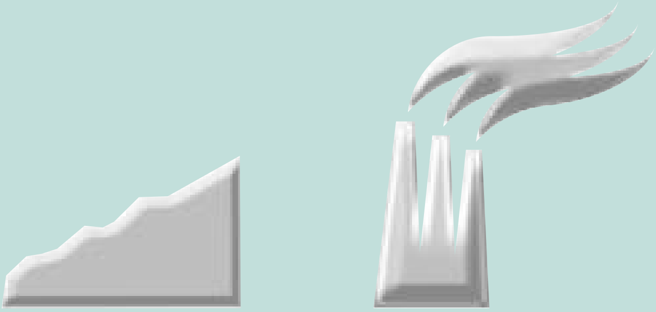

BLOCK 2

BI-2/A NATURAL HAZARDS

BI-2/B TECHNOLOGICAL RISKS AND EFFECTS

ACCORD RISQUES MAJEURS • MAJOR HAZARDS AGREEMENT
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SCHOOL OF CIVIL PROTECTION

MODULE BI-2/A

NATURAL HAZARDS

HANDBOOK

ACCORD RISQUES MAJEURS • MAJOR HAZARDS AGREEMENT
EUR-OPA
Conseil de l'Europe · Council of Europe

IOM - OIM

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NATURAL HAZARDS

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1. Introduction

Traditional hazard classification recognizes:

- natural (geophysical)
- technologic (man-made) hazards

Natural hazards are *"those elements of the physical environment harmful to Man and caused by forces extraneous to him"*, or in other words, *"the probability of occurrence, within a specific period of time in a given area, of a potentially damaging natural phenomena"* (Table 1-I).

Technologic hazards are *"major man-made accidents, that is, the initiating event in a disaster arises from a human, rather than a geophysical origin"*. In other words, technological hazards are *"accidental failures of design or of management affecting large-scale structures, transport systems or industrial activities which present life-threatening risks to the local community"* (Table 1-II).

Most environmental disasters have both natural and human components. For example, flood problems may be exacerbated by fluctuations in climate, such as increasing storm frequency, and by human activities, such as land drainage and deforestation. Or, the effects of chemical or nuclear accident will be heavily influenced by the prevailing weather conditions controlling the downwind path and the rate of fallout from the chemical or radioactive plume. These interactions have led to the increasing recognition of 'hybrid' hazards resulting from some degree of overlap between environmental, technological and social processes.

Modern science integrates all hazards continuum under the term ***environmental hazard***, defining it phenomenologically as *"extreme geophysical events, biological process and major technological accidents characterized by concentrated releases of energy or material, which pose a largely unexpected threat to human life and can cause significant damage to goods and environment".*

An understanding of the characteristics of natural hazards and of how they release energy is an essential precursor to an assurance of effective and efficient preparedness measures to mitigate their impacts. With limited exceptions, it is not yet possible to prevent the onset of natural hazards because of the enormous energies released. However, it is possible to provide organisation and resources to minimize loss of life and damage, to organize the temporary evacuation of people and property from a threatened location and facilitate timely and effective rescue, relief and rehabilitation.

The major natural hazards considered in this module are:

- Extreme winds (tropical cyclones, hurricanes and typhoons)
- Floods
- Earthquakes
- Volcanic activity
- Landslides
- Tsunamis

Whilst tropical cyclones are not characteristic for the European environment, they are discussed to some extent for the sake of the completeness of this training module. The same is true for tsunamis (tidal waves), although there is historical evidence that some major Mediterranean and Atlantic coast earthquakes (Lisbon, 1755) have been followed-up by this natural phenomenon.

Table 1 **Potential environmental hazards** /Modified after Hewitt and Burton (1971)/

I. Natural (geophysical) hazards	
1. Atmospheric	
Single event	Compound
Rain	Rain and wind storms
Freezing rain (glaze)	'Glaze' storms
Hail	Thunderstorms
Snow	Tornadic storms and tornadoes
Wind	Hurricanes
Lightening	Blizzards
Temperature: 'heat wave', 'cold wave', frost	'White-out'
Fog	Drought
2. Hydrologic	
Flooding: riverine (rain, snowmelt, natural damburst floods)	
Lake and sea-shore wave action	
Waterlogging	
Sea-ice and icebergs	
Run-off drought	
Glacier advance	
3. Geologic	
Earthquakes	
Volcanic eruptions	
Mass-movements: landslides, avalanches, mudflows, subsidence, etc.	
Silting (dykes, rivers, harbours, farmland)	
Shifting sands	
4. Biologic	
Severe epidemics in humans	
Severe epidemics in plants	
Severe epidemics in domestic and wild animals	
Animal and plant invasion (e.g. locusts)	
Forest and grassland fires	
II. Technologic (man-made) hazards	
Transport accidents	
Industrial explosions and fires	
Accidental releases of toxic gas	
Nuclear power plant failures	
Failures of public buildings or other structures	
Germ or nuclear warfare	

In practice, most severe disasters arise from compound or synergistic hazard effects, as when earthquakes set off landslides in steep terrain, or tsunamis attack shoreline regions.

Table 2 **Summary of primary and secondary effects of natural hazards**

Natural hazard	Primary phenomena	Secondary phenomena
Extreme winds	Strong winds Heavy rains	Flood and sea surge Landslide Water pollution
Flood	Flooding	Water pollution Landslide Erosion
Tsunami	Flooding	Water pollution Landslide Erosion Deposition
Earthquake	Violent ground motion Fault rupture	Soil liquefaction Fire Flood Landslide Tsunami Water pollution
Landslide	Ground failure	Flooding via river damming Water pollution Debris flows
Volcano	Lava flow Pyroclastic flow/surge Ash fall Volcanic gases	Fire Air pollution Earthquake Tsunami Lahars flows Water pollution Ground subsidence

Consequently, natural hazards are phenomenologically referred to as primary and secondary (Table 2). The primary hazard is a phenomenon triggering a spectrum of other natural phenomena with adverse effects on humans, their material property and the environment. The secondary hazard is a phenomena triggered by other [preceded] natural phenomenon.

Sometimes secondary hazard may appear as the primary one, that is, a tsunami triggered by a distant off-shore earthquake. In such a case, the vibration as the primary earthquake phenomena might be negligible for that particular location, thus, posing no danger to the population and its values. However, the triggered tsunami can generate major damage and spectra of collateral phenomena at the affected shoreline. A typical example is the Chilean earthquake of 1960 that triggered tsunami, which travelled all across the Pacific Ocean, causing major damage to shorelines of Japanese islands (56 places were affected by a tidal wave with a height of 2 metres and 22 places with a wave of 3 metres in height).

Each hazard has characteristic features - probability, frequency, intensity, coverage and duration - and effects. Their impact also depends on factors such as location, topography, geology and soil characteristics. The probability of natural hazard events occurring in a particular region can be estimated with varying degrees of accuracy. Some of the hazards can be forecast (for example, formation and track of tropical cyclones and floods). Using sophisticated monitoring techniques it is possible to predict the onset of some types of landslides, volcanic eruptions and tsunamis. However for some hazards it is possible to predict the location of the onset and the intensity of appearance, but not the time of its occurrence (earthquakes).

2. Atmospheric hazards – extreme windstorms

Wind is defined as the motion of air relative to the earth's surface. The horizontal component of the three-dimensional flow and the near-surface wind phenomena are the most significant aspects of the hazard. Extreme windstorm events are associated with tropical and extratropical cyclones, winter cyclones, and severe thunderstorms and accompanying mesoscale offspring such as tornados and downbursts. Wind speed may vary from zero at ground level to 320 kilometres per hour (90 m/s or 200 mph) in the upper atmospheric jet stream at 10 to 13 kilometres (6 – 8 miles) above the earth's surface.

2.1 Cyclones

A cyclone is a low-pressure area in the atmosphere in which winds spiral inward. A cyclone covers a large geographical area. A special, intense kind of cyclone from about 100 to 2,500 meters (300 to 8,000 feet) across is a tornado.

Meteorologists divide cyclones into two classes:

- tropical
- extratropical

While the terminology reflects their regions of occurrence, tropical and extratropical cyclones have fundamentally different structures and formation mechanisms, and derive their energy from different sources.

Table 3 **Beaufort Scale of wind force**

Beaufort number	General description	Specification	Speed	
			(km/h)	Knots
0	Calm	Smoke rises vertically	less than 1	less than 1
1	Light air	Wind direction shown by smoke drift but not by vanes	2 - 6	1 - 3
2	Slight breeze	Wind felt on face; leaves rustle; ordinary vane moved by wind	7 - 12	4 - 6
3	Gentle breeze	Leaves and small twigs in constant motion; wind extends light flag	13 - 18	7 - 10
4	Moderate breeze	Raise dust and loose paper, small branches are moved	19 - 26	11 - 14
5	Fresh breeze	Small trees in leaf begin to sway; crested wavelets form on inland waters	27 - 35	15 - 19
6	Strong breeze	Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty	36 - 44	20 - 24
7	Moderate gale (High wind)	Whole trees in motion; inconvenience when walking against wind	45 - 55	25 - 30
8	Fresh gale	Twigs broken off trees; generally impedes progress	56 - 66	31 - 35
9	Strong gale	Slight structural damage occurs, chimney pots and slates removed	67 - 77	36 - 42
10	Whole gale	Trees uprooted, considerable structural damage; seldom experienced inland	78 - 90	43 - 49
11	Storm	Very rarely experienced, widespread damage	91 - 104	50 - 56
12	Hurricane	The air at sea filled with foam and spray	Above 105	Above 56

2.1.1 Tropical cyclones

The most tropical cyclones usually occur between at 5 and 30 degrees latitude on both sides of the equator. They may or may not be accompanied by precipitation. On average, 80 cyclones are formed every year. Two-thirds of those are formed in the Northern Hemisphere. This number includes only the tropical depressions that have developed wind speeds of 12 on the Beaufort Scale (Table 3).

A tropical cyclone develops over tropical or subtropical waters. ‘Tropical cyclone’ is the generic term for the class of tropical weather systems, including:

- tropical depressions
- tropical storms
- hurricanes (“typhoons” or “cyclones”)

Tropical Depression is an organized system of clouds and thunderstorms with a defined circulation and maximum sustained winds of 37 to 62 kilometres per hour (38 mph or 33 knots) or less.

Tropical Storm is an organized system of strong thunderstorms with a defined circulation and maximum sustained winds of 63 to 117 kilometres per hour (39-73 mph or 34-63 knots).

Hurricane (“typhoons” or “cyclones”) is an intense tropical weather system (Fig. 1) with a well-defined circulation and maximum sustained winds of 118 kilometres per hour (74 mph or 64 knots) or higher.

Fig. 1 **Satelite image of hurricane Bonnie, September 1998** (Category 3 storm)

Severe tropical cyclones, with winds of 119 kilometres (74 miles) per hour or more, are known as ***hurricanes***, ***typhoons*** or ***cyclones***, depending on where they form. The three terms are applied to identical meteorological events in different parts of the world. Hurricanes form in the North Atlantic or eastern North Pacific, typhoons form in the western Pacific, and cyclones form in the Indian Ocean. These storms, in the following text referred to as **“*tropical cyclones*”**, or ***“cyclones”***, may bring winds up to 290 km/h (180 mph), terrific rains, violent thunder, and lightning. They measure 320 to 480 kilometres (200 to 300 miles) across.

Tropical cyclones are products of the tropical ocean and atmosphere. They develop as a result of high-energy build-up from continuous radiation over the ocean, and provide a means of releasing this accumulated energy. A mixture of heat and moisture forms a low-pressure centre over oceans in tropical latitudes where water temperatures exceed 26°C. Wind currents spin and organise around deepening low pressure, accelerating toward the centre and moving along a track pushed by trade winds. A depression is defined as a tropical cyclone when winds reach gale force (120 km/h).

The central area around which the air circulates is called the *‘eye of the storm’*. The atmospheric pressure in this area is extremely low (below 1000 milibars). The eye diameter ranges from 20 to more than 40 km. In the eye area, weather conditions are relatively quiet with light winds and small amounts of cloud. Violent winds and torrential rains characterise the ring from the perimeter of the eye to the storm’s outer boundary. In the Northern Hemisphere, the winds blow around the eye in a counter clockwise direction, while in the

Southern Hemisphere they blow clockwise. These strong winds may persist for many hours. The diameter of this area ranges between 100 and 300 km. Gales may occur within a diameter of even more than 600 km. From its top to sea level, the depth of a cyclone ranges between 10 and 20 km.

Powered by heat from the sea, cyclones are steered, at a speed of 10 to 50 km/h, by the easterly trade winds and the temperate westerlies as well as by their own ferocious energy. In a first phase, they run westwards or eastwards becoming larger and stronger as they travel. Then they turn from the equator and pick up speed. Later they turn in a more northerly (Northern Hemisphere) or southerly (Southern Hemisphere) direction. The distribution of the ocean water temperature, and accordingly the temperature of the lower atmospheric strata determines what course the cyclone will follow. In general, the direction will be toward a region of maximum available energy.

The average duration of a tropical cyclone is nine days. During this period it may travel over a distance of 10,000 km. Due to much lower energy supply, it will subside over land. Friction on the earth’s surface will also destroy the cyclone gradually by allowing more air to penetrate its eye.

Around the cyclone core, winds grow with great velocity, generating violent seas. When a tropical cyclone approaches land, risk of serious loss or damage arises from winds, rainfall and surges. Moving ashore, they sweep the ocean inward while spawning tornadoes and producing torrential rains and floods. When the eye of a storm passes over an area, strong winds from one direction are followed by the quiet conditions of the central area; where, the following strong winds from the other direction will have their devastating effect. Although intense rainfall can occur over a lengthy period, wind produces the most damaging effects. A tropical cyclone often triggers spectra of secondary disastrous phenomena such as river flooding, flash floods, storm surges, landslides and mudflows.

2.1.2 Extratropical cyclones

Extratropical cyclones (sometimes called mid-latitude depressions, or lows) form in the middle and high latitudes, within the belt of westerlies encircling the globe between latitudes 30 and 70. They generally move from west to east, bringing a period of generally unsettled weather, with wind, cloud, and precipitation, particularly near fronts.

Extratropical cyclones do not require heat and moisture input from the sea. Instead, the cyclone feeds on potential energy contained in horizontal temperature contrasts. These temperature contrasts are continually building as a result of the solar heating imbalance between the equator and the poles. The cyclone forms as a result of the redistribution of air that occurs when contrasting air is brought together.

As the cyclone develops, the region of thermal contrast organises itself into cold and warm fronts, giving the mature cyclone a highly asymmetric structure. The warmest air is found about and east of the low, while the coldest air occurs to the rear (west) of the cyclone in the air moving toward the equator. In addition, most of the cloud and precipitation occurs in the rising warm air about and ahead of the cyclone, in contrast to the symmetric annular rainband structure of the tropical cyclone. Extratropical cyclones generally intensify with height and comprise a cold and amplifying low-pressure trough aloft, just to the west of the surface centre. In contrast, the tropical cyclone consists of a cyclonic vortex that decreases with height, with a warm anticyclone directly above.

2.2 Tornadoes

A tornado is a rapidly rotating vortex of air extending groundward developed within a severe thunderstorm. Most of the time, vortices remain suspended in the atmosphere. When the lower tip of the vortex touches earth, the tornado becomes a force of destruction.

The path width of a single tornado generally is less than 1 km (0.6 mile). The path length of a single tornado can range from a few hundred metres to dozens of kilometres. A tornado typically moves at speeds between 50 and 200 km/h (30 and 125 mph) and can generate internal winds exceeding 500 km/h (300 mph). However, the life of a tornado is rarely longer than 30 minutes.

A tornado event occurs when a single atmospheric condition such as a thunderstorm or cyclone (hurricane, typhoon or cyclone) generates more than one tornado. Multiple tornadoes generally are the result of many thunderstorms embedded in one large extratropical cyclone or mesoscale convective process.

Fig. 2 **Seymour, Texas, tornado of April 10, 1979**

Tornadoes occur most commonly over land. When they occur over water the low pressure at the centre draws in a column of water and creates a waterspout. Geographically tornadoes are most common and most severe in the central, east and northeast US (Fig. 2). Less violent tornadoes have also been recorded in Australia, Western Europe, India and Japan.

2.3 Thunderstorms and lightning

Thunderstorms and lightning are generated by an atmospheric imbalance and turbulence due to the combination of the following conditions:

- unstable warm air rising rapidly into the atmosphere
- sufficient moisture to form clouds and rain
- upward lift of air currents caused by colliding weather fronts (cold and warm), sea breezes, or mountains

A thunder event is composed of lightning and rainfall, and can intensify into a severe thunderstorm with damaging hail, high winds, tornadoes and flash flooding. A thunderstorm is classified as severe if its wind reach or exceeds 100 km/h (58 mph), produces a tornado, or drops surface hail at least 1.9 cm (0.75 inches) in diameter.

Lightening, which occurs in all thunderstorms, can strike anywhere. Generated by the build-up of charged ions in a thundercloud, the discharge of a lightening bolt interacts with the best conducting object or surface on the ground. The air in the channel of lightning strike reaches temperatures higher than 25,000°C. The rapid heating and cooling of the air near the channel causes a shock wave which produces thunder.

Compared with other atmospheric hazards such as tropical cyclones or winter low-pressure systems, individual thunderstorms affect relatively small geographic areas. The average thunderstorm is approximately 25 km (15 miles) in diameter and typically lasts less than 30 minutes at a single location.

Table 4 **The Saffir-Simpson Hurricane Damage Intensity Scale**

Damage potential	Characteristic events
Hurricane category **ONE (Minimal)** Wind speed 119-153 km/hr 74-95 mph 64-82 kt Storm surge height above the normal 1.0-1.7 m 3-5 ft	
No real damage to building structures. Damage primarily to unanchored mobile homes, shrubbery, and trees. Some damage to poorly constructed signs. Some coastal road flooding and minor pier damage.	Hurricanes Allison of 1995 and Danny of 1997 were Category One hurricanes at peak intensity.
Hurricane category **TWO (Moderate)** Wind speed 154-177 km/hr 96-110 mph 83-95 kt Storm surge height above the normal 1.8-2.6 m 6-8 ft	
Some roofing material, door, and window damage of buildings. Considerable damage to shrubbery and trees with some trees blown down. Considerable damage to mobile homes, poorly constructed signs, and piers. Coastal and low-lying escape routes flood 2-4 hours before arrival of the hurricane centre. Small craft in unprotected anchorages break moorings.	Hurricane Bonnie of 1998 was a Category Two hurricane when it hit the North Carolina coast, while Hurricane Georges of 1998 was a Category Two Hurricane when it hit the Florida Keys and the Mississippi Gulf Coast.
Hurricane category **THREE (Extensive)** Wind speed 178-209 km/hr 111-130 mph 96-113 kt Storm surge height above the normal 2.7-3.8 m 9-12 ft	
Some structural damage to small residences and utility buildings with a minor amount of curtainwall failures. Damage to shrubbery and trees with foliage blown off trees and large tress blown down. Mobile homes and poorly constructed signs are destroyed. Low-lying escape routes are cut by rising water 3-5 hours before arrival of the hurricane centre. Flooding near the coast destroys smaller structures with larger structures damaged by battering of floating debris.Terrain continuously lower than 1.5 m (5 ft) above mean sea level may be flooded inland 13 km (8 miles) or more. Evacuation of low-lying residences with several blocks of the shoreline may be required.	Hurricanes Roxanne of 1995 and Fran of 1996 were Category Three hurricanes at landfall on the Yucatan Peninsula of Mexico and in North Carolina, respectively.
Hurricane category **FOUR (Extreme)** Wind speed 210-249 km/hr 131-155 mph 114-135 kt Storm surge height above the normal 3.9-5.6 m 13-18 ft	
More extensive curtainwall failures with some complete roof structure failures on small residences. Shrubs, trees, and all signs are blown down. Complete destruction of mobile homes. Extensive damage to doors and windows. Low-lying escape routes may be cut by rising water 3-5 hours before arrival of the hurricane centre. Major damage to lower floors of structures near the shore.Terrain lower than 3 m (10 ft) above sea level may be flooded requiring massive evacuation of residential areas as far inland as 10 km (6 miles).	Hurricane Luis of 1995 was a Category Four hurricane while moving over the Leeward Islands. Hurricanes Felix and Opal of 1995 also reached Category Four status at peak intensity.
Hurricane category **FIVE (Catastrophic)** Wind speed > 249 km/hr > 155 mph > 135 kt Storm surge height above the normal > 5.6 m > 18 ft	
Some complete building failures with small utility buildings blown over or away. All shrubs, trees, and signs blown down. Complete destruction of mobile homes. Severe and extensive window and door damage. Low-lying escape routes are cut by rising water 3-5 hours before arrival of the hurricane centre. Major damage to lower floors of all structures located less than 4.6 m (15 ft) above sea level and within 460 m (500 yards) of the shoreline. Massive evacuation of residential areas on low ground within 8-16 km (5-10 miles) of the shoreline may be required.	Hurricane Mitch of 1998 was a Category Five hurricane at peak intensity over the western Caribbean. Hurricane Gilbert of 1988 was a Category Five hurricane at peak intensity and is the strongest Atlantic tropical cyclone of record.

Source: The Columbia Encyclopaedia: Sixth Edition /2000

Dangerous and damaging aspects of a severe thunderstorm, other than tornadoes and hail, are lightening strikes, flash flooding, and the winds associated with downbursts and microbursts.

Downburst winds are strong, concentrated, straight-line winds created by falling rain and sinking air that can reach speeds of 200 km/h (125 mph). The combination induces a strong downdraft of wind due to aerodynamic drag forces or evaporation processes.

Microburst winds are more concentrated than downbursts, with speeds of up to 240 km/h (150 mph).

Severe damage can result from the spreading out of downbursts and microbursts, which generally last 5 to 7 minutes. Due to wind shear and detection difficulties, they pose the biggest threat to aircraft departures and landings.

2.4 Wind severity scales

The damaging effects of the wind are produced by a combination of their strength, their gustiness, and their persistence. When wind speeds exceed 120 km/h they are referred to as destructive winds. The destructive power of wind increases with the square of its speed; so a tenfold increase in wind speed increases its force for 100 times.

Several scales are used to indicate wind severity, including:

- the Beaufort Scale (Table 3)
- the Saffir-Simpson Hurricane Scale (Table 4)
- the Fujita Tornado Scale (Table 5).

However, there are no scales which adequately represent the force of gusts of wind in urban areas.

The Beaufort Wind Strength Scale is used to gauge wind speed using observations of the winds' effects on trees and other objects.

The Saffir-Simpson Hurricane Damage Intensity Scale (Table 4) is a standard scale for rating the severity of hurricanes as a measure of the damage they cause. It was devised in the early 1970s, rating hurricanes from category 1 through category 5 in order of increasing intensity. Each intensity category specifies the range of conditions of four criteria: barometric (central) pressure, wind speed, storm surge, and damage potential.

As popularly employed, the Saffir-Simpson scale is used to give an estimate of the potential property damage and flooding expected along the coast from a hurricane landfall. Wind speed is the determining factor in the scale, as storm surge values are highly dependent on the slope of the continental shelf in the landfall region.

The Fujita Tornado Scale measures tornado severity. The Fujita Tornado Scale of 1971, usually referred to as the F-Scale, classifies tornadoes based on the resulting damage assigning numerical values based on wind speeds and categorizes tornadoes from 0 to 5. The letter "F" usually precedes the numerical value. Scale values above F5 are usually not used because wind speeds above 513 km/h (318 mph) are unlikely.

2.5 Effects of extreme windstorms

Apart from direct damage caused by powerful winds, death and injury can be caused by solid objects, both large and small, flying through the air. The effects of air pressure differences between the windward side and the leeward (suction effect) side can also cause wind damage to buildings and structures. In some cases flying debris may cause a chain reaction of damage to buildings.

Table 5 **The Fujita Tornado Scale**

F-Scale Number	Intensity phrase	Wind Speed	Type of damage done	Frequency
F0	Gale tornado	40-72 mph 64-116 km/h	Some damage to chimneys; breaks branches off trees; pushes over shallow-rooted trees; damages sign boards.	29%
F1	Moderate tornado	73-112 mph 117-180 km/h	The lower limit is the beginning of hurricane wind speed; peels surface off roofs; mobile homes pushed off foundations or overturned; moving autos pushed off the roads; attached garages may be destroyed.	40%
F2	Significant tornado	113-157 mph 181-253 km/h	Considerable damage. Roofs torn off frame houses; mobile homes demolished; boxcars pushed over; large trees snapped or uprooted; light object missiles generated.	24%
F3	Severe tornado	158-206 mph 254-332 km/h	Roof and some walls torn off well constructed houses; trains overturned; most trees in forest uprooted	6%
F4	Devastating tornado	207-260 mph 333-418 km/h	Well-constructed houses levelled; structures with weak foundations blown off some distance; cars thrown and large missiles generated.	2%
F5	Incredible tornado	261-318 mph 419-512 km/h	Strong frame houses lifted off foundations and carried considerable distances to disintegrate; automobile-sized missiles fly through the air in excess of 100 meters; trees debarked; steel reinforced concrete structures badly damaged.	less than 1%
F6	Inconceivable tornado	319-379 mph 513-600 km/h	These winds are very unlikely. The small area of damage they might produce would probably not be recognizable along with the mess produced by F4 and F5 wind that would surround the F6 winds. Missiles, such as cars and refrigerators would do serious secondary damage that could not be directly identified as F6 damage. If this level is ever achieved, evidence for it might only be found in some manner of ground swirl pattern, for it may never be identifiable through engineering studies	-

Rainfall frequently accompanies high winds. Apart from the flooding damages, the damage that results as a direct consequence of rainfall can be enormous. Rain seeping into homes and buildings and attacking foundations may cause severe damage. Insufficient drainage will often lead to (local) flash floods and riverine flooding may result under extreme conditions.

In coastal areas, storm surges caused by highwinds may result in coastal flooding. The factors that combine to cause a storm surge are partially meteorological and partially hydrographic, including the state and nature of the tide and the topography of the seabed in the vicinity of the coast.

3. Hydrologic hazards - FLOODS

Flooding is defined as the accumulation of water within a water body and the overflow of excess water onto adjacent floodplain lands. The floodplain is the land adjoining the channel of a river (Fig. 3), stream, ocean, lake, or other watercourse or water body that is susceptible to flooding.

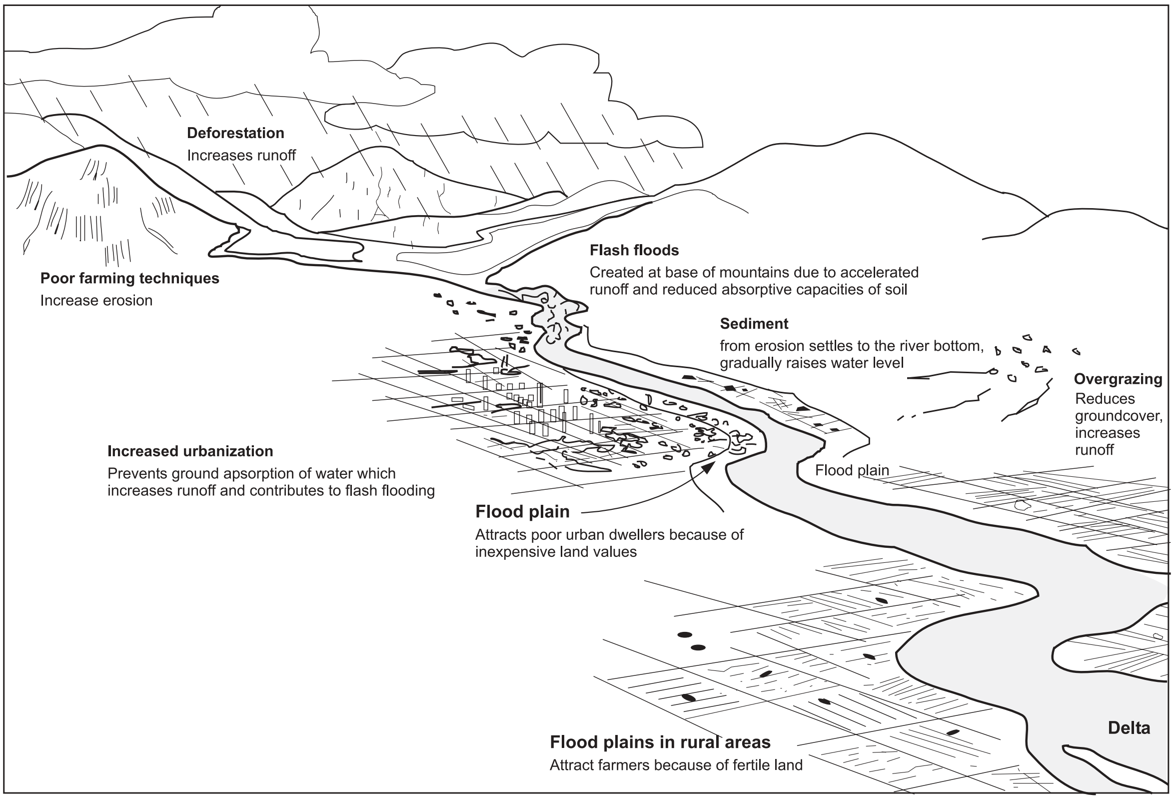


Fig. 3 **Riverine floodplain and causes of flooding**

Flooding is the most common environmental hazard. It regularly claims over 20,000 lives per year and adversely affects around 75 million people worldwide. The reason lies in the widespread geographical distribution of river flood plains and low-lying coasts, together with their long-standing attractions for human settlement.

Several types of flood hazards confront the physical planner, urban planner and emergency manager:

- riverine flooding
- fluctuating lake levels
- local drainage or high groundwater levels
- coastal flooding (or inundation) including storm surges and tsunamis

The appearance of flood hazard is dominantly limited to the prevailing weather system and geomorphological and topographical features of a given area.

Inland flooding, as distinct from coastal flooding, is generally caused by the overflow of watercourses as a result of intense rainfall or of a reduction in waterway area by landslide or debris damming (which themselves may be triggered by natural events such as earthquakes).

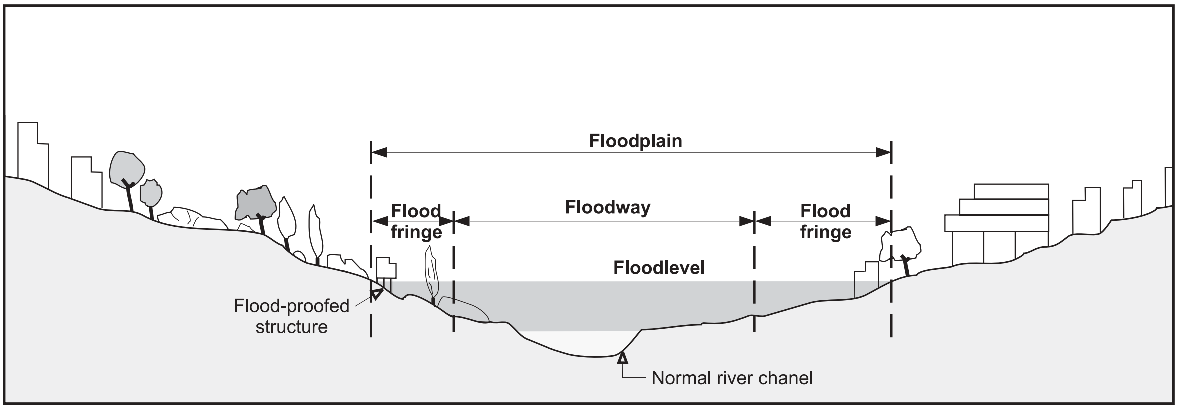


Fig. 4 **Cross section of the riverine floodplain**

Coastal flooding can, in addition, be caused by extreme winds leading to storm surges, by off-shore earthquake induced tidal waves (known as tsunamis) or the subsidence of coastal land. Human manipulation of watersheds, drainage basins, floodplains and the effects of deforestation, soil erosion, silt carriage have increased volume and speed of runoff.

3.1 Riverine flooding

Riverine flooding includes:

- overflow from river channel or river floods
- flash floods
- alluvial fan floods
- ice-jam floods
- dam-break floods

There is often no sharp distinction between river floods, flash floods, alluvial fan floods, ice-jam floods, and dam-break floods that occur due to structural failures or overtopping of embankments during flood (or other such as landsliding, rockfalling, etc.) events. Nevertheless, these types of floods are widely recognised and helpful in considering not only the range of flood risk but also appropriate emergency preparedness and responses.

In general, the river floods are caused either by rainfall of extra-tropical or frontal character, as experienced in temperate latitudes, or by large tropical atmospheric depressions with moisture-laden winds, moving from a maritime environment onto and across a land mass (for instance, seasonal monsoons in Asia and line squalls on the west coast of Africa). Rainfall in these events is generally widespread and can be heavy. The level of flooding can be high, and is influenced by topographic features.

3.1.1 River floods

Overbank flooding of rivers and streams is the most common type of flood event. River (riverine) flood plains (Fig. 3) range from narrow confined channels in the steep valleys of hilly and mountainous areas, and wide, flat areas in the plains and low-lying coastal regions. The amount of water in the floodplain is a function of the size of the contributing watershed and topographic characteristics such as watershed type and slope, and climatic and land-use characteristics.

Consequently, the magnitude and extent of a river flood depends upon the size of the catchment area of the river (contributing watershed), the topography, soil conditions and vegetation, and the weather conditions involved. Size of catchment area usually governs the character of flooding as well as the type of meteorological event, or events, which are capable of inducing extreme floods.

For instance, river flow on very large rivers (such as the Nile, the Danube or the Rhine) is relatively slow to change in the downstream reaches (Fig. 5a); floodwaters will generally be a combination of many rainfall events occurring over a wide area, sometimes augmented by melted snow. In large river basins flooding is usually seasonal and peak discharges can be reached and maintained over days or weeks.

Flooding in large rivers usually results from large-scale weather systems that generate prolonged rainfall over wide areas. These same weather systems may cause flooding in hundreds of smaller basins that drain to major rivers. Small rivers and streams are susceptible to flooding from more localized weather systems that cause intense rainfall over small areas.

The principal characteristics of river floods are their relatively slow build-up, which in river systems is usually seasonal.

However, the shape of the catchment area has a considerable effect on the peak water discharge in a river or stream (Fig. 5). The rounder the area and the more uniform routes the water takes to the point in question (Fig. 5b), the more the water tends to arrive simultaneously, increasing the possibility of an extreme flood peak (hydrograph B of Fig. 5c). As a rule, round and small catchment areas, which are commonly found in the upper reaches of rivers and in the mountains produce a quickly rising hydrograph after intense (torrential) rainfall. Thus, the flood peak at a given location is in general very pronounced.

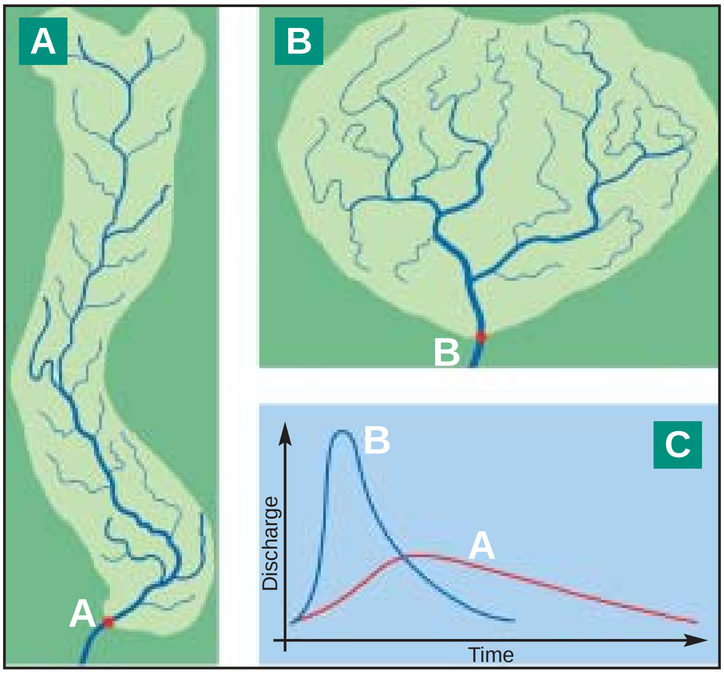


Fig. 5 **Forms of river catchments**

In longer and wider catchments the run-off is spread better over time (Fig. 5a), as is mostly encountered in flat terrains at the lower reaches of rivers. The hydrograph rises relatively slowly and then flattens out (hydrograph A of Fig. 5c). The water arrives at a given point gradually, even if rainfall is intense. The characteristics of a catchment area and its hydrograph, such as hydrograph A of Fig. 5c, can also result in the land being submerged for a long time.

However, if the rainstorm progresses over a long catchment area towards the point in question in such a manner that it adds more and more water to the flood peak, a situation can develop which is as precarious as the one seen in the hydrograph B of Fig. 5c.

3.1.2 Flash floods

“Flash flood” is a term widely used by flood experts and the general population. However, there is no single definition, and a clear means to separate flash floods from the rest of the spectrum of riverine floods does not exist. Floods of this type are particularly dangerous because of the suddenness and speed with which they occur. They develop in a basin following the occurrence of one or more previously mentioned storm types, especially if the catchment slope is conductive to acceleration of run-off rather than its attenuation.

Flash floods are events with very little time occurring between the start of the flood and the peak discharge (hydrograph B of Fig. 5c). They are often associated with a short time between the storm incidence and the arrival of the flood wave, which is not always the case; and are of short duration with relatively high peak discharge.

Flash floods are characterized by a rapid rise in water level, high velocity, and large amounts of debris. They are capable of tearing out trees, undermining buildings and bridges, and scouring new channels. Major factors in flash flooding are the intensity and duration of rainfall and the steepness of watershed and stream gradients. The amount of watershed vegetation, the natural and artificial flood storage areas, and the configuration of the streambed and floodplain are also important.

Flash floods are often associated with isolated and localised intense rainfall. In some regions, severe and destructive flash floods occur very infrequently in any one of a large number of small catchments within a given region. Efficient surveillance, warning and protection against the hazard are therefore difficult. In other regions, flash floods occur annually on the same river; warning in these cases is more a matter of timeliness. Because the warning time is invariably limited, the flash floods are now the main cause of weather-related deaths.

Flash floods may result from the failure of a dam or the sudden break-up of an ice jam. Both can cause the release of a large volume of water in a short period of time. Flash flooding in urban areas is an increasingly serious problem due to removal of vegetation, paving and replacement of ground cover by impermeable surfaces that increase runoff, and construction of drainage systems that increase the speed of runoff.

3.1.3 Alluvial fan floods

Alluvial fans are deposits of rock and soil that have eroded from mountainsides and accumulated on valley floors in a fan-shaped pattern. The deposits are narrow and steep at the head of the fan, broadening as they spread out onto the valley floor. As rain runs off steep valley walls, it gains velocity, carrying large boulders and other debris. When the debris fills channels on the fan, floodwaters spill out and cut new channels. The process is then repeated, resulting in shifting channels and combined erosion and flooding problems over a large area.

Alluvial fan floods can cause greater damage than typical riverine flooding because of the high velocity of flow, the amount of debris carried, and the broad area affected. Floodwaters typically move at velocities of 5 to 10 metres per second due to steep slopes and lack of vegetation.

Human activities often exacerbate flooding and erosion problems on alluvial fans. Roads act as drainage channels, carrying high velocity flows to lower portions of the fan, while fill, levelling, grading, and structures can alter flows patterns.

3.1.4 Ice jam floods

Flooding caused by ice jams is similar to flash flooding. Ice jam formation causes a rapid rise of water at the jam and extending upstream. Failure or release of the jam causes sudden flooding downstream.

The formation of ice jams depends on the weather and physical conditions in river channels. Ice jams are most likely to occur where the channel slope naturally decreases, where culverts freeze solid, at headwaters of reservoirs, at natural channel constructions such as bends and bridges, and long shallows where channels may freeze solid.

Ice jams floods can occur during fall freeze-up from the formation of frazil ice, during midwinter periods when stream channels freeze solid forming anchor ice, and during spring break-up when rising water levels from snowmelt or rainfall break existing ice cover into large floating masses that lodge at bridges and other constructions. Damage from ice jam flooding usually exceeds that caused by open water flooding. Flood elevations are usually higher than predicted for free-flow conditions and water levels may change rapidly. The force of ice impacting buildings and other structures can cause additional physical damage.

3.2 Dam break floods

Dam failures can occur as a result of structural failures, such as progressive erosion of an embankment or overtopping and breaching by a severe flood. Earthquakes may weaken dams. Disastrous floods caused by dam failures, although not in the category of natural hazards, have caused great loss of life and property damage, primarily due to their unexpected nature and high velocity floodwater.

3.3 Local drainage or high groundwater levels

Local heavy precipitation may produce flooding in areas other than delineated floodplains or along recognizable drainage channels. If local conditions cannot accommodate intense precipitation through a combination of infiltration and surface runoff, water may accumulate and cause flooding problems. During winter and spring, frozen ground and accumulations of snow may contribute to inadequate drainage and localized ponding. Flooding problems of this nature generally occur in areas with flat gradients, and generally increase with urbanisation which speeds the accumulation of floodwaters because of impervious areas. Shallow sheet flooding may result unless channels have been improved to account for increased flows.

High groundwater levels may be of concern and can cause problems even where there is no surface flooding. Basements are susceptible to high groundwater levels. Seasonally high groundwater is common in many areas, while in others high groundwater occurs only after long periods of above-average precipitation.

3.4 Fluctuating lake levels

Water levels in lakes can fluctuate on a short-term, seasonal basis, or on a long-term basis over periods of months or years. Heavy seasonal rainfall can cause high lake levels for short periods of time, and snowmelt can result in higher spring levels. Long-term fluctuations are a less-recognised phenomenon that can cause high water and subsequent flooding problems lasting for years or even decades.

While all lakes may experience fluctuations, water levels tend to vary the most in lakes that are completely landlocked or have inadequate outlets for maintaining a balance between inflow and outflow. These lakes, commonly referred to as closed-basin lakes, are particularly susceptible to dramatic fluctuations in water levels over long periods of time, as much as 1 to 3 metres.

Fluctuations of lake water levels over a short period of time, initiated by local atmospheric changes, tidal currents, or earthquakes, are known as *"seiches"*. These, free or standing wave oscillations of the surface of water in an enclosed basin are similar to water sloshing in a bathtub.

3.5 Coastal flooding

Devastating floods can occur as a result of extreme wind storms (typhoons, hurricanes or tropical cyclones). The Indian sub-continent (Bay of Bengal), and countries in Asia and the Pacific are all typically subject to such events. Catastrophic flooding from rainfall is often aggravated by wind-induced surge and low atmospheric pressure along a coastline

(Fig. 6), which causes a rise in sea level and inundation of coastal and inland areas. Rainfall intensities are high and the area of the storm is wide; the combination of these factors can produce extreme flood discharge in both small and large river basins, which can be maintained at high levels by a coastal discharge.

Storm surges occur when the water level of a tidally influenced body of water increases above the normal astronomical high tide. Storm surges commonly occur with coastal storms caused by massive low-pressure systems with cyclonic flows that are typical of tropical cyclones, northeasters, and severe winterstorms. Other factors influencing storm surge intensity are:

- wind velocity
- storm surge height
- coastal shape
- storm centre velocity
- nature of coast
- previous storm damage
- human activity

Storm surges generated by coastal storms are controlled by the following four factors:

- The more intense storms have higher wind speeds which drive greater amounts of water across the shallow continental shelf, thereby increasing the volume and elevation of water pushed up against the coast. In areas with mild slopes and shallow depths, the resulting flooding can reach great heights.
- The low barometric pressure experienced during coastal storms can cause the water surface to rise, increasing the height of storm surges.
- Storms landfalling during peak astronomical tides have higher surge heights and more extensive flood inundation limits.
- Coastal shoreline configurations with concave features or narrowing bays create a resonance within the area as a result of the winds forcing in water, elevating the surface of the water higher than experienced along adjacent areas of open coast.

The other causes of coastal flooding are tsunamis, the large seismic sea waves, impulsively generated by shallow-focus earthquakes.

3.6 Landscape susceptible to flood development

The most flood-susceptible landscape settings are:

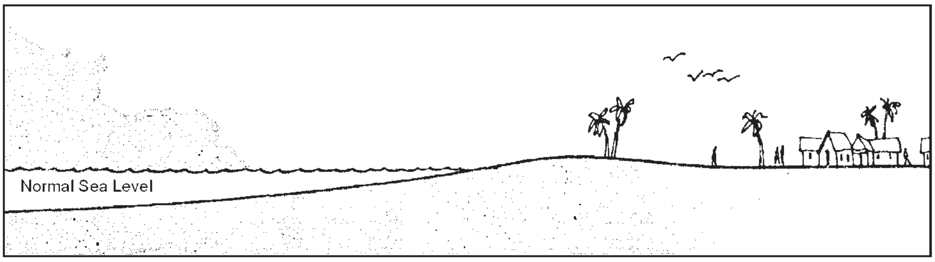
- ***Low-laying parts of active floodplains and river estuaries.*** In their natural state, these settings will suffer the most frequent inundation - coastal flooding.
- ***Low-laying inland shorelines***, that become unprotected due to erosion of barrier islands, sand dunes or bluffs, so the wind-driven wave attacks may inundate and cause damage to buildings and other immovable shoreline facilities.
- ***Small basins subjected to flash floods.*** Flash floods are formed in arid and semi-arid zones where there is a combination of steep topology, little vegetation and high intensity, short-duration connective rainstorms. They can also occur in narrow valleys and heavily developed urban settings.
- ***Alluvial fens*** can create a special type of flash flood threat, especially in semi-arid areas where the fens support urban development. The braided drainage channels can meander unpredictably across the relatively steep slopes, bringing very high velocity flows of 5-10 metres per second, which are highly

charged with sediment and produce significant hydrodynamic forces capable of destroying built structures. Velocity as low as 0.5 metres per second are capable of sweeping victims off their feet.

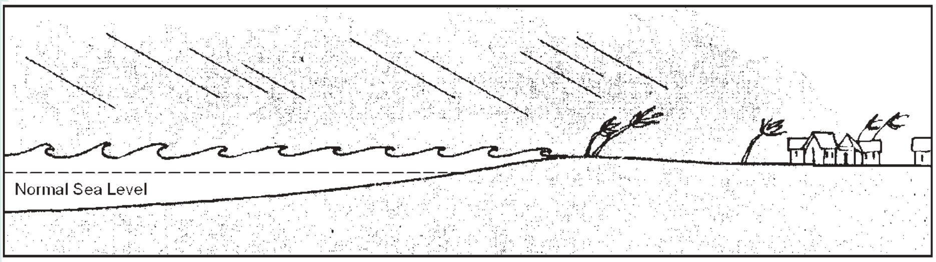
- ***Areas below unsafe or inadequate dams.*** When the foundations of the Malpasset Dam (France, 1959) failed, 421 people died. In 1963 a landslide created a major flood surge behind the Vaiont Dam (Italy). Although the structure withstood soundly, the overtopped water surge killed 3,000 people downstream. In the coal mining valley of Buffalo Creak (West Virginia, USA, 1972), 125 people were killed and 4000-5000 were made homeless when a poorly maintained dam burst.

Flood forecasting is based on seasonal patterns, capacity of the drainage basin, flood mapping, and surveys by air and land. Warnings can be issued far in advance for seasonal floods, but only shortly before onset in cases of storm surge, flash flood and tsunamis.

In its simplest form flood hazard is depicted in plan by lines that represent the areal extent of water-surface (Fig. 3). The longitudinal profiles of water-surface should also be shown (Fig. 4). Those water-surface profiles are determined both for floods of special frequency of occurrence and for historically recorded or estimated events of catastrophic magnitude. When provided with sufficient and relevant annotation, flood hazard plans serve to indicate the potential severity of inundation, thus provide relevant data for planning the organisation and resources for effective and efficient emergency response.



a) As a tropical storm forms, winds increase and atmospheric pressure drops



b) Decreased atmospheric pressure causes the sea level to rise

c) As the storm approaches land, winds pile up water to raise the sea level even higher, and the sea sweeps inland

Fig. 6 **Storm surge (coastal inundation)**

4. Geologic hazards - EARTHQUAKES

An earthquake is a phenomenon during which strong vibrations occur in the ground due to release of enormous energy within a short period of time causing sudden disturbance in the upper 15-50 km of the earth's crust.

Several phenomena may give rise to earthquakes:

- tectonic activity
- volcanic activity
- collapse of underground cave roofs
- removal or application of large loads (glaciers and/or water reservoirs)
- explosions and so on

From an engineering point of view, of far greater importance are earthquakes of tectonic origin, that is, those associated with large-scale strains in the earth's crust. It is so because of the energy the tectonic earthquake's release (Figs. 7 and 13), the frequency of their appearance, and the extent of the areas they affect (Table 6).

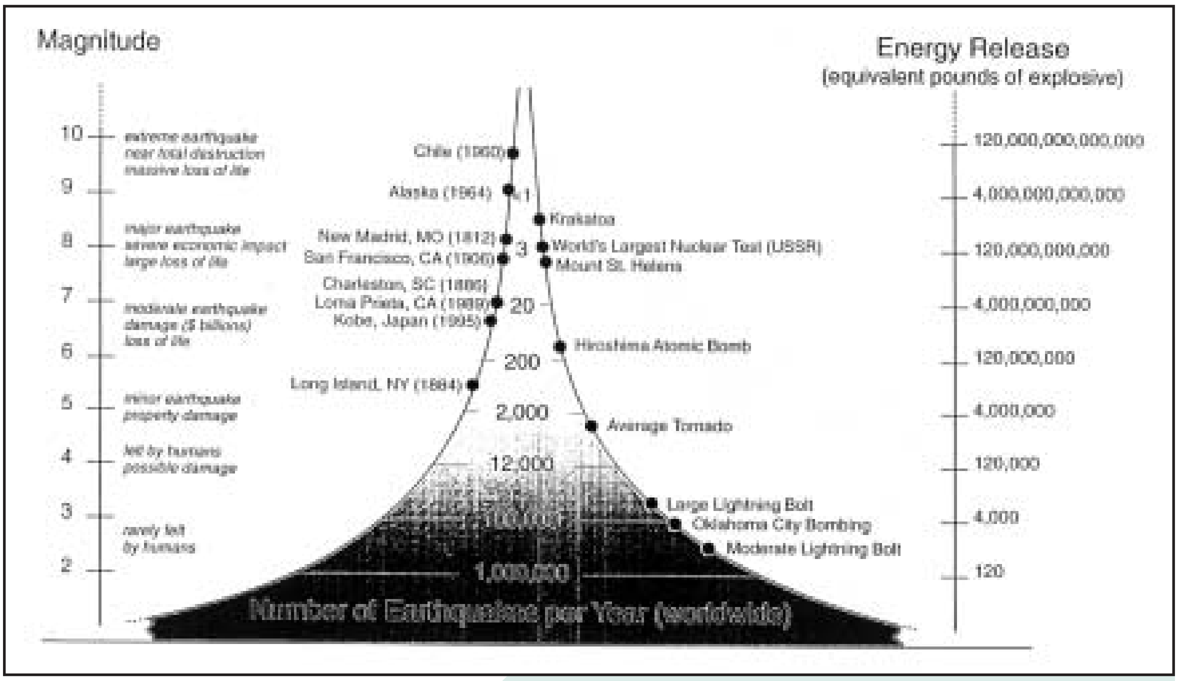


Fig. 7 **Illustration on relation between the number of earthquakes, magnitude and released energy**

4.1 Plate tectonics and earthquakes

Earthquakes can strike any location at any time. History however, shows that the world's earthquakes are not randomly distributed over the earth's surface. They tend to be concentrated in narrow zones, i.e., the zones where volcanoes and mountain ranges are concentrated, too.

An explanation is to be found in plate tectonics, a concept which combines many of the ideas about continental drift and sea-floor spreading. Plate tectonics explain the general mechanism of earthquakes generation assuming that the earth's rigid outer shell (lithosphere) is broken into a mosaic of oceanic and continental plates (Fig. 9), which slide over the uppermost plastic layer of the mantle (aesthenosphere). The plates are in constant motion. Where they interact, along their margins, important geological processes take place, such as the formation of mountain belts, earthquakes, and volcanoes.

There are seven major crustal plates, subdivided into a number of smaller plates. They are about 80 kilometres thick, all in constant motion relative to one another, at drifting rates varying from 10 to 130 millimetres per year. Their pattern is neither symmetrical nor simple.

Table 6 **Annual number of earthquakes** /Shah, 1984/

Description	Richter magnitude	Average number of earthquakes per year for the world	Duration of strong ground shaking (seconds)	Radius of region subjected to strong ground shaking (kilometres)
Great	8.0 to 8.9	1	30 to 90	80 to 160
Major	7.0 to 7.9	15	20 to 50	50 to 120
Strong	6.0 to 6.9	140	10 to 30	20 to 80
Moderate	5.0 to 5.9	900	2 to 15	5 to 30
Light	4.0 to 4.9	8,000*	0 to 5	0 to 15
Minor	3.0 to 3.9	49,000*		

(*) estimated

4.1.1 Types of seismic zones

At oceanic rifts the lithosphere moves apart at velocities of up to 18 cm per year. This lithosphere is consumed at subduction zones where it dives under other plates causing earthquakes during the process. Continents, ridging along on the lithosphere, may collide with others giving rise to shear or compressional forces and to earthquakes.

Considering the aforestated processes, plate tectonics recognise four types of seismic zones (Fig. 8) of distinct seismic patterns.

The ***spreading zone*** (divergent or constructive plate boundary, Fig. 8b) follows the line of ***midocean ridges***. It is characterised by low seismicity occurring at very shallow depths. At these zones the lithosphere is very thin and weak, so the strain cannot build up enough to cause large earthquakes. Associated with this type of seismicity is the volcanic activity along the axis of the ridges (for example, Iceland, Azores, Tristan da Cunha, etc.).

The ***subduction zone*** (convergent or destructive plate boundary, Fig. 8c) is related to the ***collision of oceanic and continental plates***. One plate is thrust or subducted under the other plate so that a deep ocean trench is produced. This type of earthquake can be shallow, intermediate, or deep, according to its location on the downgoing lithospheric slab. Such inclined planes of earthquakes are known as Benioff zones.

The ***shallow-focus earthquake*** zone unaccompanied by volcanic activity is the third type of seismic zone associated with plate tectonics. The San Andreas fault (Fig. 10) is a good example of this, so is the Anatolian fault in Northern Turkey. In these faults, two mature plates are scraping by one another. The friction between the plates can be so great that very large strains can build up before large earthquakes periodically relieve them. Activity does not always occur along the entire length of the fault during any one earthquake.

The fourth type of seismic zone occurs along the ***boundaries of continental plates***. Typical of this is the broad swath of seismicity from Burma to the Mediterranean, crossing the Himalayas, Iran, Turkey, to Gibraltar. Within this zone, shallow earthquakes are associated with high mountain ranges where intense compression is taking place. Intermediate- and deep-focus earthquakes also occur and are known in the Himalayas and in the Caucasus. The interiors of continental plates are very complex, much more so than island

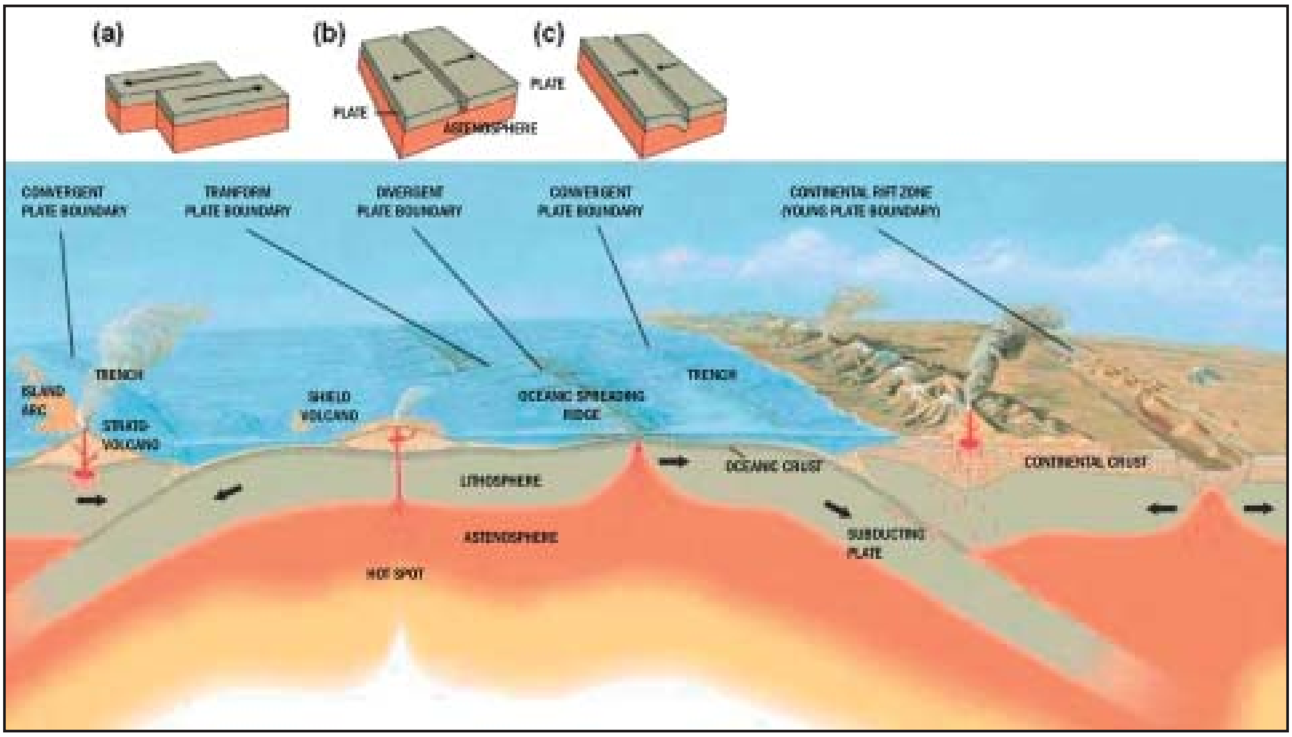


Fig. 8 **Plate boundaries /a) Transform; b) Divergent; and, c) Convergent/**

Fig. 9 **Map indicating the main tectonic plates and their predominant direction of movement**

arcs. For instance, the full relationship of the Alps or the East African rift system to the broad picture of plate tectonics is not yet known.

4.1.2 Earthquake geography

The understanding of plate tectonics can help in earthquake prediction. It is known that earthquakes occur at the following three kinds of plate boundary:

- ocean ridges where the plates are pulled apart (divergent boundary, Fig. 8b)
- margins where the plates scrape past one another
- margins where one plate is thrust under the other (convergent boundary, Fig. 8c)

Consequently, it is possible to predict the general regions on the earth's surface (Fig. 9) where large earthquakes in the future can be expected. In fact, it is known that each year about 140 earthquakes of magnitude 6 or greater (Table 6) are occurring within this area that is about 10 per cent of the earth's surface.

The world's greatest earthquake belt, ***the circum-Pacific seismic belt***, is found along the rim of the Pacific Ocean, where about 81 percent of the world's largest earthquakes occur. The belt extends from Chile, northward along the South American coast through Central America, Mexico, the west coast of the United States, and the southern part of Alaska, through the Aleutian Islands to Japan, the Philippine Islands, New Guinea, the island groups of the Southwest Pacific, and to New Zealand. So many earthquakes originate in this belt because it is a region of young growing mountains and deep ocean trenches which invariably parallel mountain chains. Earthquakes necessarily accompany elevation changes in mountains, the higher part of the earth's crust, and changes in the ocean trenches, the lower part.

The second important belt, ***the Alpide***, extends from Java to Sumatra, through the Himalayas, the Mediterranean, and out into the Atlantic. This belt accounts for about 17 percent of the world's largest earthquakes, including some of the most destructive earthquake shocks

The third prominent belt follows the submerged ***mid-Atlantic Ridge***. The remaining shocks are scattered in various areas of the world.

Earthquakes in these prominent seismic zones are taken for granted, but damaging shocks also occur occasionally outside these areas.

4.1.3 Earthquake time sequence

Strong earthquakes usually do not end with one tremor. The magnitude is gradually reduced, but a number of further quakes normally occur. The first and the most severe earthquake in a sequence is called the ***main shock***. The earthquakes following the mainshock are called ***aftershocks***. The aftershock activity may last for months, even the years. Before a main shock, mild earthquakes sometimes occur as a precursor. These earthquakes are called ***foreshocks***. The hypocentres of aftershocks do not generally coincide with that of the main shock; the latter usually being located at the edge of the focus areas of the aftershocks.

The energy of the main shock is considerably larger than that of the foreshocks or aftershocks, and it is thought that the extent of the region in which the aftershocks occur in the early stage indicates the range in which the energy causing the main shock was stored.

Foreshocks, main shocks, and aftershocks are phenomena associated with a series of fractures in the earth's crust or mantle, and characteristics of the earthquake tremor change with the progress of the fracturing.

For example, the Montenegro (SR. Yugoslavia) earthquake of April 15, 1979 (M=7.2, I_o = IX° MCS) was preceded by strong foreshock (M=5.4, I_o= VII° MCS) at April 9, 1979. The sequence of aftershocks lasted for a few years, out of which the strongest one (M=6.4, I_o = IX° MCS) took a place on 24 May, 1979.

However, many strong earthquakes are not preceded by foreshocks, but indispensably they are followed by aftershock activity during the process of relaxation of accumulated strains in the region.

4.2 Faulting

Tectonic earthquakes are caused by sudden movements along a zone where the accumulated tectonic stresses exceed the strength of the rock and the rock breaks along the pre-existing or new fracture plane. Once a weak zone is overloaded, the lithosphere breaks. The earth's crust will be torn and one part of it will be displaced relative to the other. If such a failure leaves a trace on the surface, it is called ***faulting***.

For earthquakes below Magnitude 6 it is not common to be accompanied with noticeable faulting, even if they happen at a shallow depth.

The faults are geometrically characterised by several elements (Fig. 11a):

- footwall
- hanging wall
- fault line
- dipping angle

The movement of fault walls (wings) along the fault plane defines the type of the fault, for example:

➠ A ***normal fault*** (Fig. 11b) is one where the hanging wall is displaced downwards with respect to the footwall

➠ A ***reverse fault*** (Fig. 11c) is one where the hanging wall has moved up with respect to the footwall. It is also called a ***thrust fault***

➠ A ***strike slip*** fault is the one in which one wall moves laterally with respect to the other wall. Fig. 11d illustrate a left lateral displacement [fault] because the side opposite to an observer moves, or rather seems to move, to the left

➠ The ***left lateral*** (or oblique) ***normal fault*** (Fig. 11e), as well as the ***right lateral*** (or oblique) ***normal fault*** are the result of combined downward movement of the hanging wall and apparent lateral movement in a left or right direction, respectively

➠ The ***left lateral*** (or oblique) ***reverse fault*** (Fig. 11f), as well as the ***right lateral*** (or oblique) ***reverse fault*** are the result of combined upward movement of the hanging wall and apparent lateral movement in a left or right direction, respectively

Fig. 10 **San Andreas fault system, California, USA**
/This fault and the others in the region exhibit lateral displacement/

A strike-slip faulting mechanism generally produces the narrowest zone of faulting. Shear failures over a zone 1 to 2 kilometres wide may be found.

Normal faulting may cover a substantially wider zone, that is, 5 kilometres and more if the dip angle of the fault plane is small.

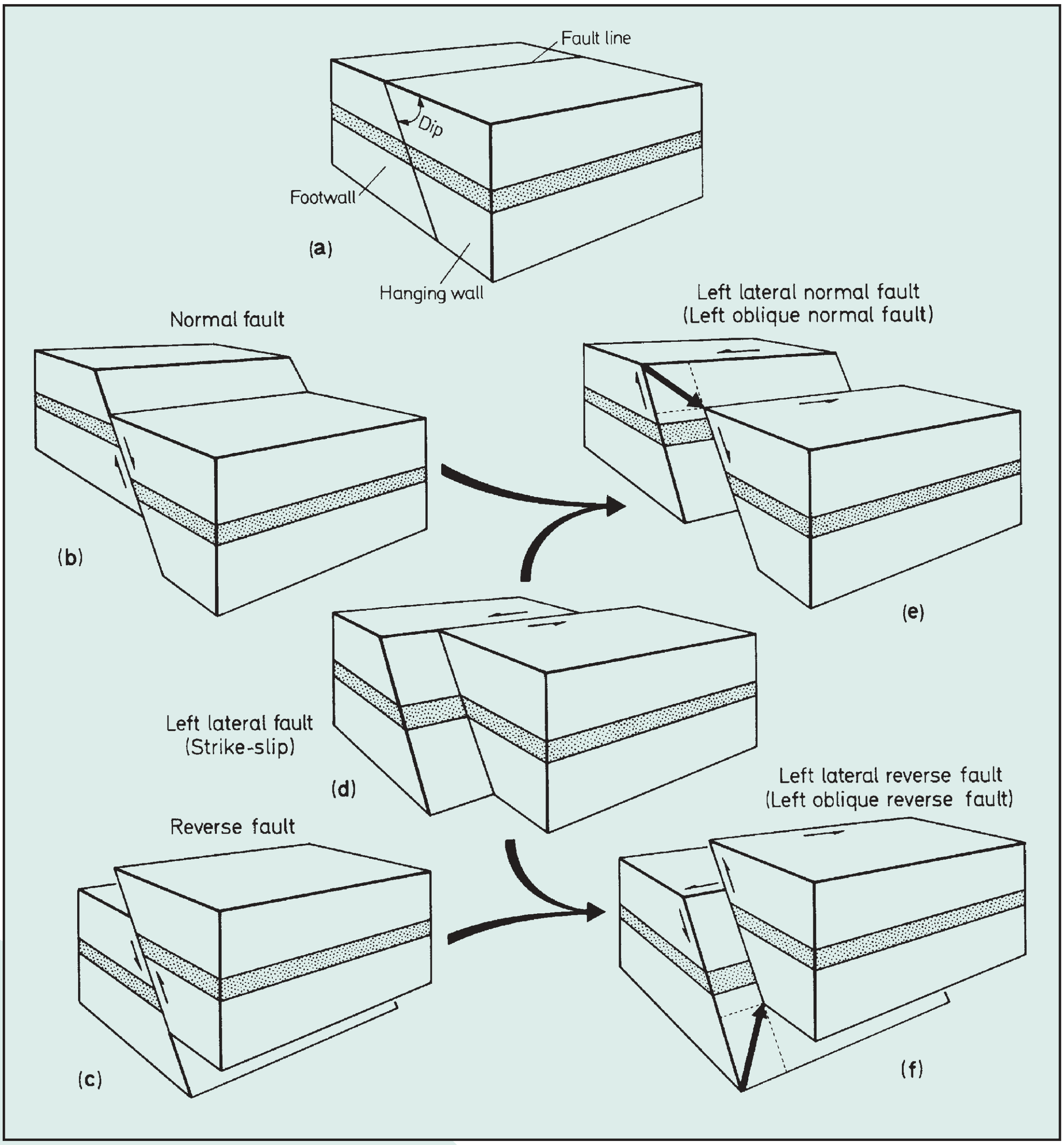


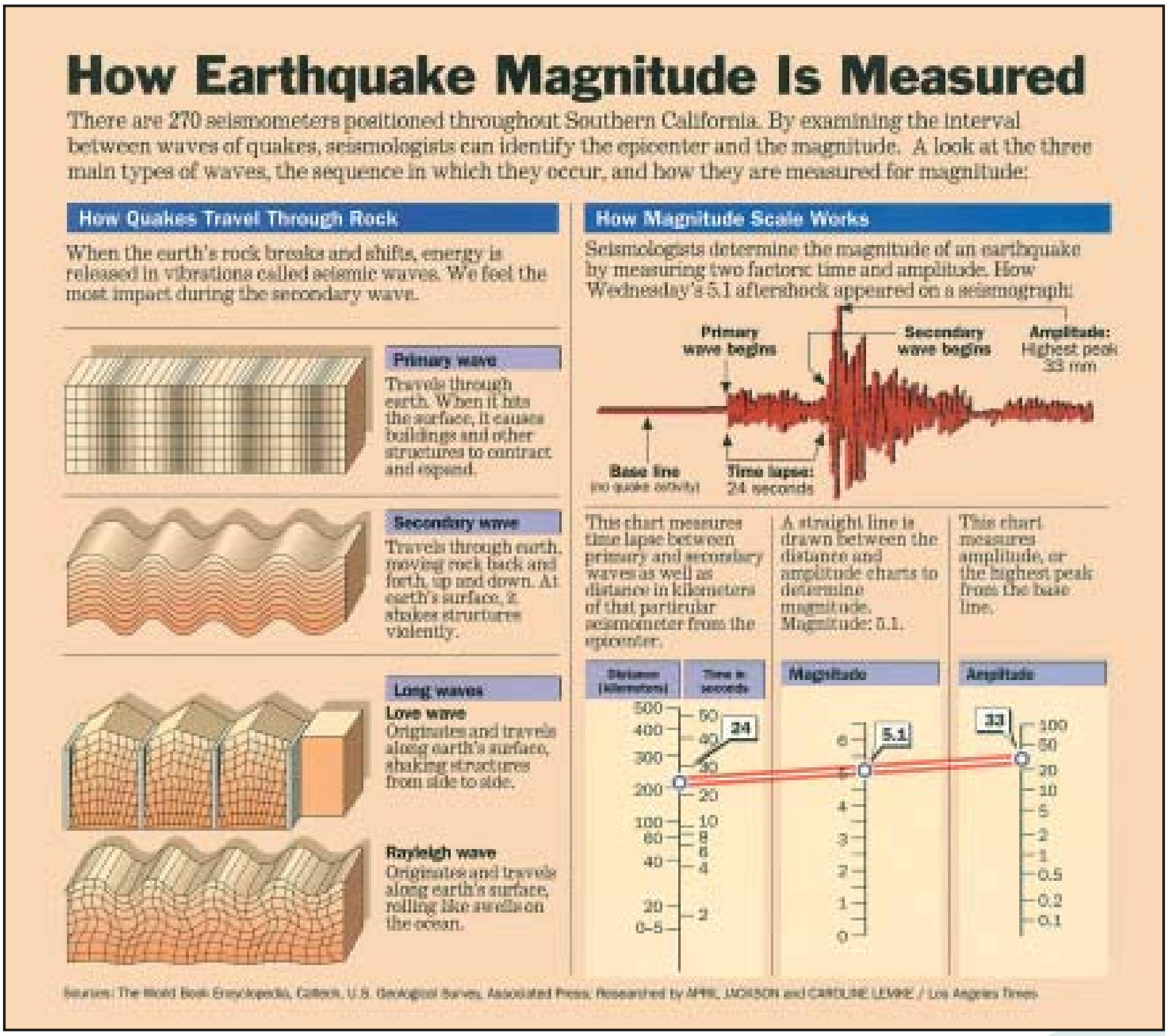
Fig. 11 **Diagrammatic sketches of fault types: a) names of components, b) normal fault, c) reverse fault, d) left-lateral strike-slip fault, e) left-lateral normal fault, f) left-lateral reverse fault. (Source: Geology, November 1971)**

4.3 Seismic waves

The sudden rupture releases the stored strain energy producing seismic waves that radiate outwards in ever-widening spheres around the fault.

The fastest are primary (or P, Fig. 12) waves, also called ***compressional (or longitudinal) waves***, which are compression-dilatation waves and travel through the crust's crystalline rock with a speed of about 5-8 km per second. The vibration generated by this wave follows the direction in which the wave travels.

The secondary (or S, Fig. 12) waves, so called ***shear (or transverse) waves*****,** are slower and travel through the earth's crust at about half the speed of the primary waves and cause vibration at angles perpendicular to the direction of wave travel (propagation).



How Earthquake Magnitude Is Measured

There are 270 seismometers positioned throughout Southern California. By examining the interval between waves of quakes, seismologists can identify the epicenter and the magnitude. A look at the three main types of waves, the sequence in which they occur, and how they are measured for magnitude:

How Quakes Travel Through Rock

When the earth's rock breaks and shifts, energy is released in vibrations called seismic waves. We feel the most impact during the secondary wave.

Primary wave

Travels through earth. When it hits the surface, it causes buildings and other structures to contract and expand.

Secondary wave

Travels through earth, moving rock back and forth, up and down. At earth's surface, it shakes structures violently.

Long waves

Love wave

Originates and travels along earth's surface, shaking structures from side to side.

Rayleigh wave

Originates and travels along earth's surface, rolling like swells on the ocean.

How Magnitude Scale Works

Seismologists determine the magnitude of an earthquake by measuring two factors: time and amplitude. How Wednesday's 5.1 aftershock appeared on a seismograph:

This chart measures time lapse between primary and secondary waves as well as distance in kilometers of that particular seismometer from the epicenter.

A straight line is drawn between the distance and amplitude charts to determine magnitude. Magnitude: 5.1.

This chart measures amplitude, or the highest peak from the base line.

Sources: The World Book Encyclopedia, Caltech, U.S. Geological Survey, Associated Press; Researched by APRIL JACKSON and CAROLINE LEMKE / Los Angeles Times

Fig. 12 **Type of seismic waves and determination of the earthquake magnitude**

/source: Images of the 1994 Los Angeles earthquake/

The slowest waves are ***surface waves*** (Fig. 12), called ***Raleigh*** and ***Love*** waves. They do not possess vertical motion but shake the ground horizontally at angles perpendicular to the direction of propagation. Love waves usually travel faster than the Raleigh waves. They travel near the surface of the earth with a speed of less than 3 km per second.

Surface waves are caused by the transformation of P and S waves emitted from the hypocentre. They do not exist in the epicentre region, occurring farther from the epicentre, at minimum distances of 0.65h (surface wave emerged from P wave) and 2.25h (surface wave emerged from S wave), where ***h*** denotes hypocentral (focal) depth (Fig. 14).

Consequently, in the epicentral region only P and S waves exist. Their direct arrival is characterised with strong vertical trembling (P wave) followed by the intense horizontal shaking (S wave) of low-rise buildings. This is a typical appearance and a way to recognise local and/or close earthquakes.

P and S waves attenuate fast. So, at certain distances from the epicentre humans cannot feel their arrival. However, the attenuation of surface waves with distance is slower. Their arrival is characterised by the horizontal shaking of tall buildings which, depending on the scale of the earthquake may range from disturbing up to violent and damaging.

This absence of vertical vibrations, but only recognisable horizontal shaking of tall buildings, is a typical characteristic of distant earthquakes. Low-rise buildings usually do not

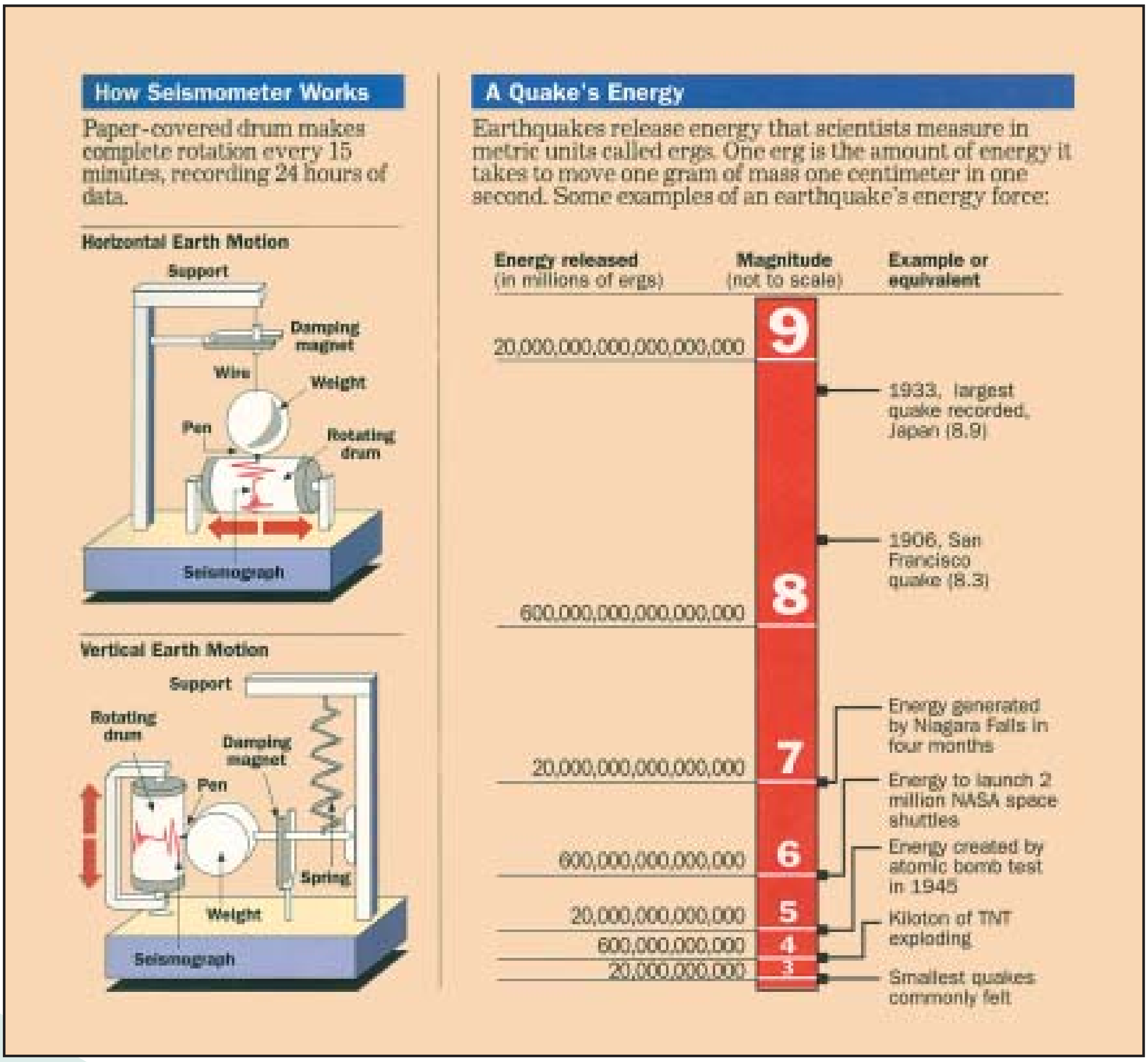


Fig. 13 **Illustration of the seismograph and examples of an earthquake's energy force**

/source: Images of the 1994 Los Angeles earthquake/

respond significantly to surface waves. Thus, it would not be surprising if part of the population were aware that a distant earthquake took a place (residents of high-rise buildings), whereas the others did not (residents of low-rise buildings).

4.4 Earthquake parameters

4.4.1 Measuring earthquakes

Vibrations produced by earthquakes are detected, recorded and measured by instruments called ***seismographs*** (Fig. 13). The zigzag trace recorded by a seismograph - called a ***seismogram*** (Fig. 12) - reflects the varying amplitude of the vibrations by responding to the motion of the ground beneath the instrument. From the data expressed in seismograms, the time, epicentre, and focal depth of an earthquake can be determined, and estimates can be made of the amount of energy that was released.

The severity of an earthquake can be expressed in several ways. Seismology principally recognises the following two parameters:

- earthquake magnitude
- earthquake intensity

4.4.2 Earthquake focus (hypocentre), focal depth and hypocentral distance

The focus (or hypocentre, Fig. 14) of an earthquake is an instrumentally located point below the earth's surface at which an earthquake originates.

Focal depth (Fig. 14) is the depth of the focus below the earth's surface. In general, earthquakes within 70 km of the surface are called shallow, those from 70 to 300 km intermediate, and those beyond 300 km deep. The limit of hypocentre depth is considered to be 700 km.

The distance between any location on the earth's surface and the earthquake focus (hypocentre) is called focal or hypocentral distance.

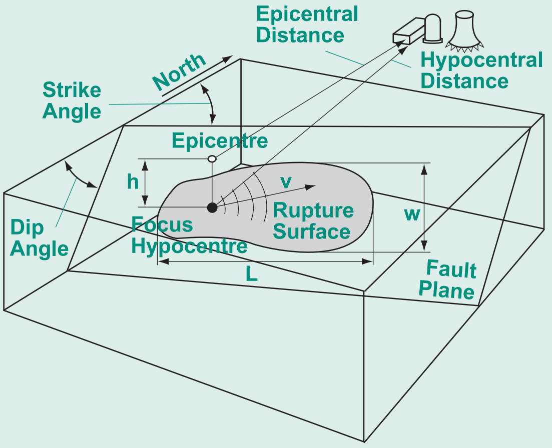
4.4.3 Earthquake epicentre and epicentral distance

The vertical projection of the earthquake focus on the earth's surface is termed the epicentre (Fig. 14). Since the earthquake focus can be an extended volume of any irregular size and shape, the projected surface region will not be a point, but a region. Consequently, the epicentre is the centre of this region. Irrespectively of this, the epicentre is always defined as a point on the earth's surface with its geographical location given in terms of latitude and longitude.

The term epicentre that is commonly used in today's written and electronic media refers to so called "instrumental epicentre", that is, the epicentre determined analytically from instrumental readings of at least three appropriately sited seismological observatories.

The region receiving the maximum earthquake impact is termed macroseismic epicentre. It can be determined based on detail post-earthquake damage surveys, syntheses and analysis of field data.

The distance between any location on the earth's surface and the epicentre is called epicentral distance (Fig. 14).



The rupture begins at the hypocenter or focus, which is h kilometers below the epicenter on the ground surface. From the hypocenter the rupture spreads at a velocity V, until it stops after involving an area of the length L and width W. The offset between the two sides of the fault may have some orientation in the fault plane. The angular deviation of the fault plane from north is the strike angle; the dip angle defines its inclination with respect to the horizontal ground surface. The distance from the element at risk is given with reference either to the epicenter (epicentral distance) or the hypocenter (hypocentral distance). In the first case the depth has to be considered, and it is evident that a relatively small strike angle would bring the energy release much closer to the elements at risk shown in the illustration. Energy radiation patterns must, however, also be allowed for.

Fig. 14 **Simple model of an earthquake source which contains the variables necessary to describe most earthquakes.**

4.4.4 Earthquake magnitude

Earthquake magnitude (M) is a measure of the strength of an earthquake, or of the strain energy released by it. It is calculated from the instrumental records (seismograms, Fig. 12) obtained from the event on a calibrated instrument called a seismograph (Fig. 13).

Earthquake magnitude is, thus, a parameter related to the size of an earthquake and is determined on the basis of the real measurements of generated ground motion amplitudes.

The volumes of the spheres are roughly proportional to the amount of energy released by earthquakes of the Richter magnitude given, and illustrate the exponential relationship between magnitude and energy. At the same scale the magnitude 7 earthquake would be represented by a sphere with a radius 1,000 times larger than that corresponding to M = 1, or 100 times than that corresponding to M = 3.

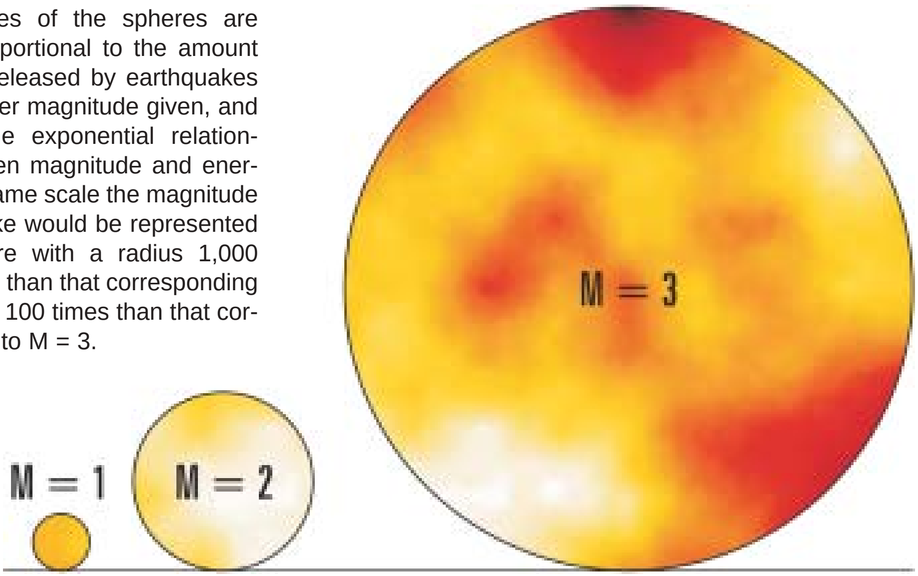


Fig. 15 **Illustration of the relation between earthquake magnitude and energy**

Magnitude (M), as a parameter, is so defined and determined that it is a measure of energy released in the earthquake hypocentre and it does not depend on the distance from the epicentre. The magnitude permits comparison of sizes of various earthquakes. It is always expressed in digits, or tenths of digits, but never in Roman numerals.

Since 1930, when seismologist C.F. Richter first defined local magnitude [1] (M_L), more than a half dozen different magnitude scales have been devised to measure earthquake magnitude. These magnitude definitions are related to the type of seismic waves they are obtained from, that is, 1) the surface wave magnitude (Ms) is based on the amplitude of surface waves with period of 20 s; 2) the body wave magnitude (m_b) is based on the amplitude of body waves (longitudinal or primary and transversal /shear/ or secondary) with periods usually from 1-10 s.

Large earthquakes with a great rupture length are not well represented by M_L scale. The reason is that seismic waves used to measure large earthquakes come primarily from only a small part of the fault rupture and do not accurately represent the total energy release in the event. Consequently, for events with $M_L > 6.5$, nowadays the moment magnitude scale (denoted by M_W) is used. It is based on the surface area of the fault displaced, it's average length of movement [in a event] and the rigidity of the ground material, rather than on a seismogram trace. One difference between the original Richter definition of the magnitude (M_L) and the moment magnitude (M_W) is that, whilst no earthquake of M_L larger or equal to 9 has ever been recorded, several of the largest events have exceeded $M_W \geq 9$ status. This is why the moment magnitude scale is usually referred as *'open ended'*.

For magnitude increase by one degree (Fig. 15), say from 4 to 5, or 5 to 6, the total energy released increases by 31.6 times. Compared to the energy released by $M_L = 5$ earthquake, a $M_L = 7$ event releases about 1,000 times more energy and a $M_L = 8$ event over 30,000 times larger energy. For M_L increase by just 0.2, the energy released is doubled.

The earthquake energy release and earthquake magnitude alone is a poor guide to the scale of hazard impact, because the magnitude concept does not account for the duration of ground shaking, neither for the siting parameters (distance from the earthquake epicentre to the damage area, local soil conditions, population density, the nature of building construction, etc.). It must be understood that earthquake magnitude is not, strictly speaking, an adequate planning or mitigation tool, unless a magnitude-intensity relation is developed for a particular area or region.

Table 7 The Medvedev-Sponheuer-Karnik Scale (MSK) of 1964

1. Types of Structures (Buildings)

A	Buildings in fieldstone, rural structures, adobe houses, clay houses
B	Ordinary brick buildings, buildings of the large block and prefabricated type, half-timbered structures, buildings in natural hewn stone
C	Reinforced buildings, well-built wooden structures

2. Definition of Quantity

Single, few: about 5 per cent
Many: about 50 per cent
Most: about 75 per cent

3. Arrangement of the Scale

(a) Persons and surroundings
(b) Structures of all kinds
(c) Nature

4. Classification of Damage to Buildings

Grade 1: *Slight damage*
Fine cracks in plaster; falls of small pieces of plaster

Grade 2: *Moderate damage*
Small cracks in walls; falls of fairly large pieces of plaster; pantiles slip off; cracks in chimneys; parts of chimneys fall down

Grade 3: *Heavy damage*
Large cracks in walls; falls of chimneys

Grade 4: *Destruction*
Gaps in walls; parts of buildings may collapse; separate parts of buildings lose their cohesion; inner walls collapse

Grade 5: Total damage
Total collapse of buildings

INTENSITY GRADES (I) AND DESCRIPTION

I Not noticeable

The intensity of the vibrations is below the limit of sensibility; the tremor is detected and recorded by seismographs only.

II Scarcely noticeable (very slight)

Vibration is felt only by individual people at rest in houses, especially on upper floors of buildings.

III Weak, partially observed only

The earthquake is felt indoors by a few people, outdoors only in favorable circumstances. The vibration is like that due to the passing of a light truck. Attentive observers notice a slight swinging of hanging objects.

IV Largely observed

The earthquake is felt indoors by a few people, outdoors by few. The vibration is like that due to the passing of a heavily loaded truck. Windows, doors and dishes rattle. Floors and walls creak. Furniture begins to shake. Hanging objects swing slightly. Liquids in open vessels are slightly disturbed. In standing motorcars the shock is noticeable.

V Awakening

(a) The earthquake is felt indoors by all, outdoors by many. A few run outdoors. Animals become uneasy. Buildings tremble throughout. Hanging objects swing. Pictures knock against walls or swing out of place. Occasionally pendulum clocks stop. Unstable objects may be overturned or shifted. Doors and windows are thrust open. Liquids spill in small amounts from well-filled open containers. The sensation of vibration is like that due to a heavy object falling inside the building.

(b) Slight waves on standing water; sometimes change in flow of springs.

VI Frightening

(a) Felt by most indoors and outdoors. Many people in buildings are frightened and run outdoors. A few persons lose their balance. Domestic animals run out of their stalls. In many instances dishes and glassware may break, books fall down, pictures move, and unstable objects overturn. Heavy furniture may possibly move and small steeple bells may ring.

(b) Damage of grade 1 is sustained in single buildings of type B and many of type A. Damage in some buildings of type A is of grade 2.

(c) Cracks of width up to 1cm possible in wet ground; in mountains occasional landslips; change in flow of springs and in level of well-water.

VII Damage to the buildings

(a) Most people are frightened and run outdoors. Many find it difficult to stand. Persons driving motorcars notice the vibration. Large bells ring.

(b) In many buildings of type C, damage of grade 1 is caused; in buildings of type B, damage is of grade 2. Most buildings of type A suffer damage of grade 3, some of grade 4. In single instances landslips of roadway on steep slopes; cracks in roads; seams of pipelines damaged; cracks in stonewalls.

(c) Waves are formed on water, and water is made turbid by mud stirred up. Water levels in wells change, and the flow of springs changes. Sometimes dry springs have their flow restored and existing springs stop flowing. In isolated instances parts of sandy or gravely bank slip off.

VIII Destruction of buildings

(a) Fright and panic; also persons driving motorcars are disturbed. Here and there branches of trees break off. Even heavy furniture moves and partially overturns. Hanging lamps are in part damaged.

(b) Most buildings of type C suffer damage of grade 2. Most buildings of type B suffer damage of grade 3, and most buildings of type A suffer damage of grade 4, here and there of grade 5. Occasional breakage of pipe seams. Memorials and monuments move and twist. Tombstones overturn. Stonewalls collapse.

(c) Small landslips in hollows and on banked roads on steep slopes; cracks in ground up to widths of several centimeters. Water in lakes becomes turbid. New reservoirs come in existence. Dry wells refill and existing wells become dry. In many cases change in flow and level of water.

IX General damage to buildings

(a) General panic; considerable damage to furniture. Animals run to and from in confusion.

(b) Many buildings of type C suffer damage of grade 3, some of grade 4. Many buildings of type B show damage of grade 4, a few of grade 5. Monuments and columns fall. Considerable damage to reservoirs; underground pipes partially broken. In individual cases railway lines are bent and roadways damaged.

(c) On flat land overflow of water, sand, and mud is often observed. Ground cracks to widths of up to 10 cm, on slopes and riverbanks more than 10 cm; falls of rock, many landslides and earth flows, large waves on water. Dry wells renew their flow and existing wells dry up.

X General destruction of buildings

(a) Many buildings of type C suffer damage of grade 4, some of grade 5. Many buildings of type B show damage of grade 5, most of type A have destruction category 5; critical damage to dams and dikes and severe damage to bridges. Railway lines are bent slightly. Underground pipes are broken or bent. Road paving and asphalt show waves.

(b) In ground cracks up to widths of several decimetres, sometimes up to 1 meter. Parallel to watercourses broad fissures occur. Loose ground slides from steep slopes. From riverbanks and steep coasts considerable landslides are possible. In coastal areas displacement of sand and mud; change of water level in wells; water from canals, lakes, rivers, etc., thrown on land. New lakes are formed.

XI Destruction

(a) Severe damage even to well-built buildings, bridges, water dams, and railway lines; highways become useless; underground pipes destroyed.

(b) Ground considerably distorted by broad cracks and fissures, as well as by movement in horizontal and vertical directions; numerous landslips and falls of rock.

XII Landscape Changes

(a) Practically all structures above and below ground are greatly damaged or destroyed.

(b) The surface of the ground is radically changed. Considerable ground cracks with extensive vertical and horizontal movements can be observed. Falls of rock and slumping of riverbanks over wide areas; lakes are dammed in; waterfalls appear, and rivers are deflected. The intensity of the earthquake requires to be thoroughly investigated.

4.4.5 Earthquake intensity

Earthquake intensity (I) is a measure of the effects of an earthquake at a particular place. It is a measure of ground shaking that correlates more directly with hazard impacts. Intensity is determined from subjective [human] observations of an earthquake's effects on people, the behaviour of hanging objects, damage of structures and the earth's surface. In other words, intensity is a parameter that appears as a measure of earthquake destructiveness.

M.S. DeRossi (Italy) and F.G. Forel (Switzerland) developed the first widely used intensity scale in Europe (1883). The Rossi-Forel scale grouped earthquake effects into 10 intensity grades, beginning with 1 for the least noticeable. In 1902, G. Mercalli introduced an improved Scale which also had 10 grade of intensity (later increased to 12).

Two intensity scales are used today: 1) the Medvedev-Sponheuer-Karnik Scale of 1964, known as the MSK scale, and 2) the Modified Mercalli scale symbolized as MM (short version of 1931). The MSK scale (Table 7), which is much more elaborate and explicit than MM, is used predominantly in eastern European countries. It was also used in former Yugoslavia. The MM scale (Table 8) is used in USA and certain western countries of Europe.

Intensity ratings are expressed as roman numerals between *I* at the low end and *XII* at the high end.

The Intensity Scale differs from the Richter Magnitude Scale in that the effects of any one earthquake vary greatly from place to place. Depending on the epicentral distance there may be many intensity values (for example: IV, V, VI, VII) measured from one earthquake. Each earthquake, on the other hand, should have just one magnitude, although the several methods of estimating it will yield slightly different values (e.g.: 6.1, 6.3).

4.4.6 Comparison of magnitude and intensity

It is difficult to compare magnitude and intensity because intensity is linked with the particular ground and structural conditions of a given area, as well as distance from the earthquake epicentre, while magnitude is a measure of the energy released at the focus of the earthquake.

Table 9 **Approximate comparison of magnitude and intensity** /C.F. Richter, 1958/

Richter magnitude	Expected Modified Mercalli Maximum Intensity (at epicentre)	
2	I - II	Usually detected only by instruments
3	III	Felt indoors
4	V	Felt by most people; slight damage
5	VI - VII	Felt by all; many frightened and run outdoors; damage minor to moderate
6	VII - VIII	Everybody runs outdoors; damage moderate to major
7	IX - X	Major damage
8	X - XII	Total and major damage

Table 8 **The Modified Mercalli Scale (MM) of 1931**

INTENSITY GRADES (I) AND DESCRIPTION

I	Not felt except by a very few persons under especially favourable circumstances	**VII**	Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; some chimneys broken. Noticed by persons driving motorcars.
II	Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.	**VIII**	Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Disturbs persons driving motorcars.
III	Felt noticeably indoors, especially on upper floors of buildings, but many people do not recognise it as an earthquake. Standing motorcars may rock slightly. Vibration like passing of a truck. Duration estimated.	**IX**	Damage considerable in specially designed structures; well-designed frame structures thrown out of the plumb; damage great in substandard buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.
IV	During the day felt by many, felt outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls make creaking sound. Sensation like heavy truck striking building. Standing motorcars rocked noticeably.	**X**	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Railway lines bent. Landslides considerable from riverbanks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks.
V	Felt by nearly everyone; many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles and other tall objects sometimes noticed. Pendulum clocks may stop.	**XI**	Few, if any (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Railway lines bent greatly.
VI	Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.	**XII**	Total damage. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown into the air.

4.5 Primary and secondary earthquake hazards

When an earthquake occurs, it does not involve merely shaking of the earth, but is accompanied by various other phenomena. The different phenomena give rise to a variety of earthquake hazards and impacts. Generally two principal earthquake hazard groups are distinguished (Fig. 16):

- primary
- secondary

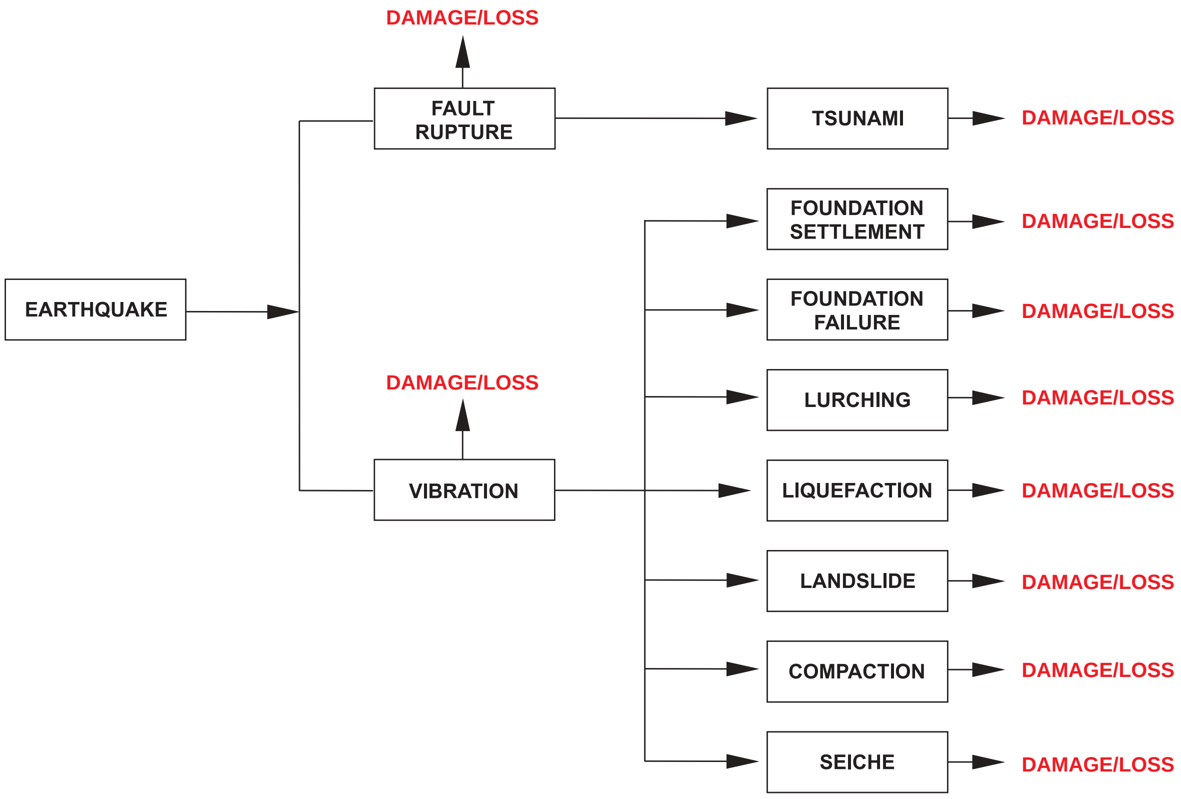


Fig. 16 **Schematic illustration of the primary and secondary hazards caused by an earthquake causing damages and losses**

The primary hazards are:

- ground shaking or vibration
- surface faulting
- terrestrial (tectonic uplift or subsidence) deformations

The principal secondary hazards include:

- soil liquefaction
- land and mudslides
- ground subsidence and collapse
- snow and ice avalanches
- tsunamis and seiches
- submarine avalanches; etc.

Some author treats the ground motion amplification as a secondary hazard caused by ground vibration.

In the past history of earthquakes, all types of seismic hazards (Fig. 16) are well known with dominant influence of ground shaking and hazards associated with soil instabilities. By far, the most important is ground shaking, which causes buildings and structures to collapse partially or totally, producing damage at great distances from the epicentral zone. Ground shaking affects the soil and foundations under structures, therefore a lot of earthquake-induced structural damage is a consequence of ground failure and differential ground settlements. Sometimes the ground will lurch, particularly along roadsides, culverts, riverbanks, and in low-lying areas producing fissures and unstable soil conditions.

Ground shaking can also initiate devastating rock and mud slides, producing the greatest disasters ever experienced from seismic causes (Peru earthquake, 1970). A very common earthquake hazard is liquefaction of sandy soils, especially in river valleys and coastal regions. During earthquake shaking, water saturated fine-grained soils and sands take on liquid characteristics due to the rapid alternative action of shearing stresses. Water-saturated sands are widespread, particularly in flat areas where population tends to concentrate, so that soil liquefaction and damage of buildings and structures due to this earthquake hazard are observable in almost every earthquake. Soil liquefaction effects are very frequently associated with rather low accelerations of ground shaking. A much more restricted hazard comes from surface rupturing of geological faults. Buildings that straddle fault displacements may be critically wrenched. Elimination of this hazard is difficult in practice and depends upon adequate building codes and the availability of special geological fault maps.

The other earthquake hazards are related to water and fire. Due to undersea faulting, gigantic sea waves-tsunamis rush up along the coastline and devastate coastal man-made facilities. Floods from sudden failure of dams in earthquakes are an ever-present danger which can have enormous destructive effects, sometimes larger than the ground shaking itself. Fires are potential secondary effects in modern urbanised areas with the presence of chemical industries, oil and gas supplies. Ground shaking could cause breakage of pipelines, failure of oil or gas tanks, damage to chemical industries, etc.; causing explosions, release of toxic chemicals and fire in parts of towns or entire towns (Kanto earthquake, Japan, 1923; Loma Prieta, USA, 1989; Northridge, USA, 1994; Huogo-ken-Nanbu /Kobe/, Japan, 1995; Marmara Sea, Turkey, 1998, etc.).

4.5.1 Primary hazards

Ground shaking. In terms of human, social and economic losses ground shaking is the most significant factor contributing to the overall earthquake hazard. Shaking contributes to losses not only directly through vibration damage to man-made structures and other property, but also indirectly through triggering of secondary effects. The intensity and character of ground shaking depends upon earthquake source parameters (magnitude, driving stress causing the fault to slip and dimensions of the slip surface), distance from the fault and the site's surface geology (topography, lithology, sedimentation and stratification patterns). The damage potential of ground shaking is governed by three factors:

- ***amplitude*** of the ground motion
- its ***frequency contents***
- ***duration*** of the shaking

The relation between damage and ground shaking amplitude is complex because of the complexity of the response of the man-made structures to strong ground motions. However, the damage usually tends to increase with an increase of the amplitude. Frequency content is another critical factor because structures may respond in a resonant manner, depending upon the frequency content of the ground motion. The duration of shaking, which is perhaps the least widely recognised factor influencing shaking damage, is important because the failure mechanism in structures is controlled by the cumulative number of induced stress and strain cycles, and their amplitudes as well.

The geological structure near the surface can have a significant effect on the level of shaking during an earthquake (Fig. 17). Thick, dry sediments can amplify the shaking. Shaking can be amplified in steep hilly areas because the shape of the land surface focuses the waves. The study of these effects is known as ***microzoning***.

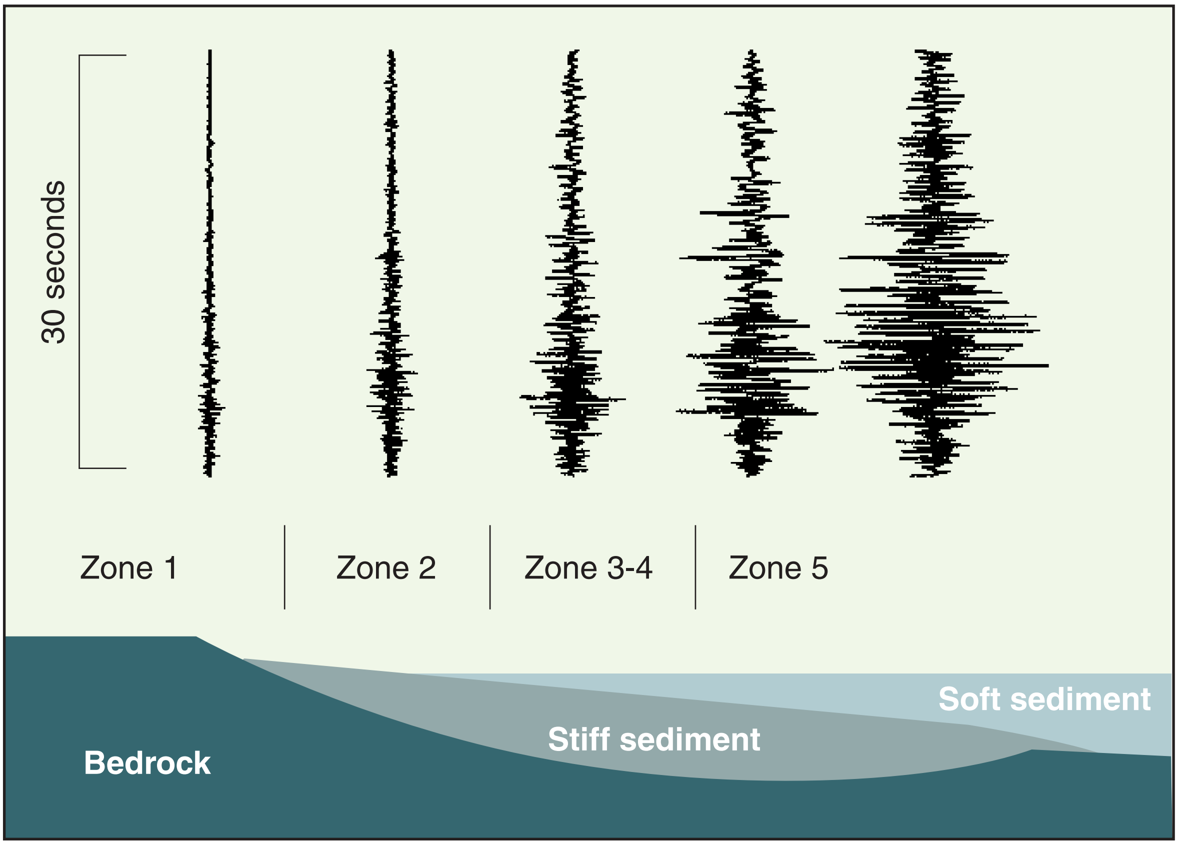


Fig. 17 **Seismograph traces illustrating the influence of underlying rock types on ground shaking**

b) Typical liquefaction sand boils

a) Bearing capacity failures of Kawagishi-cho apartment buildings

c) Failure of Showa bridge due to lateral spreading

Fig. 18 **Liquefaction phenomena caused by Niigata earthquake of 1964**

The main reason for the large amount of damage in Mexico City (Michoacan earthquake of 1995, M=8.1) was the fact that the amplitude of seismic waves was magnified by the local ground conditions. The city is founded on a dry lake bed of soft sediments. This caused the seismic waves to slow down as they travelled, and as they did so, they significantly built up in amplitude (Fig. 17). Not only that, but also the particular size and the shape of the old lake bed caused amplification of waves at a certain frequencies that matched the frequency characteristic of some of the buildings. This had disastrous effects on these buildings (which were 10 to 14 stories high).

Surface faulting. The offset or tearing of the earth's surface by different movement along a fault is an obvious hazard to structures built across active fault zones. Ground rupture occurs when movement along faults intersects the ground surface (the five basic types of movement are shown in Fig. 11). Ground ruptures are most likely to cause damage to linear structures such as roads and railways, to public utilities such as electricity and telephone cables and pipelines for gas, water, and sewerage. Surface faulting can be particularly severe for structures partially embedded in the ground and for all kinds of buried pipelines and tunnels. However, losses from fault displacements, ranging from a fraction of a centimetre to more than 10 metres, tend to be relatively low compared to losses from ground shaking. Surface faulting generally affects a long, but narrow zone (from several centimetres to several hundreds of metres); the total area of which is small compared with the total area affected by ground shaking.

Tectonic uplift and subsidence (terrestrial changes). Tectonic deformations of the Earth's surface usually accompany surface faulting. The deformation may be local, affecting a narrow zone near the fault rupture, or it may involve major differential vertical and/or horizontal movements over broad parts of the Earth's crust. Regional uplift or subsidence may accompany earthquakes that are caused by larger displacements on shallow buried faults, particularly those of the reverse or thrust type. Regional tectonic deformation constitutes a primary hazard to shoreline facilities and extensive hydraulic systems where broad-scale changes in land elevations occur relative to water.

4.5.2 Secondary hazards

Ground subsidence or collapse. Earthquake ground motion in areas that are already susceptible can accelerate ground subsidence or collapse. Areas of infield karsts, intensive mining or salt exploitation by pumping-out the underground [salty] water, are typical examples. Engineering geological mapping and subsurface investigations can identify those areas that are likely to be most susceptible to subsidence or collapse.

Landslides. Earthquake shaking can dislodge rock and debris on steep slopes, triggering rock falls, avalanches, slides, and other forms of mass movement. The mass movement phenomenon may occur on clay slopes steeper than about 7 degrees and on jointed rock slopes. In situations where liquefaction of strata can occur, the landslides might be triggered on even shallower slopes. Consequently, they are restricted to hilly and mountainous areas, including the margins of alluvial basins. Earthquakes increase the occurrence of landslides in ground that is already susceptible to them. Intense rainfalls can also trigger landslips. Discussion on the characteristics and the phenomenology of landslides is presented in the section 6 of this module treating mass movement hazards.

In general, landslides damage structures, either by impacting them from above or removing support from below. They can also seriously affect the transportation system, causing a total loss of access for the emergency operation.

Liquefaction. During strong ground shaking, areas having clay-free sands and silts (typically deposited in the past 10,000 years) and ground water within 15 metres of the surface, can temporarily lose strength and behave as viscous fluids. Structures founded on these materials can settle, topple or be ripped apart as the ground spreads laterally. This process, or liquefaction, takes place when seismic shear waves pass through the saturated granular soil layer, distort its granular structure, and cause some of the void spaces to collapse. Disruptions to the soil generated by these collapses cause transfer of the ground-shaking load from grain-to-grain contacts to the pore water. This transfer of load increases pressure in the pore water, either causing drainage or, if drainage is restricted, a sudden build-up of pore-water pressure. When it reaches a critical level (grain-to-grain stress approaches zero) the granular material suddenly behaves as a liquid rather than as a solid.

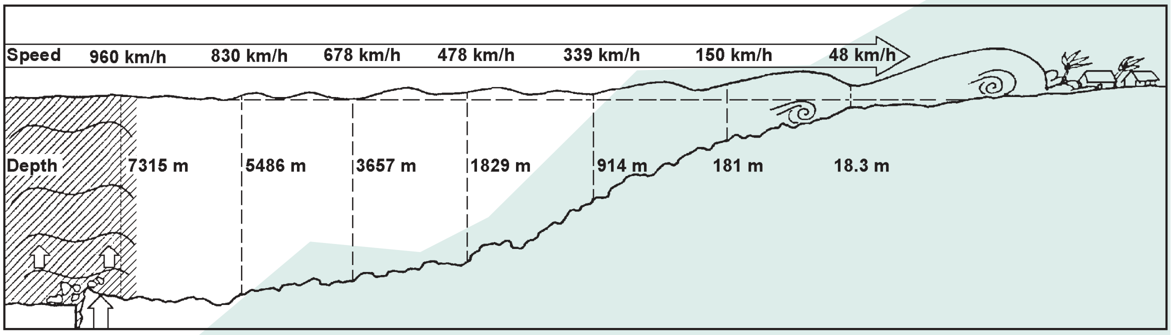
The soil changes from solid to liquid abruptly, as one eyewitness observed: *“ … the ground boiled, fissures opened, and the earth shook with violence … “.*

Ground shaking can cause lateral movement of large blocks of soil on top of a liquefied subsurface layer. These lateral spreads, which break up into numerous fissures and scarps, generally develop on gentle slops, most commonly on those between 0.3 and 3 degrees. Horizontal movements on lateral spreads commonly are as much as 3 to 5 metres, but, where slopes are favourable and the duration of ground shaking is long, lateral movement may be as much as 30 to 50 metres.

Flow failures (lahars) - consisting of liquefied soil or blocks of intact materials riding on a layer of liquefied silt – can form in loose saturated sands or soil on slopes greater than 3 degrees. These flows typically move several metres and, if conditions permit, can travel tens of kilometres at velocities as great as many tens of kilometres per hour.

The Niigata (Japan) earthquake, together with the Alaska (USA) earthquake also of 1964, brought liquefaction phenomena and their devastating effects to the attention of engineers and seismologists. A remarkable ground failure occurred near the Shinano riverbank where the Kawagishi-cho apartment buildings suffered bearing capacity failures and tilted severely (Fig. 18a). Despite the extreme tilting, the buildings themselves suffered remarkably little structural damage.

Sand boils (Fig. 18b) and ground fissures were observed at various sites in Niigata. Lateral spreading caused the foundations of the Showa Bridge to move laterally so much that the simply supported spans became unseated and collapsed (Fig. 18c).



An earthquake or other disturbance causes a column to form above the ocean floor that radiates outwards.

The velocity of a tsunami is determined by the depth of water over the earthquake or other disturbance.

Forward motion of the waves becomes increasingly restricted as they approach shore, shortening the wave length and building up greater water crests.

Fig. 19 **Development of a Tsunami**

Tsunami. Offshore earthquakes frequently cause tsunamis (Fig. 19), popularly known as *‘tidal waves’*. A tsunami consists of a series of waves of extreme length in time and space. They are caused typically by a sudden vertical displacement of a large area of the sea bed during an undersea earthquake. The wave generated can travel thousands of kilometres at speed of up to 800-1,000 km/h. Damage is caused by the run-up of water on to the land which may reach heights of as much as 30 metres above sea level. The interaction of the wave with the bathymetry and topography of the coastal region controls the distribution and severity of the inundation. Damage is dependent on the size and velocity of the wave and can vary from flooding to the destruction of buildings and the uprooting of trees.

Seishi. Seiches occur on lakes due to resonant response of the water to the ground shaking. They are usually smaller than tsunamis, but can cause damage close to the shoreline.

5. Geologic hazards - VOLCANOES

A volcano is a mountain that opens downward to a reservoir of molten rock below the surface of the earth. It is formed when magma is propelled through weak or fractured points in the earth's crust by the pressure and effervescence of dissolved gases. Unlike most mountains, which are pushed up from below, volcanoes are built up by an accumulation of their own eruptive products, that is, lava, ashflows, and airborne ash and dust.

More than 500 volcanoes have been active throughout history. There are also many hundreds of others now dormant, which show evidence of eruptive activity in the recent prehistoric past. Some of these will undoubtedly erupt again; eruptions have also occurred at volcanoes previously thought to be extinct. In addition, from time to time entirely new volcanoes are formed within volcanic zones.

Volcanic eruptions are among the most violent, spectacular, and awesome manifestations of nature, and the most feared of all natural phenomena. Myths, legends and recorded history abound in testimonies to their destructive power, and the geological record shows that volcanic processes have been important throughout the earth's history. These processes continue at the present time, often with profound effects on human life and activity.

Since 1700 A.D. volcanic activity has killed more than 260,000 people, destroyed entire cities and forests, and severely disrupted local economies for months to years. Even with improved ability to identify hazardous areas and warn of impending eruptions, increasing numbers of people face certain danger. It has been estimated that by the year 2000, the population at risk from volcanoes is likely to increase to at least 500 million, which is comparable to the entire world's population at the beginning of the 17th century.

5.1 Volcano classification

Geologists generally group volcanoes into four main kinds:

- Cinder cones (Fig. 20a)
- Composite volcanoes (Fig. 20b)
- Shield volcanoes (Fig. 20c)
- Volcanic or lava domes (Fig. 20d)

5.1.1 Cinder cones

Cinder cones (Fig. 20a) are the simplest type of volcano. They cause explosive eruptions.

A cinder cone has a narrow base and steep sides. It is a conical hill of volcanic fragments that accumulate around and downwind from a vent and are built from particles and blobs of congealed lava ejected from a single vent. As the gas-charged lava is blown violently into the air, it breaks into small fragments that solidify and fall around the vent to form a circular or oval cone. These rock fragments, often called cinders or scoria, are glassy and contain numerous gas bubbles "frozen" into place as magma exploded into the air and then cooled quickly.

Most cinder cones have a bowl-shaped *crater* at the summit. Cinder cones range in size from tens to hundreds of metres high and rarely rise more than 250-300 metres or so above their surroundings.

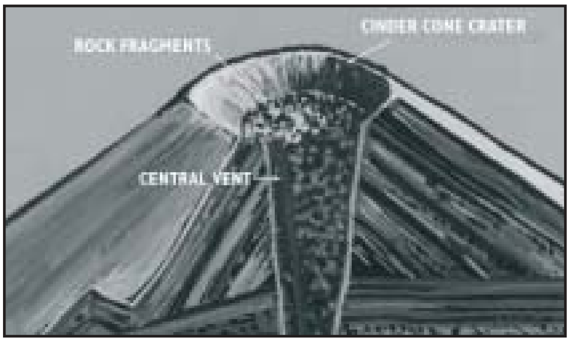


Fig. 20a **Cinder cones and scoria cones**

Cinder cones usually eject lava flows, either through a breach on one side of the crater or from a vent located on a flank. Lava rarely issues from the top (except as a fountain) because the loose, non-cemented cinders are too weak to support the pressure exerted by molten rock as it rises toward the surface through the central vent.

5.1.2 Composite volcanoes

Composite volcanoes, or stratovolcanoes (Fig. 20b) are typically steep-sided, symmetrical cones of large dimension built by the eruption of viscous lava flows, tephra, and pyroclastic flows. They are built of alternating layers of lava flows, volcanic ash, cinders, blocks, and bombs and may rise as much as several thousand metres above their bases. Of the earth's 1,511 volcanoes known to have erupted in the past 10,000 years, 699 are composite or stratovolcanoes.

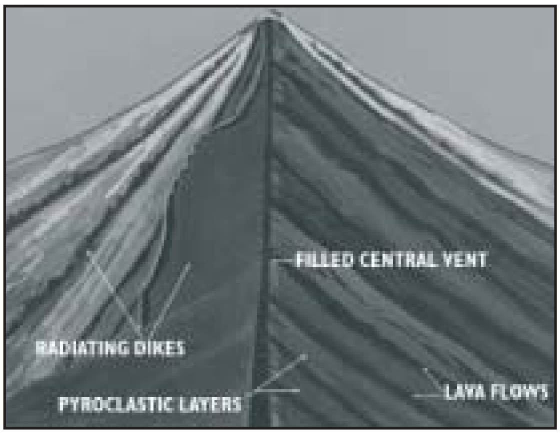


Fig. 20b **Composite (Strato) volcanoes**

Usually constructed over a period of tens to hundreds of thousands of years, stratovolcanoes may erupt a variety of magma types, including basalt, andensite, dacite, and rhyolite. All but basalt magma eruptions are usually highly explosive eruptions.

Most composite volcanoes have a crater at the summit which contains a central vent or a clustered group of separate vents, some of which may have erupted cinder cones and domes on the volcano's flanks. Lavas either flow through breaks in the crater wall or issue from fissures on the flanks of the cone. Lava, solidified within the fissures, forms dikes that act as ribs which greatly strengthen the cone.

The essential feature of a composite volcano is a conduit system through which magma from a reservoir deep in the earth's crust rises to the surface. The volcano is built up by the accumulation of material ejected through the conduit and increases in size as lava, cinders, ash, etc., are added to its slopes.

When a composite volcano becomes dormant, erosion begins to destroy the cone. Continued erosion removes all traces of the cone and the land is worn down to a surface of low relief. As the cone is stripped away, the hardened magma filling the conduit (the volcanic plug) and fissures (the dikes) becomes exposed, and it too is slowly reduced by erosion. Finally, all that remains is a projecting plug or the 'volcanic neck', a small lava-capped mesa, and vestiges of a once lofty volcano and its surrounding lava plateau – a telltale remnant of the vanished volcano.

Composite volcanoes tend to erupt explosively and pose considerable danger to nearby life and property.

Occasionally the eruptions of composite volcanoes are so large and violent that enormous volumes (tens to hundreds of cubic kilometres of magma) of pyroclastic products are spread so widely that no large cone forms, except where lava flows may pile up on top of each other. These large-volume eruptions rapidly drain the shallow underground magma reservoir. The removal of large volumes of magma may weaken the upper part resulting in loss of structural support for the overlying rock, thereby leading to collapse of the mountaintop into the emptied space (‘hole’) and formation of a huge, usually circular, depression at the summit of a volcano.

These depressions, formed by the collapse of volcanoes, are known as *calderas*. They are usually large, steep-walled, basin-shaped depressions formed by the collapse of a large area over, and around, a volcanic vent or vents. Calderas range in form and size from roughly circular depressions 1 to 25 kilometres in diameter to huge elongated depressions as much as 100 kilometres long. Calderas are different from craters, which are smaller, circular depressions created primarily by explosive excavation of rock during eruptions. The other caldera-forming process is erosion.

In large caldera-forming eruptions, a lot of the ejected material accumulates within the caldera itself as it collapses, and the old land surface may be buried up to several kilometres in depth.

5.1.3 Shield volcanoes

Shield volcanoes (Fig. 20c) are built almost entirely of fluid lava flows. Flow after flow pours out in all directions from a central summit vent, or group of vents, building a broad, gently sloping cone of flat, domical shape, with a profile much like that of a warrior’s shield.

They are built up slowly by the accretion of thousands of highly fluid (runny) lava flows, called basalt lava that spread widely over great distances, and then cool as thin, gently dipping sheets. Lavas also commonly erupt from vents along fractures (rift zones) that develop on the flanks of the cone. In some eruptions, basaltic lava pours out quietly from long fissures instead of central vents and floods the surrounding countryside with lava flow upon lava flow, forming broad plateaus.

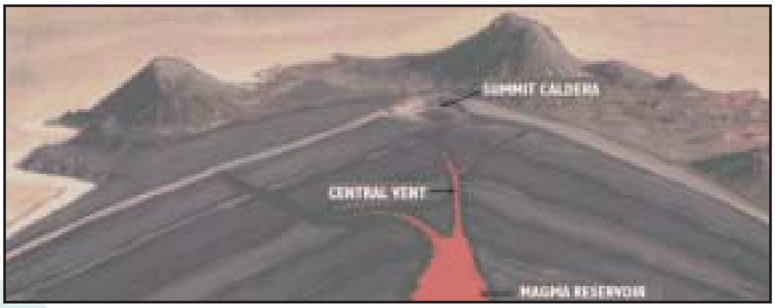


Fig. 20c **Shield volcanoes**

The largest volcanoes on Earth are shield volcanoes. Of the 1,511 volcanoes known to have erupted in the past 10,000 years, 164 are shield volcanoes.

5.1.4. Volcanic or lava domes

Volcanic or lava domes (Fig. 20d) are formed by relatively small, bulbous masses of lava too viscous to flow any great distance; consequently, on extrusion, the lava piles over and around its vent. A dome grows largely by expansion from within. As it grows its outer surface cools and hardens, then shatters, spilling loose fragments down its sides. Some domes form craggy knobs or spines over the volcanic vent, whereas others form short, steep-sided lava flows known as “coulées.” Volcanic domes commonly occur within the craters or on the flanks of large composite volcanoes.

Lava domes are rounded; steep-sided mounds built by very viscous magma, usually either dacite or rhyolite. Such magmas are typically too viscous (resistant to flow) to move far from the vent before cooling and crystallising. Domes may consist of one or more individual lava flows.

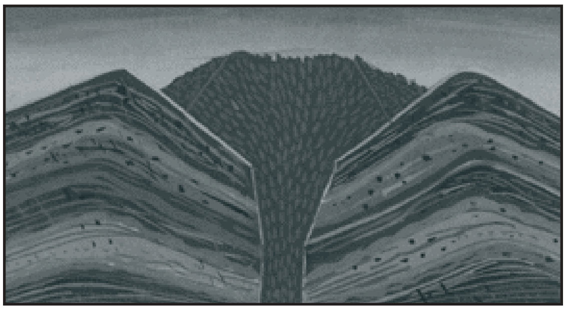
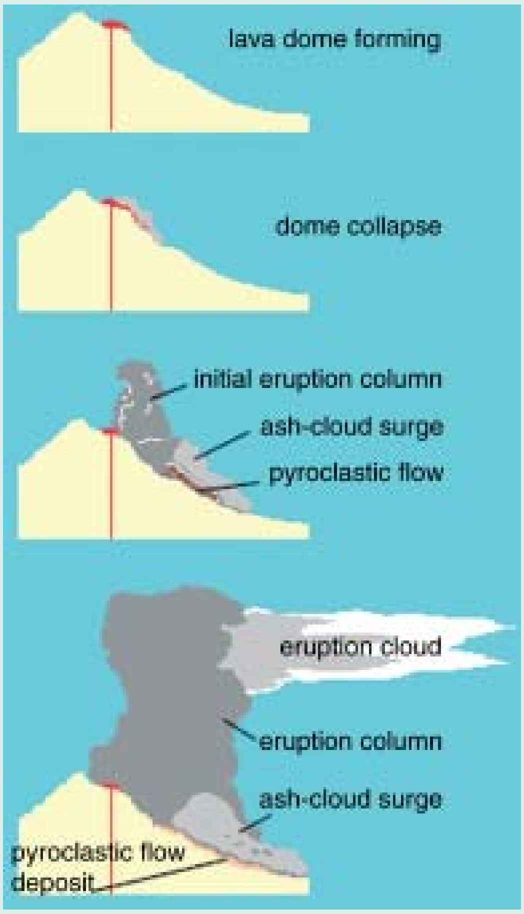


Fig. 20d **Lava domes**

Of the 1,511 volcanoes known to have erupted in the past 10,000 years, only 40 are classified as independent lava domes not associated with another volcano. Lava domes often erupt, however, on the top and sides of stratovolcanoes.

Although lava domes are built by nonexplosive eruptions of viscous lava, domes can generate deadly pyroclastic flows (Fig. 21). The sides of a dome or an erupting lava flow on a dome can collapse down a steep slope to form a hot avalanche of hot lava fragments and gas (pyroclastic flow). Some domes erupt obsidian, which is volcanic glass that may form in rhyolite or dacite lava flows. Most obsidian is black, but red, green, and brown obsidian is known. Obsidian forms when magma is cooled so quickly that individual minerals cannot crystallise.



Sketch by B. Myers; Source: USGS

During collapse events of the Unzen dome, an avalanche of hot lava blocks crashed downslope. The avalanche quickly became a fast-moving pyroclastic flow of shattered lava fragments, volcanic gas, and air. Within seconds, a faster moving "cloud" of smaller ash-sized fragments, called an ash-cloud surge, formed above and in front of the pyroclastic flow. Finally, as the flow spread away from the volcano, ash and hot gas rose to build an eruption column; when detached from the volcano, the volcanic ash and gas became an eruption cloud.

Fig. 21 **Sequence of a lava dome collapse**

5.2 Magmatic activity and eruption

The volcanic activity is associated with the magmatic activity in the upper part of earth's crust. Magma is a molten material within the earth's crust (Fig. 22). It is a complex mixture of silicates, containing dissolved gases and sometimes crystallised minerals in suspension. As it rises, the pressure decreases, enabling the dissolved gases to effervesce and expand, and driving magma upward through the volcanic vent. The degree of violence of volcanic eruption depends mainly on the amount and rate of effervescence of the gases and on the geochemistry and viscosity of the magma.

5.2.1 Types of magma (molten rock)

Naturally occurring magma is divided into types according to their silica content, which controls their viscosity (ease of flowing) and hence influence their eruptive styles.

The most silica-poor (47-52% SiO_2) fluid magmas are *basalts*, then come intermediate compositions called *andesites* and *dacites*. The most silica-rich, viscous magmas (>72% SiO_2) are *rhyolites*.

Magmas contain dissolved gases, mostly steam (H_2O) but also with lesser amounts of noxious or toxic gases such as carbon dioxide (CO_2), sulphur compounds (H_2S, SO_2), and chlorine (Cl_2).

5.2.2 Types of eruption

Eruptions vary widely in magnitude and duration, not only from one volcano to another but even at the same volcano. The frequency of eruptions also varies, from volcanoes, which are in almost continual eruption to those that erupt only at intervals of hundreds or even thousands of years.

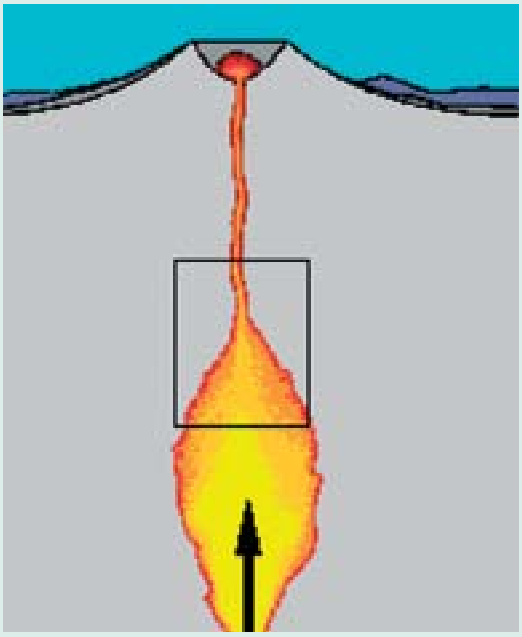
There are two major eruption types:

- effusive
- explosive

Effusive eruptions are processes where liquid magma emerges passively at the earth's surface to form a lava flow. In any magma, if the gas content is low, or the viscosity is low so that gases can easily escape, the lava flow is the likely end product. Basalts often erupt as lava flows.

Explosive eruptions are occurring when pressure from gases and the molten rock become strong enough to cause a major explosion. The escaping gases tear the magma apart into fragments, and then gasses and rock shoot up through the opening and fill the air with lava fragments. The fragments are termed pyroclasts ('fiery broken'). High viscosity, gas-rich rhyolite tends to erupt explosively and violently, and form pyroclastic deposits.

The end products of explosive eruption are flow and/or fall pyroclastic deposits. Flow deposits (ignimbrite) form when the fragments travel laterally as a kind of high-speed avalanche across the landscape. Fall deposits result when the fragments are carried up in an eruption column high above the earth's surface and then are 'rained' out over the landscape to form a 'blanket'.



Sketch by B. Myers; Source: USGS

Magma

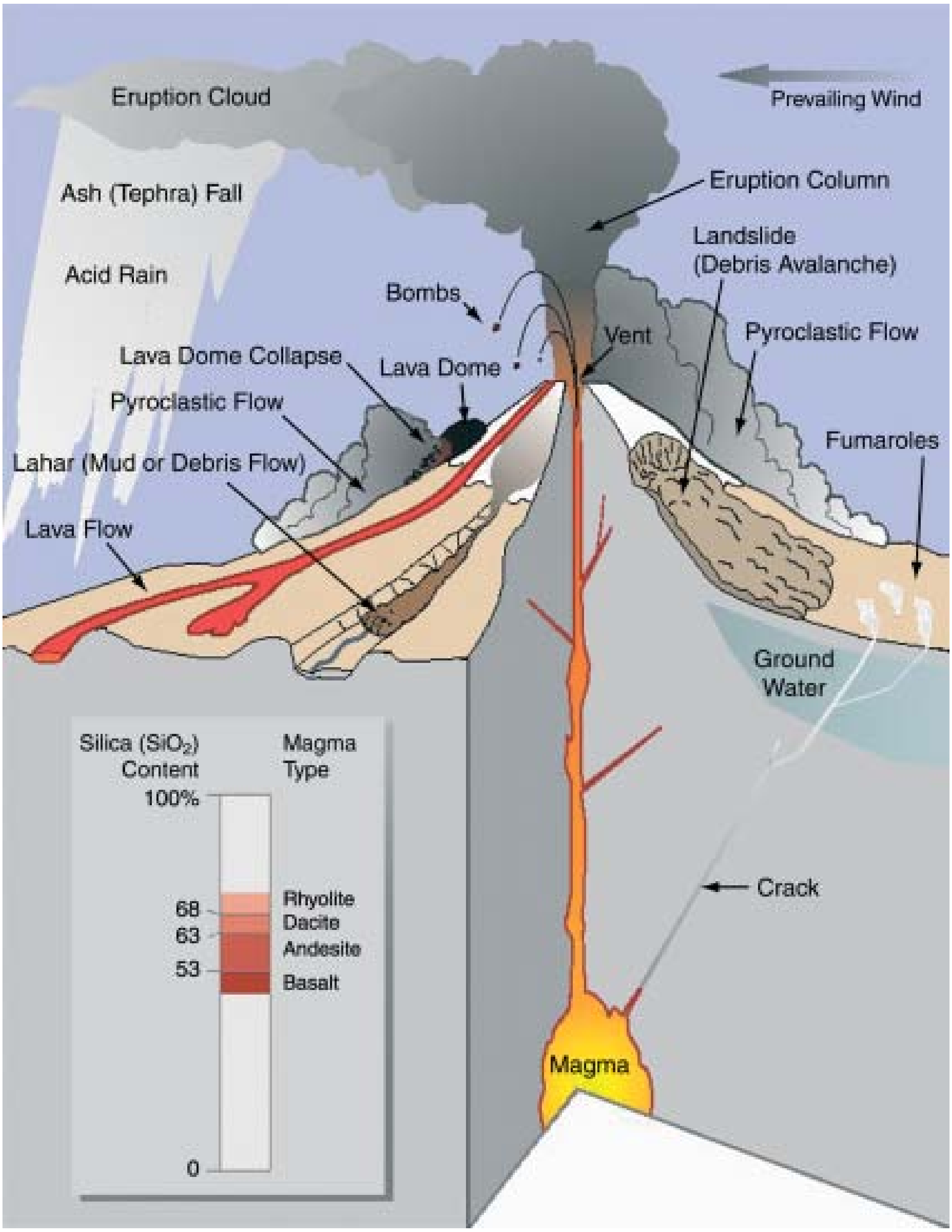
Magma is molten or partially molten rock beneath the Earth's surface. Magma typically consists of:

- *a liquid portion (often referred to as the melt); solid portion made of minerals that crystallized directly from the melt;*
- *a solid rocks incorporated into the magma from along the conduit or reservoir, called xenoliths or inclusions; and,*
- *dissolved gases.*

When magma erupts onto the surface, it is called lava.

Arrow indicates direction of magma movement from a deeper source.

Fig. 22 **Magma reservoir beneath a volcano and a conduit leading up to a lava dome at the surface**



Sketch by B. Myers; Source: USGS

Volcanoes produce a wide variety of natural hazards that can kill people and destroy property. This simplified sketch shows hazards accompanying a typical composite (strato) volcano. Many of these hazards also pose risks at other volcano types. Some hazards, such as lahars and landslides, can occur even when volcano is not erupting or may be triggered by other natural phenomena (earthquakes, floods, etc.).

Fig. 23 **Volcano hazards**

Table 10 **Summary description of volcanic hazards**

Characteristic features	Lava flows	Hot avalanches, mudflows and floods	Volcanic ash (tephra) and gases
Origin and characteristics	Result from non-explosive eruption of molten lava. Flows are erupted slowly and move relatively slowly; usually no faster than a person can walk.	Hot avalanches can be caused directly by eruption of fragments of molten or hot solid rock; mudflows and floods commonly result from eruption of hot material on to snow and ice and eruptive displacement of crater lakes. Mudflows also commonly caused by avalanches of unstable rock from volcano. Hot avalanches and mudflows commonly occur suddenly and move rapidly, at tens of kilometres per hour.	Produced by explosion of high-speed expulsion of vertical to low-angle columns or lateral blasts of fragments and gas into the air; materials can then be carried great distances by wind. Gases alone may issue non-explosively from vents. Commonly produced suddenly and move away from vents at speed of tens of kilometres per hour.
Location	Flows are restricted to areas downslope from vents; most reach distances of less than 10 kilometres. Distribution is controlled by topography. Flows occur repeatedly at central-vent volcanoes, but successive eruptions may affect different flanks. Elsewhere, flows occur at widely scattered sites, mostly within volcanic "fields".	Distribution nearly completely controlled by topography. Beyond volcano flanks, effects of these events are confined mostly to floors of valleys and basins that head on volcanoes. Large snow-covered volcanoes and those that erupt explosively are principal sources of these hazards.	Distribution controlled by wind directions and speeds, and all areas towards which wind blows from potentially active volcanoes are susceptible. Zones around volcanoes are defined in terms of whether they have been repeatedly and explosively active in the last 10,000 years.
Size and area affected by single event	Most lava flows cover no more than a few square kilometres. Relatively large and rare flows probably would cover only hundreds of square kilometres.	Deposits generally cover a few square kilometres to a few hundreds of square kilometres. Mudflows and floods may extend down valley from volcanoes many tens of kilometres.	An eruption of "very large" volume could affect and spread over tens of thousands of square kilometres. Even an eruption of "moderate" volume could significantly affect thousands of square kilometres.
Effects	Land and objects in affected areas subject to burial, and generally they cause total destruction of areas they cover. Those that extend into areas of snow may melt it and cause potentially dangerous and destructive floods and mudflows. May start fires.	Land and objects subject to burning, burial, dislodgment, impact damage, and inundation by water.	Land and objects near an erupting vent subject to blast effects, burial and infiltration by abrasive rock particles, accompanied by corrosive gases, into structures and equipment. Blanketing and infiltration effects can reach hundreds of kilometres downwind. Odor, "haze", and acid effects may reach even further.
Predictability of location of areas endangered by future eruptions	Relatively predictable near large, central-vent volcanoes. Elsewhere, only general locations predictable.	Relatively predictable, because most originate at central-vent volcanoes and are restricted to flanks of volcanoes and valleys leading from them.	Moderately predictable. Voluminous ash originates mostly at central-vent volcanoes; its distribution depends mainly on winds. Can be carried in any direction; probability of dispersal in various directions can be judged from wind records.

Explosive volcanic explosions occur in two different ways:

- dry
- wet

In ‘dry’ explosive activity, gases dissolved in the magma escape, tearing magma apart in the process. ‘Wet’ (hidrovolcanic: combined magma-steam) activity is when the hot magma meets a supply of water (for example, a lake), flashing the water to steam and making the eruption violently explosive.

5.3 Volcanic hazards

A number of types of volcanic hazards (Fig. 23, Table 10) will result from a volcanic eruption. Each hazard poses different risks affecting different areas. This is a key difference between eruptions and the other principal natural hazards, floods and earthquakes. The most threatening volcanic hazards include:

- pyroclastic falls
- pyroclastic flows and surges
- lava extrusions (flows and domes)
- debris avalanches
- lahars
- volcanic gases

In any given area, the nature of volcanic hazards will vary with:

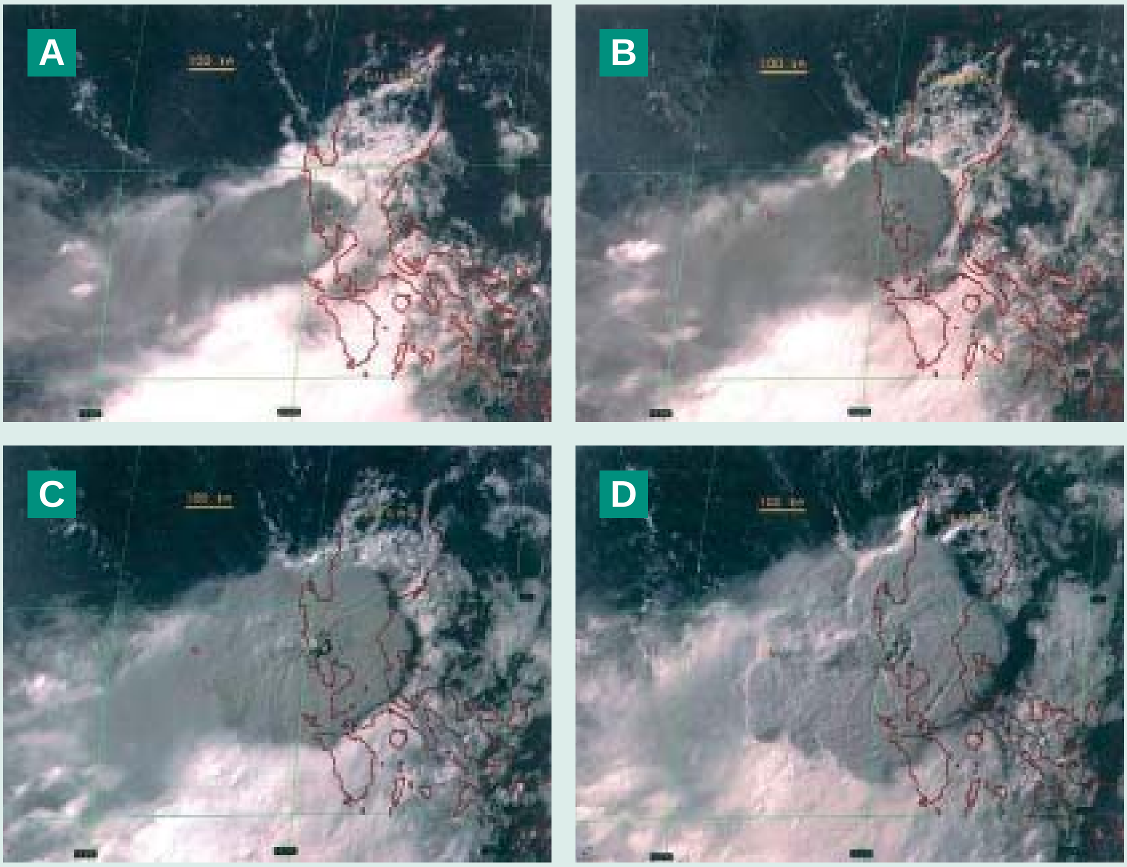
- the size of the eruption, which cannot be pre-determined, except within broad limits
- the eruption type or style (for example, lava flow, fire-fountaining, steam explosions) which can vary both in time and scale
- the distance from the volcano
- proximity to any waterway draining the volcanic area that might act as a pathway for flooding or lahars

5.3.1 Pyroclastic falls – eruption columns and clouds

An explosive eruption blasts solid and molten rock fragments (tephra) and volcanic gases into the air with tremendous force. Pyroclastic fall deposits consist of material which rains out from an eruption column. The largest rock fragments (blocks and bombs) follow ballistic trajectories and are highly damaging. These fragments rarely land more than 2 to 3 kilometres from the vent. Finer fragments (less than 2-3 mm across) of volcanic glass, minerals, and rock (ash) convects upward forming a huge billowing eruption column, before setting out downwind to form pyroclastic fall deposits.

Eruption columns grow rapidly and can reach more than 20 kilometres above a volcano in less than 30 minutes, forming an eruption cloud. Large eruption clouds can extend hundreds of kilometres downwind (Fig. 24), resulting in ash fall over enormous areas.

The volcanic ash is the product most likely to affect the largest area and the most people during an eruption. The ash particles commonly have sharp broken edges therefore the volcanic ash is highly abrasive. Volcanic clouds will block out sunlight and total darkness may result where moderate to heavy falls of ash occur. The volcanic ash in the cloud can pose a serious hazard to aviation [2]. Heavy ash fall can collapse buildings, and even minor ash fall can damage crops, electronics, and machinery.



The images from the GMS-4 (Japanese Geostationary Meteorological) Satellite provided some details of this part of the eruption. As the cloud subsided and entered higher wind fields at lower altitudes, GMS satellite images of the entrained plume shows that it covered an area of 2.7x10^6 km^2 36 h after the eruption. This size is unprecedented in recent times. Several studies estimated the top of the umbrella cloud to be at least 35 km during the eruption climax.

Fig. 24 **GMS visible satellite images of top of giant umbrella cloud developing above eruption column of Mount Pinatubo**

5.3.2 Pyroclastic flows and surges

The collapse of all or part of an eruption column into a descending fountain of rock and gas produces pyroclastic flows and surges (Figs. 21 and 23). These high-speed avalanches of hot ash, rock fragments, and gas, travelling across the landscape, can move down the sides of a volcano during explosive eruptions or when the steep side of growing lava dome collapses and breaks apart. Pyroclastic flows and surges often move at speeds of more than 200 kilometres per hour, usually are very hot (several hundred degrees centigrade), and cause widespread destruction. Such flows tend to follow valleys and are capable of knocking down and burning everything in their paths. Lower-density pyroclastic flows, called pyroclastic surges can easily overflow ridges several tens of metres high.

5.3.3 Lava extrusions (flows and domes)

Molten rock (magma) that pours or oozes onto the earth's surface is called lava and forms lava flows. The higher a lava's silica (SiO_2) content, the more viscous the lava is and the less easily it flows. For example, low-silica basalt lava can form fast-moving (15 to 50 km per hour) streams or can spread out in broad thin sheets up to several kilometres wide.

In contrast, flows of higher-silica andensite and dacite lava tend to be thick and sluggish, travelling only short distances from a vent. Dacite and rhyolite lavas often squeeze out of a vent to form irregular mounds called lava domes.

Debris avalanche (Landslides)

A single mass of rock debris breaks loose high on the flank of a volcano and slides into a wide valley.

Note the initial development of a headwall scarp at the top of the landslide (Fig. 25a), the widening path of the landslide as it enters the valley, and the horseshoe-shaped crater carved from the cone (Fig. 25c).

Many landslides actually involve several large blocks of debris that collapse and merge together on the volcano or as they spread into low-lying areas. Such large landslides typically travel much farther from a volcano than shown in these two illustrations.

If the rock debris contains a high water content or consists of a significant amount of clay particles (>3-5 percent), a landslide typically transforms directly into a lahar and continues flowing for many tens of kilometers.

Many landslides transform into lahars and travel tens of kilometers from the volcano.

Lahar

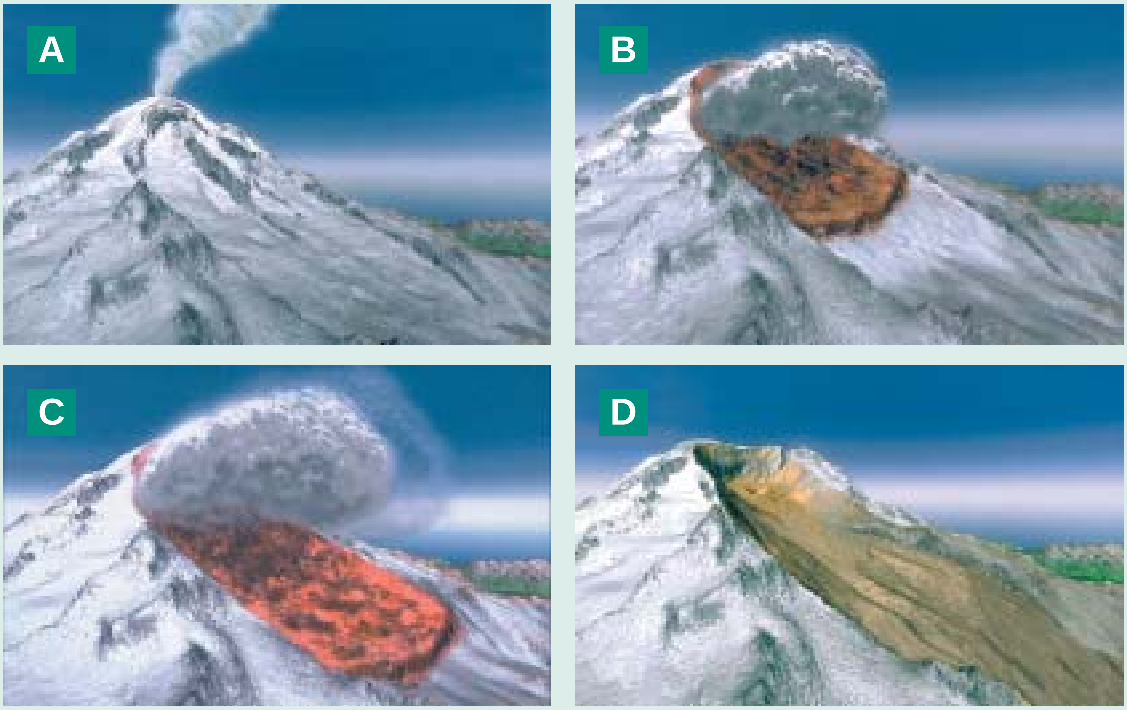
Debris avalanches are moving masses of rock, soil and snow that occur when the flank of a mountain or volcano collapses and slides downslope. As the moving debris rushes down a volcano and into river valleys, it incorporates water, snow, trees, bridges, buildings, and anything else in the way. Debris avalanches may travel several kilometers before coming to rest, or they may transform into more water-rich lahars, which travel many tens of kilometers downstream.

a) Start of Landslide

b) Development of Landslide/Lahar

c) Landslide/Lahar Enters the Vally

Fig. 25 **Development of volcanic landslide and lahar - a debris avalanche rushes down the side of a volcano to the valley floor**



A mass of sliding rocks, snow, and ice swept down the NE side of Mount Rainier volcano about 5,600 years ago. The landslide quickly transformed into an enormous lahar, raced down the west and main forks of the White River, and spilled into Puget Sound more than 50 km downstream. The landslide removed the summit area of the volcano and created a deep horseshoe-shaped crater. A relatively small explosion accompanied the landslide. This event is known as the Osceola Mudflow.

Fig. 26 **Development of volcanic landslide and lahar**

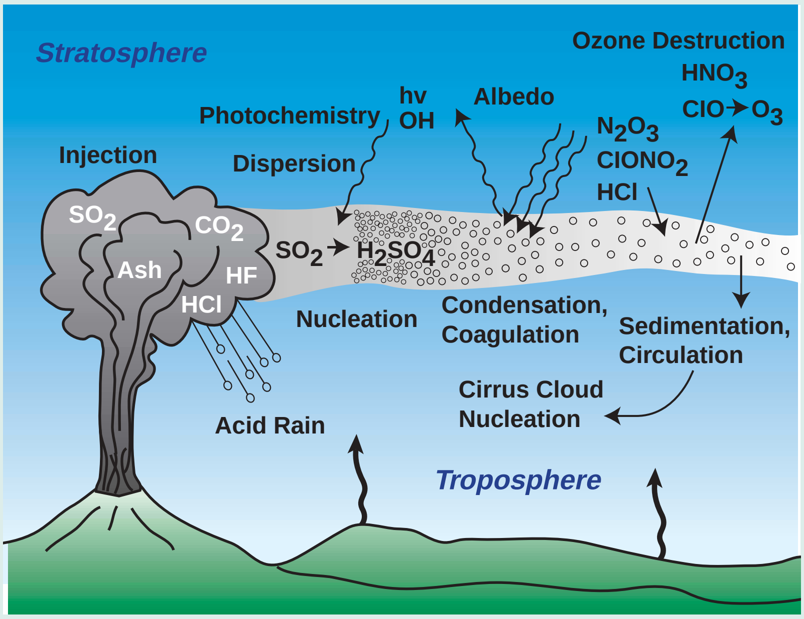
5.3.4 Debris avalanches (Volcano landslides)

A volcano landslide or debris avalanche (Figs. 25 and 26) is a rapid downhill movement of rocky material, snow, and/or ice. Volcano landslides range in size from small movements of loose debris on the surface of a volcano to massive collapses of the entire summit or sides of a volcano. Steep volcanoes are susceptible to landslides because they are built up partly of layers of loose volcanic rock fragments. Some rocks on volcanoes have also been altered to soft, slippery clay minerals by circuiting hot, acidic ground water. Landslides on volcano slopes are triggered when eruptions, heavy rainfall, or large earthquakes cause these materials to break free and move downhill. Debris avalanches can travel a considerable distance from the source area, but generally are confined to one sector of the volcano.

5.3.5 Lahars

Mudflows or debris flows composed mostly of volcanic materials on the flanks of a volcano are called lahars (Figs. 25 and 26). These flows of mud, rock, and water can rush down valleys and stream channels at speeds of 35 to 70 kilometres per hour and can travel more than 90 kilometres. Some lahars contain so much rock debris (60 to 90 % by weight) that they look like fast-moving rivers of wet concrete. Close to their source, these flows are powerful enough to rip up and carry trees, houses, and huge boulders many kilometres downstream. Further downstream they entomb everything in their path in mud.

Historically, lahars have been one of the deadliest volcano hazards. They can occur both during an eruption and when a volcano is quiet. The water that creates lahars can come



Large, explosive volcanic eruptions inject water vapor (H_2O)*, carbon dioxide* (CO_2)*, sulfur dioxide* (SO_2)*, hydrogen chloride (HCl), hydrogen fluoride (HF) and ash (pulverized rock and pumice) into the stratosphere to heights of 15-35 kilometers above the Earth's surface. The most significant impacts from these injections come from the conversion of sulfur dioxide to sulfuric acid* (H_2SO_4)*, which condenses rapidly in the stratosphere to form fine sulfate aerosols. The aerosols increase the reflection of radiation from the Sun back into space and thus cool the Earth's lower atmosphere or troposphere; however, they also absorb heat radiated up from the Earth, thereby warming the stratosphere. Several eruptions during the past century have caused a decline in the average temperature at the Earth's surface of up to 0.1-1.5 degree (Celsius scale) for periods of one to three years. The sulfate aerosols also promote complex chemical reactions on their surfaces that alter chlorine and nitrogen chemical species in the stratosphere. This effect, together with increased stratospheric chlorine levels from chlorofluorocarbon pollution, generates chlorine monoxide (ClO), which destroys ozone* (O_3)*. As the aerosols grow and coagulate, they settle down into the upper troposphere where they serve as nuclei for cirrus clouds and further modify the Earth's radiation balance. Most of the hydrogen chloride (HCl) and hydrogen fluoride (HF) are dissolved in water droplets in the eruption cloud and quickly fall to the ground as acid rain. The injected ash also falls rapidly from the stratosphere; most of it is removed within several days to a few weeks. Finally, explosive volcanic eruptions release the greenhouse gas carbon dioxide and thus provide a deep source of carbon for biogeochemical cycles.*

/Figure modified from Richard Turco in American Geophysical Union Special Report: Volcanism and Climate Change, May 1992; Source: USGS/

Fig. 27 **Volcanic Interactions With the Atmosphere**

from melting snow and ice (especially water from a glacier melted by a pyroclastic flow or surge), intense rainfall, or the breakout of a summit crater lake. Large lahars are a potential hazard to many communities downstream from glacier-clad volcanoes.

5.3.6 Volcanic gases

Volcanoes emit gases during eruptions (Fig. 27). Even when a volcano is not erupting, cracks in the ground allow gases to reach the surface through small openings called fumaroles. Ninety per cent of all gases emitted by volcanoes are made up of water vapour (steam), most of which is heated ground water (underground water from rainfall and steam). Other common volcanic gases are carbon dioxide, sulphur dioxide, hydrogen sulphide, hydrogen, and fluorine. When sulphur dioxide reacts with water droplets in the atmosphere it creates acid rain, which causes corrosion and harms vegetation. Carbon dioxide is heavier than air and can be trapped in low areas in concentrations that are deadly to people and animals. Fluorine, which in high concentrations is toxic, can be adsorbed onto volcanic ash particles that later fall to the ground. The fluorine on the particles can poison livestock grazing on ash-coated grass and also contaminate domestic water supplies.

Cataclysmic eruptions inject huge amounts of sulphur dioxide gas into the stratosphere, where it combines with water to form an aerosol (mist) of sulphuric acid. By reflecting solar radiation, such aerosols can lower the earth's average surface temperature for extended periods of time. Moreover, these sulphuric acid aerosols also contribute to the destruction of the ozone layer by altering chlorine and nitrogen compounds in the upper atmosphere.

5.4 Eruption products

The principal products of volcanic eruptions may be grouped into several broad categories according to the type of material ejected and its mode of transport from the vent to its place of deposition. These are:

- ash falls
- pyroclastic flows
- lava flows
- gas emissions

Magma flowing out onto the surface is known as ***lava***; all solid particles ejected are known as ***tephra***.

In an eruption, magma comes to the earth's surface, along with ***dust***, ***ash***, ***cinders*** and ***bombs***.

Dust is the smallest particle. It is less than one quarter of a millimetre wide.

Ashes are from one quarter to five millimetres in diameter. Volcanic ash can affect people hundreds of kilometres away from the volcano. Several of the deaths from the Mount St. Helens volcano in 1980 were caused by inhalation of volcanic ash. Volcanic ash can contaminate water supplies, cause electrical storms, and collapse roofs.

Cinders are about the size of golf ball.

Bombs can be about the size of a golf ball. However they can be several metres large. These bombs are usually called ***blocks***. Volcanic eruptions known as lateral blasts which are sideways blasts can shoot bombs at high speeds for several kilometres. These blasts have been known to knock down entire forests.

5.5 Eruption predictability

Most eruptions are preceded by premonitory signs which, if recognized and heeded, can give timely warning of the impending events. However, these signs may be subtle or complex, and may demand careful and detailed study before they can be interpreted correctly. Some of the history's greatest catastrophes have been caused by eruptions whose early signs were unrecognised, misunderstood or ignored.

Volcanoes are mainly located in a clearly defined volcanic belt. The study of their geologic history, seismic activity, ground deformation, sulphur dioxide emissions and other observations, may indicate an impending volcanic eruption. There is not yet a reliable method of forecasting, and precursory signs do not always occur, although a number of classified "active" volcanoes are monitored for associated seismic activity and hazard maps, based on historical evidence, have been constructed for certain regions.

5.6 Effects of eruption

The primary volcanic effects posing sudden and urgent threats to life or property include ash flows, pyroclastic flows, mudflows, lava flows and volcanic gases. Volcanic dust suspended in the atmosphere can also affect the world climate, communications and air transport.

Eruptions can cause secondary hazardous phenomena, such as ground failure, ground subsidence (sudden or gradual), debris avalanches, mudflows (lahars), glacier bursts, volcanic earthquakes and tsunamis. Volcanic earthquakes frequently precede or accompany eruptions, but are rarely of sufficient magnitude or intensity to cause severe damage.

Not all these phenomena are observed in each eruption. Individual volcanoes may behave in different ways at different times, but in general their eruptions fall into one or other of a few distinct types, identifiable by reference to the nature of their previous eruptions. In the absence of more specific guidance, it is reasonable to assume that future eruptions at any volcano will be of the same type as in the past, as revealed by geological studies of the earlier deposits.

Volcanoes affect the lives of people in both negative and positive ways. Any volcanic eruption, whatever its degree of violence, can be dangerous to people in its neighbourhood. The type of damage depends of the material ejected. Yet, during their periods of inactivity, volcanoes attract human settlement because of the fertility of volcanic soils and the often-spectacular beauty of volcanic landscapes.

6. Mass movement hazards – LANDSLIDES AND AVALANCHES

The downslope movement of large volumes of surface materials under gravitational influences represents an important type of environmental hazard, especially in mountainous terrain. Rapid movements cause loss of life and damage, slow movements have less potential to kill but can be costly. Depending on the dominant material, these movements tend to be grouped generally into:

- landslides (rock or soil)
- avalanches (snow and ice)

Mass movements may physically be triggered by either seismic and/or volcanic activity (or any other strong vibration) or atmospheric events. To that extent, this hazard lies at the interface between endogenous and exogenous earth processes.

6.1 Landslides

The term landslide covers most downslope movements of rock and soil debris that have become separated from the underlying, stable part of the slope by a shear zone or slip surface. The type of movement, which may include falling, sliding and flowing, depends largely on the nature of the geologic environment, including material strength, slope configuration and pore water pressure.

Different types of landslides move downslope at a wide range of speeds. The more rapidly moving landslides may pose a greater hazard to life because they can destroy dwellings or damage roads quickly and with little warning. Slower moving landslides will gradually cause increasing amounts of damage, but the expected movements can be anticipated.

Individual slope failures can be as damaging (and therefore as costly) as earthquakes, major floods, or some other environmental catastrophe. Yet they are more widespread and, over the years, may cause more property loss than any other environmental hazard. For example, total financial losses from ground failure in the United States are greater than the loss from all other natural hazards combined.

6.1.1 Classification of landslides

Landslides are usually classified according to the following two criteria (Table 11):

- types of movement
- types of material involved

Classification by typology of the movement

Falls (Fig. 28) are masses of rock and/or other material that move downslope primarily by falling or bouncing through the air. They are most common along steep road or railroad cuttings, along steep scarps formed either by landsliding or stream erosion, and along steeply under-cut cliffs in coastal areas. Large individual boulders or blocks of rock can cause considerable damage to houses or roads located at the base of the slope.

Table 11 **Classification of Landslides** /Varnes, 1978/

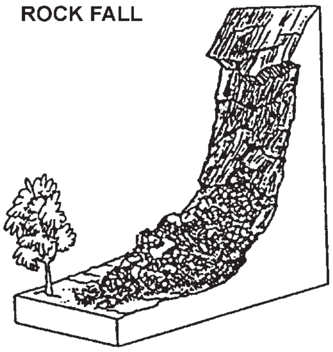
Type of movement	Type of material		
	Bedrock	Soils	
		Coarse-grained (debris)	Fine-grained (earth)
1. Falls	Rock fall	Debris fall	Earth fall
2. Toppless..........	Rock topple	Debris topple	Earth topple
3. Slides	Rock-block slide	Debris-block slide	Earth -block slide
• Rotational	Rock slump	Debris slump	Earth slump
• Translational ..	Rock slide	Debris slide	Earth slide
4. Lateral spreads	Rock spread	Debris spread	Earth spread
5. Flows...............	Rock flow	Debris flow	Earth flow
6. Complex..........	Combination of two or more of the above		

Topple (Fig. 29) is an overturning movement that, if not blocked by other masses, will result in a fall or slide.

Slides (Fig. 30) result from shear failure along one or several surfaces. The slide materials can be broken up and deformed, or remain fairly cohesive and intact. A cohesive slide is called a slump. Primarily pre-existing structural features such as faults, joints and bedding control movement in both slides and slumps. Two sliding movements can be distinguished:

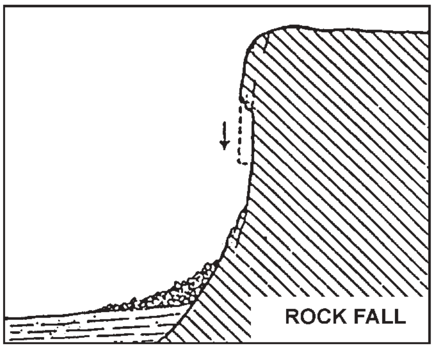
- the rotational slide where movement involves turning about a point
- the translational slide where movement is predominantly along planar or gently undulatory surface

Lateral spread (Fig. 31) is a lateral movement of a fractured mass. Horizontal movements are commonly as much as 3.0 to 4.5 metres, but when slopes have the adequate angle, lateral movements may be as much as 30 to 45 metres. Some spreads are without a well-defined basal shear surface; others include extension of rock or soil resulting from liquefaction or plastic flow of subjacent material.



Rock that has moved primarily by falling through the air

Description: Falls are abrupt movements of masses of geologic materials that become detached from steep slopes or cliffs (i.e. rock fall). Movement occurs by free bouncing and rolling. Depending on the type of earth materials, the result in a rock fall, soil fall, debris fall, boulder fall and so on. All types of falls are promoted by undercutting, differential weathering, excavation, or stream erosion.



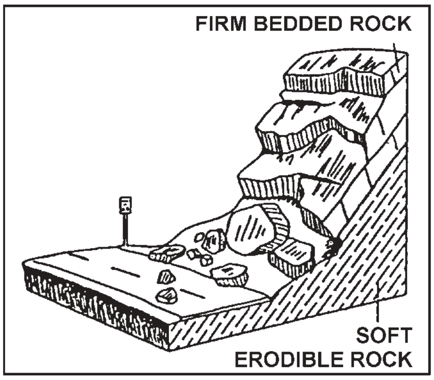
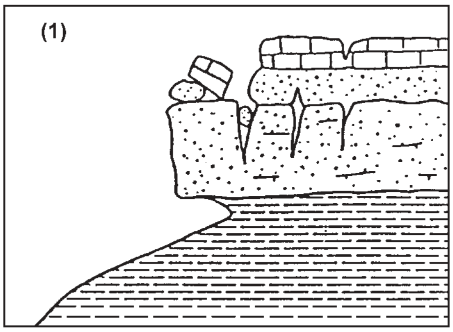
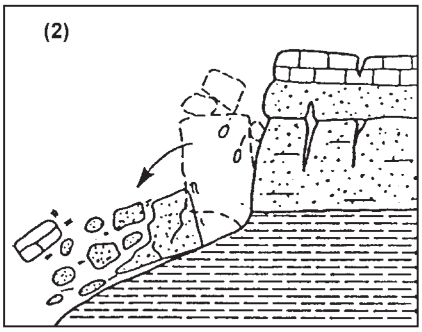
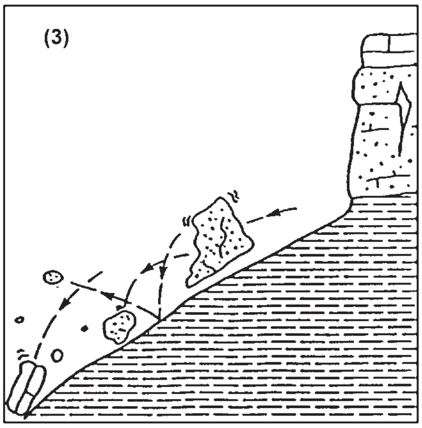


Fig. 28 **Falls**

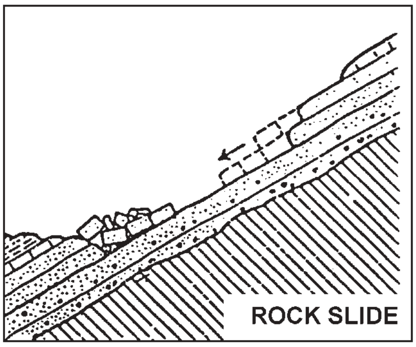


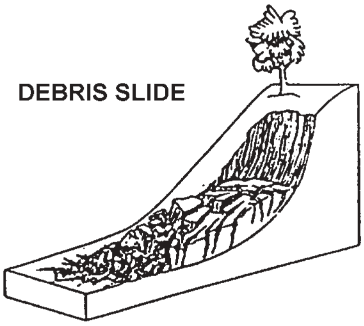




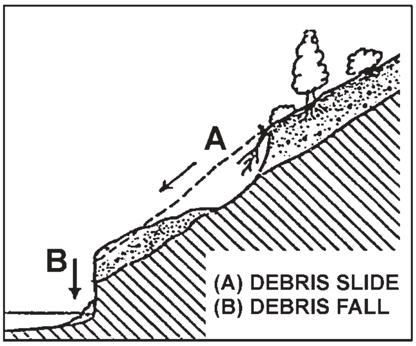
Description: A topple is a block of rock that tilts or rotates forward on pivot or hinge point and then separates from the main mass, falling to the slope bellow, and subsequently bouncing or rolling down the slope.

Fig. 29 **Topple**





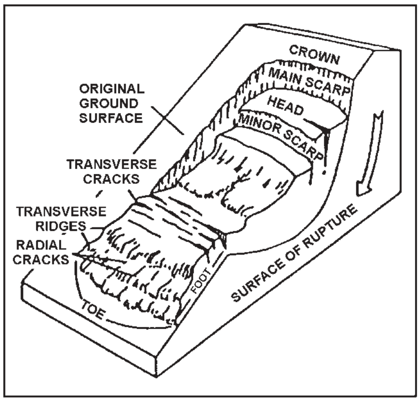
Incoherent or broken masses of rock and other debris that move down-slope by sliding on a surface that underlines the deposit



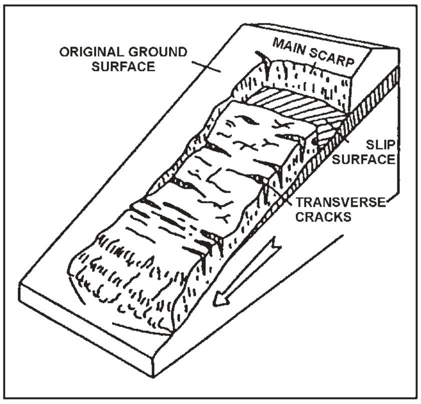
Description: Although many types of mass movement are included in the general term "landslide", the more restrictive use of the term refers to movements of soil or rock along a distinct surface of rupture which separates the slide material from more stable underlying material. The two major types of landslides are rotational slides and translational slides.

Rotational slide. A rotational slide is one in which the surface of rupture is curved concavely upwards (spoon shaped) and the slide movement is more or less rotational about the axis that is parallel to the contour of the slope.

Slump. A "slump" is an example of a small rotational slide.



Rotational landslide

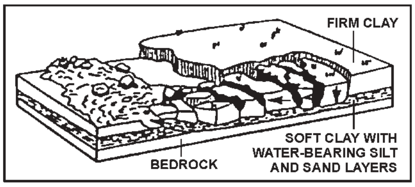


Translational slide

Translational slide. In a translational slide, the mass moves out, or down and outward along a relatively planar surface and has little rotational movement or backward tilting. The mass commonly slides out on top of the original ground surface. Such a slide may progress over great distances if conditions are right. Slide material may range from loose unconsolidated soils to extensive slabs of rock.

Block slide. A block slide is a translational slide in which the moving mass consist of single unit, or a few closely related units that move down-slope as a single unit.

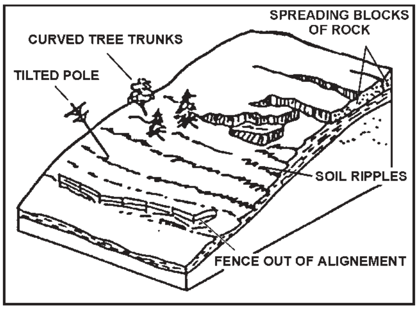
Fig. 30 **Slides**



Lateral Spread

Description: Lateral spreads are a result of the nearly horizontal movement of geologic materials and are distinctive because they usually occur on very gentle slopes. The failures caused by liquefaction, the process whereby saturated, loose cohessionless sediments (usually sands and silts) are transformed from a solid into a liquefied state; or by plastic flow of subjacent material. Failures usually triggered by rapid ground motions such as that experienced during an earthquake, or by slow chemical changes in the pore water and mineral constituents.

Fig. 31 **Lateral spreads**



Creep

Description of various forms of flows:

Creep. Creep is the imperceptibly slow, steady downward movement of slope-forming soil or rock. Creep is indicated by curved tree trunks, bent fences or retaining walls, tilted poles or fences, and small soil ripples or terracettes.

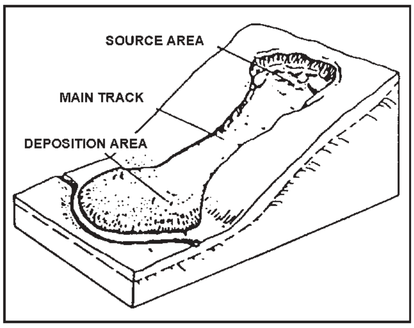
Debris flow. A debris flow is a form of rapid mass movement in which loose soils, rocks and organic matter combine with entrained air and water to form slurry that flows down-slope. Debris-flow areas are usually associated with steep gullies. Individual debris-flow areas can usually be identified by the presence of debris fans at the termini of the drainage basins.

Debris avalanche. A debris avalanche is a variety of very rapid to extremely rapid debris flow.

Earth flow. Earth flows have a characteristic "hourglass" shape. A bowl or depressions forms at the head where the unstable material collects and flows out. The central area is narrow and usually becomes wider as it reaches the valley floor. Flows generally occur in fine-grained materials or clay-bearing rocks on moderate slopes and with saturated conditions. However, dry flows of granular material are also possible.

Mud flow. A mudflow is an earth flow that consists of material that is wet enough to flow rapidly and that contains at least 50 percent sand-, silt- and clay-sized particles.

Lahar. A lahar is a mudflow or debris flow that originates on the slope of a volcano. Lahars are usually triggered by such things as heavy rainfall eroding volcanic deposits; sudden melting of snow and ice due to heat from volcanic vents; or by the breaking out of water from glaciers, crater lakes, or lakes dammed by volcanic eruptions.



Earth Flow

Fig. 32 **Flows**

Flow (Fig. 32) is a movement similar to that of a viscous fluid and slip surfaces are almost non-existent. Flow can take place as one or more lobes move at different rates, depending upon the viscosity of the material and the local slope angle. Water is not necessary for flows to take a place, but most flows occur during or after periods of heavy rainfall, when the cohesiveness of soil and the bonding of soil by clay minerals breaks down, permitting downslope flow even on fairly gentle slopes. These landslides can move very rapidly and cover distances of several kilometres along available paths.

Many landslides exhibit features characteristic of several types, so precise classification may be impossible.

Classification by typology of the material

Landslide materials are divided into two classes:

- bedrock
- soils (which further are sub-divided into debris and earth)

Bedrock designates hard or firm rock that was intact and in its natural place before the initiation of movement.

Engineering soil includes any loose, unconsolidated or poorly cemented aggregate of solid particles, generally of natural mineral, rock, or inorganic composition and either transported or residual, together with any interstitial gas or liquid. Natural soils may contain variable amounts of organic material.

Debris refers to an engineering soil, generally surfacial, that contains a significant proportion of coarse material. “Debris” may be used to specify material in which 20 to 80 per cent of the fragments are greater than 2 millimetres in size, and the remaining fragments less than 2 millimetres.

Earth connotes material in which about 80 per cent or more of the fragments are smaller than 2 millimetres; it includes a range of rock and mineral fragments from non-plastic sand to highly plastic clay.

During landslide movement, slope materials are subjected to different degrees of internal disruption; therefore, parts of names that describe materials can change accordingly. Falling bedrock blocks can be broken by impact and bouncing into mixtures of rock fragments appropriately termed “debris”. Engineering soils (including debris) can be disaggregated into their constituent particles. Some special kinds of parent materials can be altered in place by dynamic shaking during an earthquake. For example, some layers of wet sand can undergo liquefaction and flow, causing “sand boils”, and dry loess (wind-deposited silt and sand) with a porous structure may collapse into dry flow.

6.1.2 Mechanism and rate of movement

Mechanism and rate of movement are closely associated; however most mechanisms operate over a range of rates (Table 12) that overlaps with the ranges of other mechanisms.

Table 12 **Summary classification by rate of movement** /Varnes, 1978/

Extremely Rapid	3 m/sec or greater
Very Rapid	0.3 m/min - 3 m/sec
Rapid	1.5 m/day - 0.3 m/min
Moderate	1.5 m/month - 1.5 m/day
Slow	1.5 m/year - 1.5 m/month
Very Slow	0.06 m/year - 1.5 m/year
Extremely Slow	less than 0.06 m/year

The rate of movement of any slide or flow can change quickly. Slides that move at rates described as moderate to slow are commonly at or near equilibrium between gravitational forces tending to drive the mass downslope and the frictional forces that resist sliding and/or internal deformation. Movement at rates described as moderate to very rapid commonly reflects sufficient disequilibria so that rapid acceleration and de-acceleration can occur. An extreme example is provided by rapid debris that develops from soil slips in colluvial soils on steep hillsides. Soil creep movement in colluvial soils on hillsides is generally extremely slow and may be undetectable. When saturated, as a result of heavy rainfall or rapid snowmelt, thin slabs of the material can fall as soil slips, with a relatively slow initial rate of movement. If the moisture content of the moving mass equals or exceeds the liquid limit of saturated material, remoulding caused by the slide movement can result in a change of state from a solid, sliding slab to fluid slurry that moves by flow. The change of state to a fluid is accompanied by a sudden, drastic reduction in the frictional resistance to movement, so that even though the gravitational driving forces remain constant, the mass accelerates downslope and can reach very high speeds.

Table 13

Landslides Classification by Slope Angle

Type of Landslide	Slope Angle
Mild slope	5° - 15°
Steep slope	15° - 45°
Very steep slope	> 45°

Table 14

Landslides Classification by Depth of the Sliding Body

Type of Landslide	Depth (m)
Surface	< 1
Shallow	1 - 5
Deep	5 - 20
Very deep	> 20

Table 15

Landslides Classification by Area Affected and Volume of the Sliding Body

Type of Landslide	Area Affected (m^2)	Volume (m^3)
Very small	< 100	< 100
Small	100 - 1,000	100 - 5,000
Moderately big	1,000 - 10,000	5000 - 100,000
Big	10,000 - 50,000	100,000 - 1,000,000
Very big	> 50,000	> 1,000,000

The other frequently used landslide classifications are generally made according to:

- slope angle of the incline susceptible to landsliding (Table 13)
- depth of the sliding body (Table 14)
- area affected and volume of the sliding body (Table 15), etc.

6.1.3 Causes of landslides

For the identification of causes of landslides it is necessary that the investigators have through knowledge of the conditions that affect slope stability, and expertise of slope failure. The elements that affect the slope stability are numerous and varied, and they interact in complex ways. They can be divided in four general groups:

- geology
- geomorphology
- hydrology and climatology
- vegetation

6.1.4 Triggering factors

Landslides will occur after sudden or gradual changes in the shear stress and strength conditions. The most important factors are:

- the water content of the geologic mass
- vibrations caused by earthquakes

The other factors influencing the triggering potential of landslides are:

- removal of lateral support
- loading of the slope (by natural or man-made means)
- weathering and other physical or chemical actions, etc.

6.2 Snow Avalanches

An avalanche is a mass of snow sliding down a mountainside. Avalanches are also called snowslides; there is no difference in these terms.

A snow avalanche results from an unequal contest between stress and strength on an incline. An avalanche occurs when the stress (from gravity) trying to pull the snow downhill exceeds the strength (from bonds between snow grains) of the snow cover. There are four dominant factors controlling the development of an avalanche:

- a steep slope
- a snow cover
- a weak layer in the snow cover
- a trigger

The strength of the snowpack is related to its density and temperature. Compared to other solids, snow layers have the unique ability to sustain large density changes. Thus, a layer deposited with an original density of 100 kg/m^3 may densify to 400 kg/m^3 during the course of a winter, largely due to the weight of over-laying snow, pressure melting and recrystallisation of the ice. On the other hand, the shear strength decreases as the temperature approaches 0°C. As the temperature rises, and liquid meltwater exists in the pack, the risk of movement of the snow blanket grows.

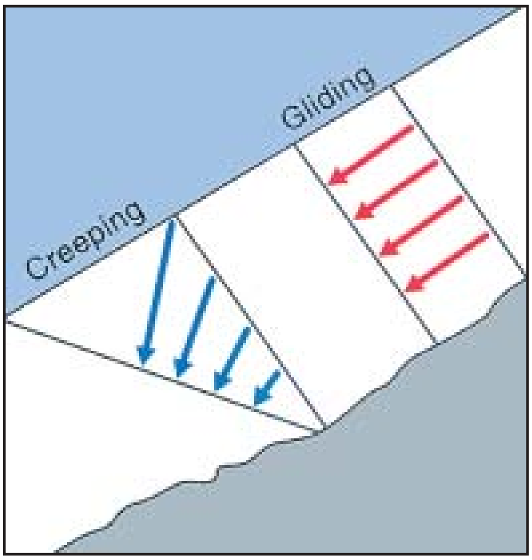
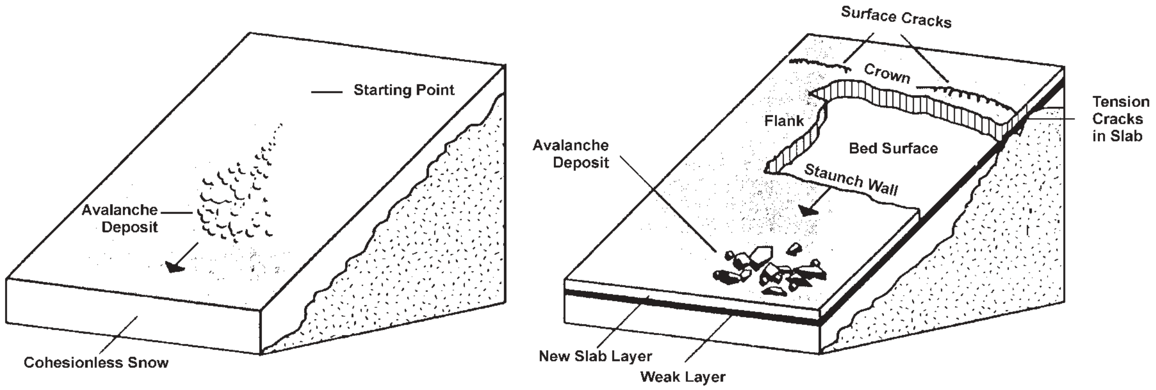


Fig. 33 **The creeping and gliding of a snow cover**

The snow cover on a slope (or a roof) is in both a slow-creeping and gliding state (Fig. 33). The normal creep rate of snow is usually several centimetres per day. Such motion is not an avalanche, unless the snow cover starts to break apart. Any object that is in the path of the creeping and gliding snow may be damaged if that object cannot withstand the snow pressure.

Most of snow loading on slopes occurs slowly. This gives the pack some opportunity to adjust by internal deformations, because of its plastic nature without any damaging failure taking place. The most important triggers of pack failure [and consequently the start of avalanche] tend to be heavy snowfall, rain, thaw or some artificial increase in dynamic loading, such as skiers traversing the surface, strong noise, etc.



a) Loose-snow Avalanche

b) Slab Avalanche

Fig. 34 **The creeping and gliding of a snow cover**

For a hazardous snowpack failure to occur, the slope must be sufficiently steep to allow the snow to slide. Avalanche frequency is thus related to the angle of the slope. Most events (about 90%) occur on intermediate slope gradients of 30° to 45°, and about 98% of all avalanches occur on slopes of 25° to 50°. Angles below 20° are generally too low for failure to occur and most slopes above 60° rarely accumulate sufficient snow to pose a major hazard.

Most avalanches start at a fracture point in the snow blanket where there is high tensile stress, such as a break of ground slope, an overhanging cornice or where the snow fails to bond to another surface, such as rock outcrop.

Avalanches release most often on slopes above the timberline that faces away from prevailing winds (leeward slopes collect snow blowing from the windward sides of ridges). They can also run on small slopes well below the timberline, such as gullies, road cuts, and small openings in the trees. Very dense trees can anchor the snow to steep slopes and prevent avalanches from starting; however, avalanches can release and travel through a moderately dense forest. Most avalanches occur in the backcountry, outside of developed ski areas.

Fig. 35 **Slab avalanche: The remaining layers show where the snow broke away**

All avalanches follow an avalanche path which comprises three elements: *the starting zone* where the snow initially breaks away, *the track* or actual path followed and *the route zone* where the snow decelerates and stops.

Avalanches tend to recur at the same sites, so the threat of future events can often be detected from the recognition of previous avalanche paths in the landscape. Clues in terrain include breaks of slope and eroded channels on the hillsides and evidence from damaged vegetation. Heavily forested avalanche paths can be identified by the age and species of trees and by sharp 'trimlines' separating the mature, undisturbed forest from the cleared slope.

6.2.1 Snow slope failure processes

In practice, avalanches are started by one of two quite distinct slope failure processes:

- *Loose snow avalanche* - this occurs in cohesionless snow where inter-granular bonding is very weak, thus producing behaviour rather like dry sand (Fig. 34a). Failure begins near the snow surface when a small amount of snow, usually less then 1m^3, slips out of place and starts to move down the slope. The sliding snow spreads to produce an elongated, inverse V-shaped scar.
- *Slab avalanche* - this occurs where a strongly cohesive layer of snow breaks away from a weaker underlying layer (Fig. 35), to leave a sharp fracture line or crown (Fig. 34b). Rain or high temperatures, followed by re-freezing, can create ice-crusts which may well provide a source of instability when buried by subsequent snowfalls. The fracture often takes place where the underlying topography produces some upward deformation of the snow surface, which leads to high tensile stress, and the creation of associated surface cracking of slab layer. The initial slab, which breaks away, may be up to 10,000 m^2 in area and up to 10 metres in thickness. Such large slabs release considerable amounts of energy and represent the most dangerous type of avalanche. When a slab breaks loose, it may bring down as much as 100 times the initially released amount of snow which is then deposited in a rather chaotic heap.

The character of avalanche motion also depends on the type of snow and the terrain. Most avalanches start with a gliding motion but then rapidly accelerate on slopes greater than 30°.

6.2.2 Types of avalanches

There are three types of avalanches:

Powder avalanches (Fig. 36) are formed of an aerosol of fine, dry and diffused snow behaving like a body of dense gas. They flow in deep channels and are not influenced by obstacles in their path. The speed of a powder avalanche is approximately equal to the prevailing wind speed but, being of much greater density than air, it is much more destructive than wind storms. At the leading edge its typical speed is 20-70 m/s and victims often die by inhaling snow particles. The turbulent dust cloud can reach heights of 400 metres and speeds of 200 kilometres per hour. The high pressure in front of the cloud can cause damages similar to an explosion.

Fig. 36 **An artificially triggered powder snow avalanche in an experimental test-site in the Vallee de la Sionne**

Granular flow avalanches: When the snow cover fails, a snow slab is set in motion and breaks up into blocks of different sizes. While in motion, the blocks become rounded and disintegrate into smaller granules or pellets. The granular mass flows like a massive river down the slope, reaching speeds of 50 to 100 kilometres per hour and destroying everything in its path. Granular avalanche deposits are as hard as concrete, making it extremely difficult for avalanche rescue and clearing teams. Considering the characteristics of the flowing snow, two types of avalanches containing primarily a dense core of granular snow are distinguished:

- *dry-flowing avalanches* are formed of dry snow travelling over steep or irregular terrain with particles ranging in size from powder grains to blocks of up to 0.2 metres in diameter. These, granular types of avalanches follow well-defined surface channels, such as gullies, but are not greatly influenced by terrain irregularities. Typical speeds at the leading edge range from 15 to 60 m/s but can reach speeds up to 120 m/s whilst descending through free air.
- *Wet-flowing avalanches* occur mainly in spring and are composed of wet snow either formed of rounded particles (0.1 to several metres in diameter) or a mass of sludge. Wet snow tends to flow in stream channels and is easily deflected by small terrain irregularities. Flowing wet snow has a high mean density (300 to 400 kg/m^3 compared to 50 to 150 kg/m^3 for dry flows) and can achieve considerable erosion of its track, despite reaching speeds of only 3 to 30 m/s.

6.2.3 Anatomy of an avalanche

An avalanche has three main parts:

- the starting zone
- the avalanche track
- the runout zone

The ***starting zone*** is the most volatile area of a slope, where unstable snow can fracture from the surrounding snow cover and begin to slide. Typical starting zones are higher up on slopes, including the areas beneath cornices and “bowls” on mountainsides. However, given the right conditions, snow can fracture at any point on the slope.

The ***avalanche track*** is the path or channel that an avalanche follows as it goes downhill. Large vertical swaths of trees missing from a slope or chute-like clearings are often signs that large avalanches run frequently there, creating their own tracks. There may also be a large pile-up of snow and debris at the bottom of the slope, indicating that avalanches have run.

The ***runout zone*** is where the snow and debris finally come to a stop. Similarly, this is also the location of the deposition zone, where the snow and debris pile the highest. Although underlying terrain variations, such as gullies or small boulders, can create conditions that will bury a person further up the slope during an avalanche, the deposition zone is where a victim will most likely be buried.

6.2.4 Factors causing an avalanche

The following factors dominantly affect the likelihood of an avalanche:

- weather
- temperature
- slope steepness
- slope orientation

- wind direction
- terrain
- vegetation
- general snowpack conditions

Different combinations of these factors can create low, moderate or extreme avalanche conditions. Some of these conditions, such as temperature and snowpack, can change on a daily or even hourly basis. These factors often occur in combination to produce an avalanche, but if a slope is unstable in any way, it may take only the weight of one skier to set off an avalanche.

Weather: Avalanches are most likely to run either during or immediately after a storm where there has been significant snowfall. The 24 hours following a heavy snowstorm are the most critical. Consequently, it becomes important to be aware of current weather conditions as well as the conditions from the previous couple of days. Temperature, wind, and snowfall amount during storms can create fatal avalanche conditions.

Snowfall: Recent snowfall puts extra stress on the existing snowpack, especially if it does not adequately bond to the pre-existing surface layer. The extra weight of new snow alone can cause a slab to break off and fall down the slope, particularly in storm-induced avalanches. Snowfall amounts of 30 to 40 centimetres or more (frequent in mountainous areas) create the most hazardous situations, producing avalanches that are often large enough to block highways and cause major destruction. Amounts of 15 to 30 centimetres pose some threat, particularly to skiers and recreationists. Amounts less than 15 centimetres seldom produce avalanches.

Temperature: Snow is a good insulator, therefore, small temperature changes do not have as much effect on snowpack as larger or longer changes do. For instance, shadows from the sun crossing the snow surface throughout the day will not significantly change snowpack stability. Changes that last several hours or days, such as a warm front moving through, can gradually increase temperatures that cause melting within the snowpack. This can seriously weaken some of the upper layers of snow, creating increased avalanche potential, particularly in combination with other factors.

When temperatures rise above freezing during the daytime and drop back down again at night, melting and re-freezing occurs, which can stabilize the snowpack. This is particularly common during the springtime. When temperatures stay below freezing, especially below 20 degrees Celsius, the snowpack may remain relatively unstable.

Wind direction: Wind usually blows up one side of a slope or mountain (the windward side), and down the other (the leeward side). Blowing up the windward slope, wind will “scour” snow off the surface, carry it over the summit, and deposit it on the leeward side. What this does is pack snow unevenly on the leeward side, making it more prone to avalanche. A cornice or icy overhang at the top of a mountain or ridge is a telltale sign of wind scouring.

Although it seems like a small amount because the snow may look light and powdery, the weight can add up significantly and can be a critical factor if a slope is already unstable. In the Northern Hemisphere, storms generally move from west to east. Consequently, the leeward slopes are most often the northeast, east, and southeast facing slopes. These slopes become easily wind-loaded and will more readily provoke an avalanche.

Snowpack conditions: Perhaps the most significant factor (but not the only one) is how the snowpack has developed over the season. The surface and maybe the top few layers of snow can only be seen, but it can be a deeper layer of snow that may ultimately determine whether the slope will fail.

Understanding the history of snowpack for that season can reveal several clues about slope stability. The snowpack as a whole may change not only during the course of the winter season, but throughout the course of a single day, due to changing weather and temperature conditions.

Snowpack conditions are extremely important because many layers of snow build up over the winter season. Each layer is built up under different weather conditions and will bond differently to the subsequent layers. Snowflakes, or snow crystals, within the snowpack eventually become more rounded due to melting/re-freezing and settlement. This metamorphism allows them to compress and (generally) form stronger bonds.

In between snowfalls, the temperature may rise and melt the exposed surface layers, which, when re-freeze, create a smoother, less stable surface for the next snowfall. Failure is much more likely to occur during or after the next few snowfalls. Rain between snowfalls creates a slicker surface as well, and can weaken the bonds between snow layers. On the other hand, light snowfalls and consistently cold temperatures help strengthen the snowpack and make it more resistant to avalanche. Weak layers deep in the snowpack can cause avalanches even if the surface layers are strong or well bonded.

A type of snow called *depth hoar* (a coarse, grainy form of snow crystal) is often the culprit behind avalanches. Because of its granular structure, similar to dry sand, depth hoar bonds poorly and creates a very weak layer in the snowpack. Unfortunately, the weather conditions necessary to produce depth hoar most often occur very early in the season, and these weak layers are buried under subsequent snows. All too often, deeper depth hoar layers are discovered only after an avalanche has swept off the overlying layers.

Slope angle: Most avalanches occur on slopes between 30 and 45 degrees, but can occur on any slope angles given the right conditions. Very wet snow will be well lubricated with water, meaning it might provoke an avalanche on a slope of only 10 to 25 degrees. Very dry or granular snow will most likely provoke an avalanche on a slope close to the 22-degree angle of repose. Compacted, well-bonded layers create a snowpack that can cling to steeper slopes until a weak layer is created.

Slope orientation: Although avalanches will run on slopes facing any direction, most avalanches run on slopes facing north, east, and northeast (also the slope directions that most ski areas are located on). Because the sun is at such a low angle, particularly during the winter, a colder and deeper snowpack develops. Slopes that are under shadow throughout most of the day are suspect because the snowpack remains cooler, without much of the melting and bonding that can make the snow layers stronger.

Certain slope orientations are much more affected by wind-loading, particularly northeast, east, and southeast (similar to the orientations mentioned above).

Terrain: Bowls and gullies are suspect for avalanche potential at any time, regardless of other conditions. Snow can accumulate deeply and quickly in these areas, increasing the possibility of an avalanche. Even if an avalanche has already run, there is a possibility for the next one to be generated. Avalanches can fall in a “piecemeal” fashion, where one avalanche will run and leave the rest of the slope weakened, and the slightest provocation can cause subsequent avalanches on that same slope. Smaller depressions or shallow gullies in the mountainside can also be hazardous. During an avalanche, these *“terrain traps”* serve as accumulation points for snow and debris in which a victim could be buried.

Vegetation: On a snow-covered slope, heavily forested areas are much safer than open spaces, but it should not be assumed that any vegetation at all would be protective. Lone trees, bushes, or large rocks on a mountainside can sometimes weaken the stability of the snowpack. A fracture line (the break-off point for an avalanche) may run from a lone tree, to a rock, or to another tree. Also, during avalanches, trees and rocks catch debris and cause excessive snow pile-up, as well as provide lethal obstacles for anyone caught in an avalanche.

The tree line, above which conditions become too harsh for trees to grow, also plays a significant role in avalanche areas. Many avalanches start above the tree line, making high-elevation mountains especially risky. Although forests help stabilise the snowpack, if an avalanche starts above the tree line, it can cut its own path, or chute, through the trees below. Likewise, where there is a swath of trees missing from a forested mountainside, there are probably frequent avalanches running down that particular chute.

Smooth surfaces, such as a rock face or grassy slope, may cause avalanches during the spring melting season. On the other hand, if the vegetation is very low-lying, such as tree stumps or shrubs, it can become buried underneath the first few snows and be relatively ineffective at anchoring the upper layers of the snowpack.

6.2.5 Avalanche danger scale

American and European avalanche danger scales (Table 16) rate avalanche hazard similarly. However they use slightly different colours. The differences are as noted in Table 16.

Table 16 **Avalanche danger scale**

Danger degree	Description
LOW	• Snowpack is generally stable • Only isolated areas of instability • Backcountry travel is fairly safe • Natural or human-triggered avalanches unlikely GREEN in both European and American scales
MODERATE	• Some areas of instability • Natural avalanches unlikely; human-triggered avalanches possible • Backcountry travel possible with caution YELLOW in both European and American scales
CONSIDERABLE	• Unstable areas probable • Natural avalanches possible; human-triggered avalanches probable • Backcountry travel possible with extreme caution OCHRE in European scale, ORANGE in American scale
HIGH	• Unstable areas highly likely on various slopes and aspects • Natural and human-triggered avalanches highly likely • Backcountry travellers should avoid steep slopes and wind-loaded slopes ORANGE in European scale, RED in American scale
EXTREME	• Extremely unstable layers in snowpack • Natural and human-triggered avalanches are certain • Large destructive avalanches probable • Backcountry travellers should avoid any steeply angled terrain or known avalanche areas RED in European scale, BLACK in American scale

7. Biophysical hazards - WILDFIRES

The term *'biophysical hazards'* covers a wide spectrum of environmental hazards that exists because of interactions between the geophysical environment and biological organisms, including humans.

Wildfire is a generic term for uncontrolled rural fires. Wildfires occur as a result of simultaneous action of three basic factors:

- Fuel (vegetation of all kinds)
- Weather conditions
- Ignition source

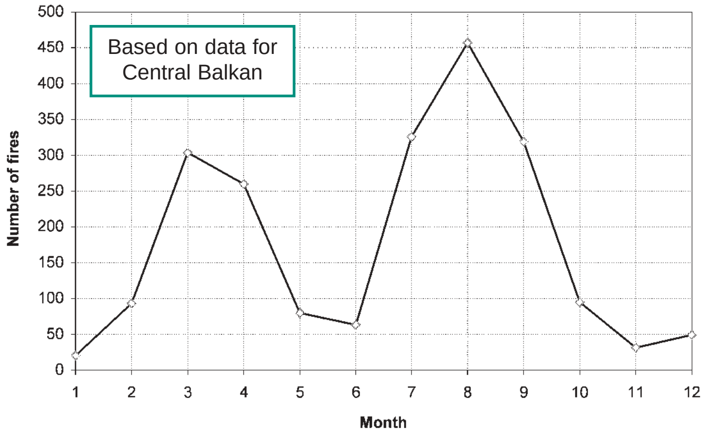


Fig. 37 **Typical annual rate of forest fire occurence**

Unfavourable combination of these three factors constitutes a potential wildfire hazard.

In general, high temperatures and drought following an active period of vegetation growth provide the most hazardous conditions. This means that the most hazardous zones tend to have either a Mediterranean or a continental climate with xerophytic and sclerophyllous vegetation. In the former, most of the rain which supports the natural cover of forests and grassland, as well as the agricultural crops, falls in the winter so that the vegetation is dry during the annual summer drought. Moreover, most continental interiors experience dry air for much of the year and have, consequently, a long fire season.

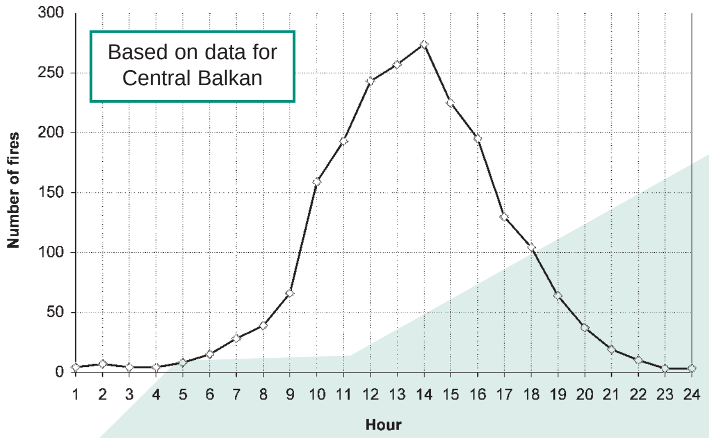


Fig. 38 **Typical daily rate of forest fire occurence**

Because wildfires are primarily rural hazards, there is always some damage to ecosystems. After the major event, timber and forage may be destroyed, animal habitats disrupted, soil nutrient stores depleted and the value of amenities greatly reduced for a long period of time. When the burned areas consist of steep canyons, debris flows, rill erosion and floods are likely to follow due to lack of stabilising vegetation and the amount of loose ash left by the fires.

7.1 Parameters controlling the wildfire risk

Assuming that a source of ignition exists, the occurrence and severity of wildfires are determined by two interdependent factors:

- fuel
- weather

Fuel influences both the intensity of the fire (heat energy output) and the rate of speed of the fire front. The grassland fires, therefore, rarely produce the intensity of burn, and degree of threat that is associated with forestland. Apart from the quantity and energetic potential of the fuel, its moisture content is important depending on factors such as season and weather. These relationships lead to a marked seasonal procession of risk (Fig. 37).

This risk procession is determined by the moisture content of the fuel, which is climatically driven by the sequence of rains.

Weather conditions are also crucial for wildfires. Drought periods, followed by hot, dry winds blowing from arid regions over a period of days, have a cumulative heating and drying effect on vegetation. These are also atmospheric conditions which promote dry lightning storms that are a frequent ignition source. Once ignited, the rate of fire spread is closely related to the surface wind strength.

Topography and weather conditions combined play a paramount role. On a plain terrain and under conditions of wind non-existence, the fire form is a circle (Fig. 39). Driven by single-directivity wind, the fire has an elliptical form (Fig. 40). The irregular fire form is a consequence of sloped terrain and wind blowing in several directions (Fig. 41).

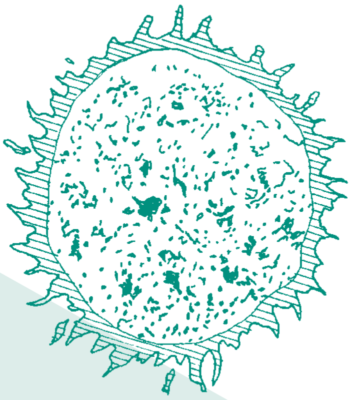


Fig. 39 **Circular shape of forest fire**
/flat terrain, no wind/

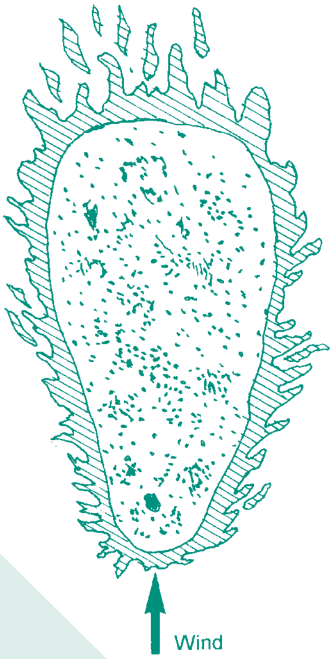


Fig. 40 **Eliptical shape of forest fire**
/flat terrain, wind in one direction/

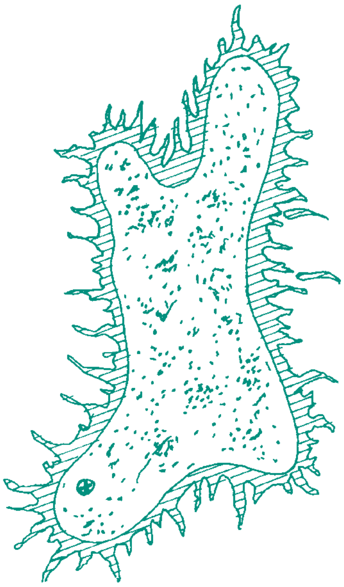


Fig. 41 **Irregular shaped forest fire**
/inclined terrain, variable wind directions/

Compared with the total duration of fire, the most wildfire damage, including loss of life, occurs during a relatively short period of time – usually a few hours. These high-loss episodes are associated with extreme fire risk weather, often involving high winds which shift in direction and cause the fire to accelerate and advance in unexpected directions. Such fire acceleration and advances can be greatly aided by topography. For a fire driven upslope (Fig. 42), wind and slope acting together increase propagating heat influx by exposing vegetation ahead of the fire to additional convective and radiant heat. The combined effect of wind and slope is to position the advancing flames in an acute angle so that, once the slope exceeds 15-20°, the flame front is effectively a curtain moving parallel to the slope. Data (Australia, grassland and eucalyptus land) have shown that the rate of forward fire advance on level ground doubles by 10° slope and increases nearly four times when travelling up a 20° slope.

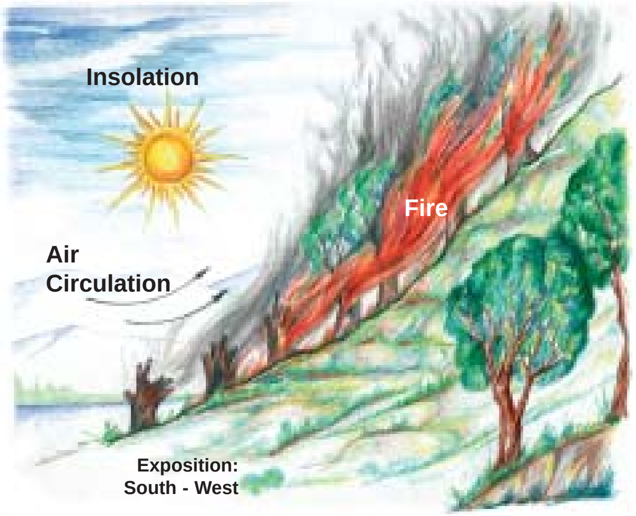


Fig. 42 **Influence of the relief on forest fire spreading**

7.2 Process of ignition and burning

The fire-susceptible material (fuels) which is permanently present in forests is more or less represented by the leaves of the forest trees and bushes, the trunks and branches, the low growing vegetation consisting of annual and perennial plants (life fuels) and a covering layer consisting of fallen leaves, branches and withered plants (dead fuels).

The fire can occur only in the presence of oxygen. The concentration of oxygen varies from case to case depending on the fuel type. The concentration of oxygen is lower in compact fuel material, as is the covering layer of fallen leaves, branches, withered plants and thick pieces of wood. Hence their burning is slower - initial smouldering, whereas in loose fuels the occurrence of flames that stir up the fire is easier due to the larger concentration of oxygen.

Unlike the fuel material and the oxygen that are always present in the forests, the inflammable spark results from external factors.

The process of ignition and burning of fires consists of three phases:

- ***Heating up.*** This is the phase when the inflammable spark with its heat increases the temperature of the fuel material up to 100°C leading to its loss of moisture and drying. If the heating continues, it causes a further rise in temperature of up to 200°C which leads to total loss of moisture.
- ***Burning*** of gases starts at a temperature between 300 and 400°C leading to expansion of inflammable gases and the occurrence of flames. In this phase, the temperature rises to 600 to 1000°C. Apart from the gases, there is expansion of heat that stimulates the burning process and the spreading of fire. The timber burns in a bluish fire accompanied by smoke.
- ***Carbonisation of wood*** that burns into ashes. In this phase, the fire is almost extinguished for a while and its continuation depends on whether there is a sufficient quantity of easily inflammable, compact fuel material. In this phase, a slight smoke most frequently accompanies the fire wherefore it may not be detected for a longer period of time.

7.3 Fire spreading

If the fire sustains the carbonisation phase, it spreads over the adjacent fuel materials. This may happen in three different ways:

- radiation – the heat is transferred via the air molecules
- conduction – the heat is transferred through the fire material
- convection – the heat is transmitted upward to the cooler layers

A special problem of rapid spread is known as *"spotting"*. This occurs when ignited fuel is blown ahead of an advancing fire front by strong winds to create new *"spot"* fires. The main reason for this is bark shedding by the stringy bark and candle bark species, which produce loose, fibrous tapers easily torn loose by strong winds and convection currents. Spotting distances recorded in deciduous hardwood and coniferous forest fires may be up to 15 km, and even more depending on the wind speed.

7.4 Causes of wildfires

Two origins of wildfires have been clearly distinguished:

- ➠ lightning (natural origin)
- ➠ human action (anthropogenic factor)

Forest fires ignited by lightning most frequently occur in the deep forests in Canada, the USA, Scandinavia and Siberia (20 to 40% of the fires). In Australia, the most fire-prone country in the world, lightning is responsible for less than 10% of the 2,000 or so wild fires that occur each year. In the Mediterranean countries this percentage is much lower (1 to 3%).

Most of the forest fires are of anthropogenic origin (Fig. 38). They are classified into several groups:

- accidents (explosions, traffic)
- carelessness (passer-by, tourists, children's games, disorganized garbage depots, etc.)
- agricultural fires (burning of stubble fields as agrotechnic measure)
- arson fires

7.5 Wildfire typology

Fires are usually recognized according to the layer of vegetation which they consume, that is:

- ➠ ground fires are fires that burn below the surface in deep organic matter such as peat beds
- ➠ surface fires and fires that burn the surface vegetation such as grass, crops, low scrubby vegetation, etc.
- ➠ crown fires are forest fires that consume the three canopies

Ground fires. Ground fires "smoulder" below the ground surface where burning of deep and dense moss deposits, peat, decayed leaves, tree stumps, roots and other remains takes place. Ground fires can hardly be detected. Sometimes a period exceeding one month may pass before they are detected, especially if they occur in forests that are far from inhabited places.

Surface fires. Surface forest fires spread over fuel materials involving weathered grass, shoots and bushes, the covering layer of the ground, fallen branches, and other forest litter. Such a fuel material contains small and easily inflammable particles that add to the burning process. Under wind conditions, the fire spreads quickly over loose fuel materials, i.e., it smoulders slowly through the fuel material deposits protected from the wind. If the surface of the terrain is covered by a sufficient amount of compact fuel material, the surface fire can become very strong and spread over the three canopies developing into a crown fire.

Crown fires. Crown fires occur when the fire reaches the canopy and the high tree trunks. The fire quickly spreads through the canopy, especially in evergreen forests reaching a speed of up to 10 km/hour. During the burning process, large flames and strong air vortexes are formed, accompanied by a large number of inflammable sparks and firebrands that add to the spreading of the fire. Crown fires most frequently occur in periods of heavy droughts and strong winds and are extinguished with a great difficulty.

8. Biologic hazards - EPIDEMICS

The World Health Organization has defined an epidemic as *"the occurrence of a number of cases of a disease, known or suspected to be of infectious or parasitic origin, that is usually large or unexpected for the given place and time. An epidemic often evolves rapidly so that a quick response is required".*

From this definition it is clear that epidemics share many characteristics of rapid-onset environmental hazards.

The conditions necessary for epidemics often exist long before the outbreak occurs and the disease itself may well be endemic to the region. In all cases, a pathogen needs to be introduced into a suitable environment followed by an incubation period. The outbreak itself is often triggered by other events, which may include natural disasters, since they provoke large population movements and the subsequent over-crowding and poor sanitation found in refugee camps. The migrants themselves can bring in new pathogens or may move into contaminated area and catch the disease because of their higher susceptibility.

The other factor that can significantly add to the deterioration of the sanitary conditions, and therefore contribute to epidemic outbreak, is physical disruption of water supply and sewage disposal systems. The problem becomes more severe in areas where sanitation levels are already minimal.

Despite the above comments, it appears that major outbreaks of communicable diseases after natural disasters are comparatively rare, although considerable potential exists. Such a disaster-related disease outbreak could occur as a result of the following six factors:

- the diseases present in the population before the event
- ecological changes resulting from a disaster
- population movements
- damage to public utilities
- the disruption of disease control programmes
- altered individual resistance to disease

Such factors often act together.

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[1] In its original definition, magnitude (denoted by M) is the common logarithm of the trace amplitude (in microns) of a standard Wood-Anderson seismograph having a magnification of 2,800, a natural period of 0.8 s, and a damping coefficient of 80 percent, located on firm ground 100 km from the epicentre.

[2] During the past 15 years, about 80 commercial jets have been damaged by inadvertently flying into ash clouds, and several have nearly crashed because of engine failure.

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