see above, when 75 people were killed over a period of three weeks), or even of 1950–51, when more than 265 people died in three months.

Heavy snowfall combined with rain and an easing of the extreme cold prompted Météo France, the national meteorological service, to raise the avalanche warning to level 4 (out of 5), meaning 'high risk'.

In 2009, scientists in London warned that global warming, in the form of rising temperatures and melting permafrost, could make avalanches more frequent.

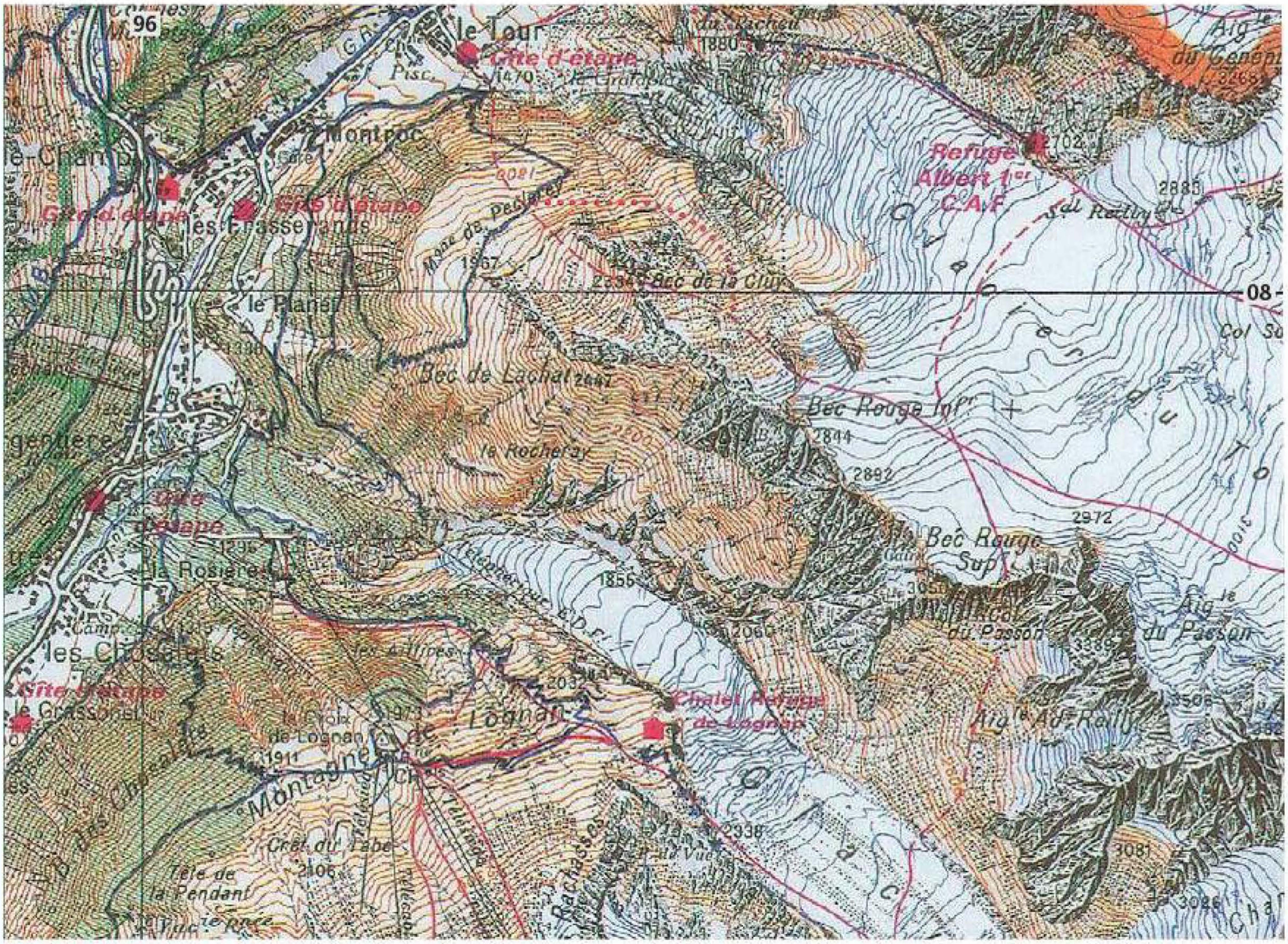

Figure 9.31 Survey map of the Alps – area affected by 1999 avalanches

Section 9.2 Activities

1 What is an *avalanche*?
2 What are the factors that increase the risk of an avalanche?
3 What were the conditions in Europe in February 1999 that led to widespread avalanches?
4 How and why may the threat of avalanches change in the next decades?
5 Study Figure 9.30.
  a Describe the site of Montroc and Le Tour.
  b What are the attractions for tourists shown on Figure 9.31? Use the grid provided to give grid references.
  c What is the map evidence to suggest that the area is at risk of hazardous events?

Prediction and hazard mapping

Landslides and other forms of mass movement are widespread and cause extensive damage and loss of life each year. With careful analysis and planning, together with appropriate stabilisation techniques, the impacts of mass movement can be reduced or eliminated.

Assessment of the hazards posed by potential mass movement events are based partly on past events, to evaluate their magnitude and frequency. In addition, mapping and testing of soil and rock properties determines their susceptibility to destabilising processes. Maps showing areas that could be affected by mass movement processes are important tools for land-use planners.

For example, valleys in the Cascade Range of Washington and Oregon, USA, have experienced extensive mudflows from volcanic activity over the last 10000years. Hazard maps prepared before the eruption of Mt St Helens and Mt Pinatubo proved extremely useful, as the mudflows generated by these eruptions had very similar distributions to those produced in earlier times (Figure 9.32).

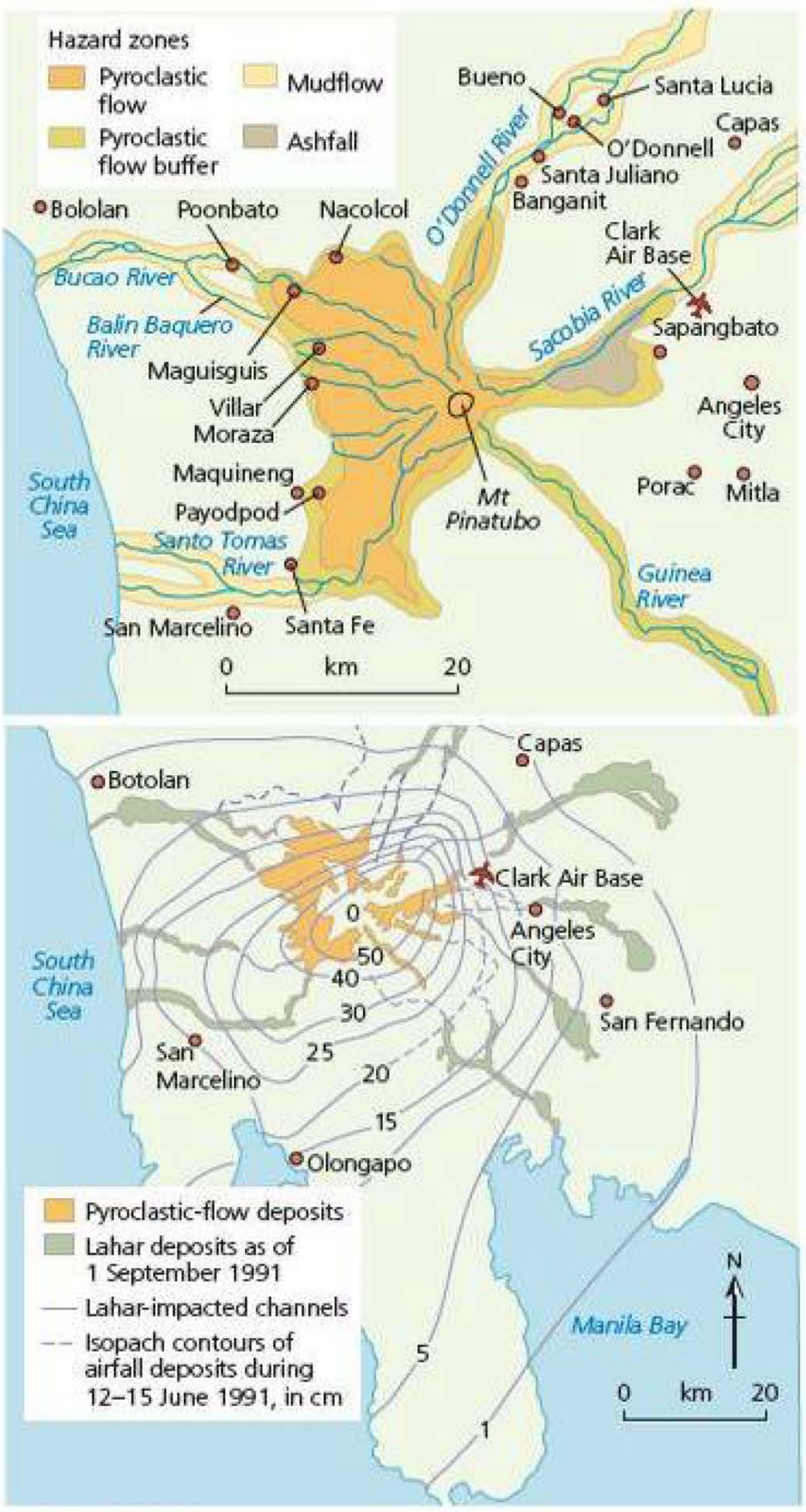

Figure 9.32 Hazard map of Mt Pinatubo

In addition to assessment, prediction and early warning, some engineering schemes can be applied to reduce the damage of mass wasting (Figure 9.33).

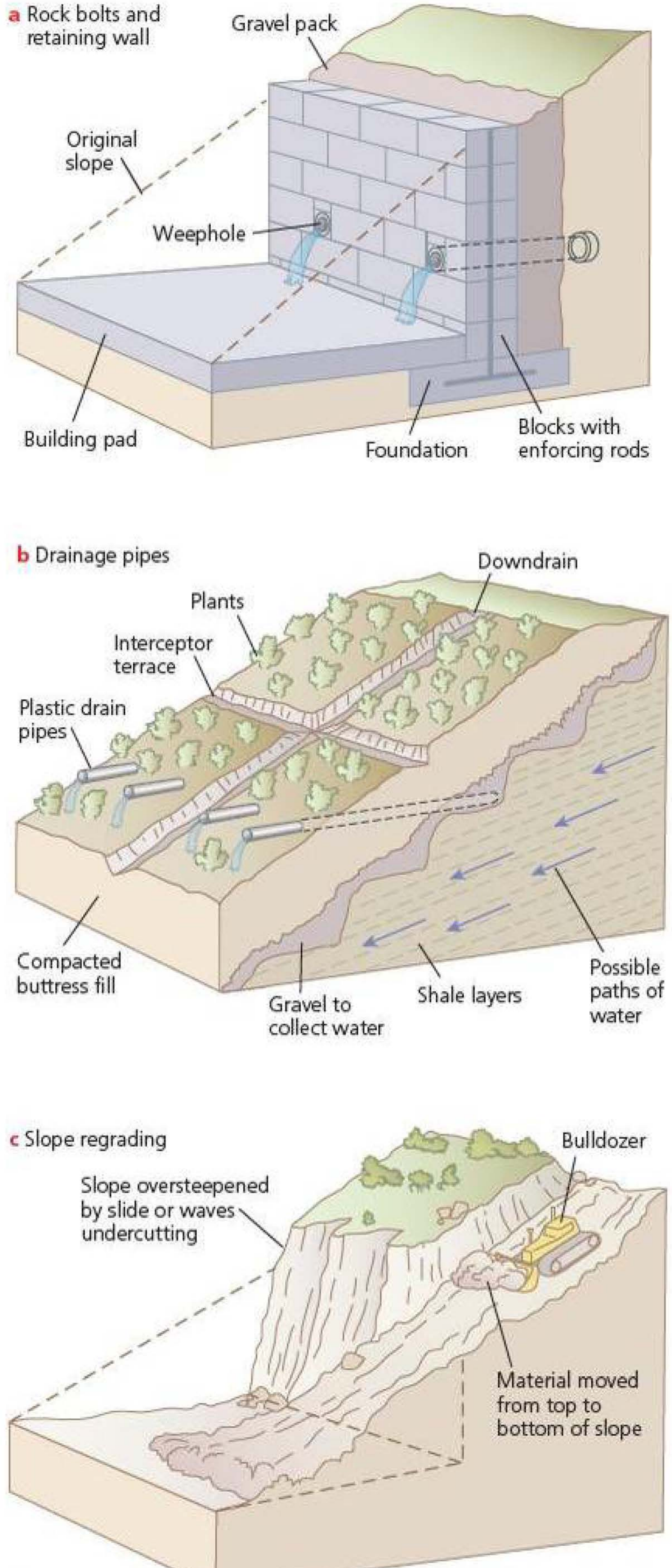

Figure 9.33 Engineering techniques for slope stabilisation