HAZARDS AND THE HIMALAYA

LANDSLIDES AND EARTHQUAKES

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1. NATURAL HAZARDS

In this chapter we will explore the following questions:

- What is a natural hazard?
- When does a hazard become a disaster?
- How can we reduce the risk of disasters?

1.1. WHAT IS A NATURAL HAZARD?

Figure 1. Small volcanic eruption at Santiaguito, in Guatemala.

A natural hazard is the threat of **a naturally occurring event that can cause damage to the environment and the people living in it**. This definition includes all naturally occurring dangerous events whether they occur because of active geology or extreme weather. Examples include: **earthquakes, volcanic eruptions, landslides, tsunamis, hurricanes, wildfires** and **floods**.

Events such as war, traffic accidents or disease are not considered to be natural hazards as they are not a result of the natural physical processes of the Earth.

The threat that a particular hazard event presents will vary depending on geographic location. For example, countries located around the Pacific Ocean have a higher threat of large earthquakes and volcanic eruptions than many countries in Northern Europe. The threat of a large earthquake in Japan is much greater than in the United Kingdom.

In mountainous regions, such as the Himalaya, significant threats come from rockfalls, landslides, extreme storms, floods and earthquakes.

Many **natural hazards can trigger another hazard to occur**. For example, a large earthquake in the rock beneath the sea can generate a tsunami (a large ocean wave caused by the displacement of the sea), or heavy rainfall from a large storm can cause floods and large landslides (as rain is absorbed into the landscape and weakens slopes).

Natural hazards can directly and indirectly affect people. People living on the slopes of a volcano will be directly affected if there is an eruption. However the ash and dust thrown out by an eruption can also affect people many hundreds of kilometres away. Another example can be seen in the December 2004 earthquake in Indonesia, one of the largest earthquakes ever recorded. The earthquake directly killed thousands of people in Indonesia, however the tsunami generated by the earthquake also killed hundreds of thousands of people, both in Indonesia and other countries far away (e.g., Sri Lanka, Tanzania).

1.2. HOW DOES A HAZARD BECOME A DISASTER?

A disaster is an event in which there is large loss of life and widespread damage to infrastructure and property, i.e. roads, buildings and bridges. The 2005 Kashmir earthquake was a disaster because it resulted in a large number of deaths (around 86,000), the destruction of thousands of buildings in the region and tremendous economic loss.

A very common term used by media is **'natural disaster'**. In reality **there is nothing natural about disasters.** A disaster is a result of the impact of a hazard on people and societies. The decisions we make within these communities and societies can impact whether the occurrence of a hazard becomes a disaster.

This concept is best explained with an example: the earthquake hazard for a region may be very high but if no people live there the occurrence of an earthquake will not cause any loss to human life or property, there will not be a disaster. The occurrence of an earthquake in a region where people live and infrastructure or properties exist could result in a disaster.

Disasters only occur when people are affected by a natural hazard.

Some key ideas relating to how and why disasters can occur are (i) **exposure** and (ii) **vulnerability of individuals, communities and society** to natural hazards. Exposure and vulnerability are both important concepts that address the relationship between humans and hazard.

EXPOSURE

Exposure is essentially an indicator of **the number of people who may be affected,** without any protection, by a particular natural hazard. It could also be the number of properties, or the value of assets. Exposure depends on geographic location. For example, people living in mountain regions are highly exposed to landslide hazards, those living close to rivers are exposed to flooding.

Example: Imagine you have two identical mountain slopes, each with a community of people living on them. Slope A has 1000 people and Slope B has 500 people. The exposure to landslides on Slope A is twice as big as the exposure on Slope B, as there are twice as many people that could be affected by a dangerous event such as a landslide.

VULNERABILITY

Vulnerability is a highly complex concept and no single definition exists.

One helpful definition is that **vulnerability is the capacity of an individual, community or society to anticipate, cope with, resist and recover from the impact of a natural hazard**. In general this refers to the potential of an individual or group to be harmed by a natural hazard.

Vulnerability is **dynamic**; it can change (either increasing or decreasing) as factors change. It is influenced by gender, age, poverty, inequality, culture, effectiveness of policy making and planning, corruption and many other factors.

For example, women are often more vulnerable to natural hazards than men. This is in part because women are less likely to have access to financial resources and education, and more likely to be politically marginalized due to sexism in societies around the world. Women often face additional burdens as family caretakers. When a hazard occurs, it is often women who are responsible for protecting children and the elderly. This leaves them less mobile, therefore more likely to experience harm.

EXPOSURE VS. VULNERABILITY

The difference between exposure and vulnerability can be explained with an example. Nomadic tribes living in the high plains of Tibet are **highly exposed** to very low, life threatening, temperatures. However, these people have been living on the Tibetan plains for many generations and have a lifelong experience of living with such extreme cold weather. They know how to dress appropriately to keep warm and protect themselves from low temperatures. Therefore they have a **low vulnerability** to the freezing temperatures.

Together exposure and vulnerability give a measure of how badly a community might be affected by a natural hazard. Low exposure and low vulnerability is the ideal situation. Any other combination is not desirable.

A disaster will only occur if a natural hazard impacts upon a vulnerable community who are exposed to the hazard.

1.3. CAN WE REDUCE THE IMPACTS OF DISASTERS?

Over the last couple of decades there has been a major shift in our approach to managing disasters. The traditional approach was focused on **disaster response** and how to help those affected by a particular event, whereas now the approach focuses more on **disaster reduction**.

Disaster reduction involves **planning ahead** and trying to reduce the chance of a disaster by **better understanding natural hazards** and **reducing people's vulnerability**, rather than helping people once they are already affected (disaster response).

A number of large international organisations help countries to consider disaster reduction. They include the United Nations Office for Disaster Risk Reduction (UNISDR), the Global Facility for Disaster Risk Reduction (GFDRR) and the World Bank. National and local governments, NGOs/charities and universities are also involved in this important work.

The key approach to reducing the impacts of a disaster is by minimising the risk societies face to these events. The risk of a particular hazard is a product of the **likelihood the hazard could occur multiplied by the exposure and vulnerability of a society to that hazard** (**Figure 2**).

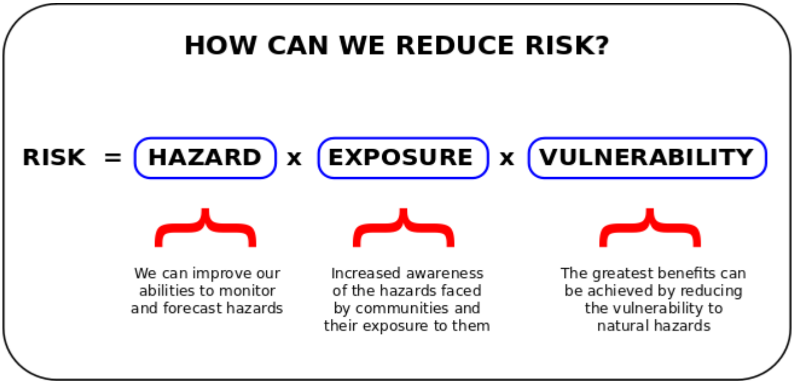


Figure 2. Disaster Risk. Hazard, exposure and vulnerability are all important parts of the risk calculation. The above figure shows how risk is calculated and highlights how we can reduce risk.

In order to reduce the risk, we can attempt to minimise or better understand (A) the hazard, (B) the exposure or (C) the vulnerability.

A. IMPROVED KNOWLEDGE OF THE HAZARD

Accurate and detailed knowledge of the hazards faced by society is critical for reducing disaster risk. A better understanding of hazards in a particular area will enable scientists to make improved forecasts that will ultimately aid in preparing for the event when it does occur. For example, a better understanding of floods can help to improve the accuracy of forecasts, allowing the people likely to be affected to be evacuated in good time. The work of understanding natural hazards is often undertaken by geologists and geoscientists.

B. INCREASED AWARENESS OF EXPOSURE

Once a hazard is known about, we can accurately assess who is exposed to it and attempt to reduce that exposure. Reductions in exposure will often require better planning of where communities can settle. For example, people living at the base of an actively eroding mountain are exposed to landslides. Exposure can be reduced by building houses away from the base of the mountain.

C. REDUCE VULNERABILITY

The greatest scope to reducing risk lies in reducing individual and community vulnerability to the hazards. Methods include improving education and awareness of the hazards faced by communities, empowering women, reducing poverty and inequality, improving construction standards for houses and infrastructure, and better planning for what to do when a hazard does occur.

Reducing the risk to disasters requires efforts on all levels from the international community, to governments and individuals.

International organisations such as UNISDR and GFDRR work together with scientists, businesses and governments to help developing countries reduce their vulnerability to natural hazards and adapt to climate change. These organisations can also pressure governments to create and implement better **policies for disaster preparation and management**. A policy is a set of rules (maybe a law) that details how one should behave/act in certain situations. For example, the government of Japan has recognised that it has a high potential for earthquake hazards. They have created policies to manage building construction and ensure all buildings are earthquake resistant.

Creating good policies is an important step to reducing vulnerability to natural hazards on a large scale. Once policies are in place, citizens and organisations of a country must follow them or face legal action. On the other hand, individuals can also contribute to reducing their own and their family's risk to disasters.

For example, if you live in a landslide prone region then keeping a small pack of tinned food, clean water and a first aid kit might keep you alive while you're stuck in a building. If you live in a flooding prone region you can build your house on raised platforms to reduce the chance of flood waters entering your home. People living in earthquake prone regions can ensure all large easily movable furniture (e.g. book cases) is bolted to the wall, exits out of the house are never blocked, and children are taught what to do in an earthquake, who to contact and where to go.

Small lifestyle changes will often make a family and individual less vulnerable in the face of a disaster.

2. LANDSLIDES

In this chapter we will explore the following questions:

- What is a landslide?
- What natural and human factors influence whether a landslide occurs?
- What are the impacts of landslides? Why is it important to study them?
- Is there anything we can do to manage the risk from landslides?

2.1. INTRODUCTION

WHAT IS A LANDSLIDE?

A **landslide** is the general term for the **downwards movement of surface materials** (including rock, soil, earth or debris). The photographs in **Figure 3** show a number of examples of landslides in China and India.

Figure 3. Landslides in Gansu, China (top row) and Ladakh, India (bottom row)

In these photos we see that landslides can be a range of sizes, involving different volumes and types of material.

WHY STUDY LANDSLIDES?

Landslides are a serious problem in many parts of the world. They cause loss of life, injuries, damage to property and infrastructure and destruction of crops and farmland. It is important to understand these geological processes, what causes them and what actions we can take to reduce their occurrence or impact.

LANDSLIDE TYPES

Landslides can be categorised into different types depending on the (i) type of **material**, (ii) amount of **water**, and (iii) type of **movement**. **Figure 4** (from the United States Geological Survey) shows a range of landslide types.

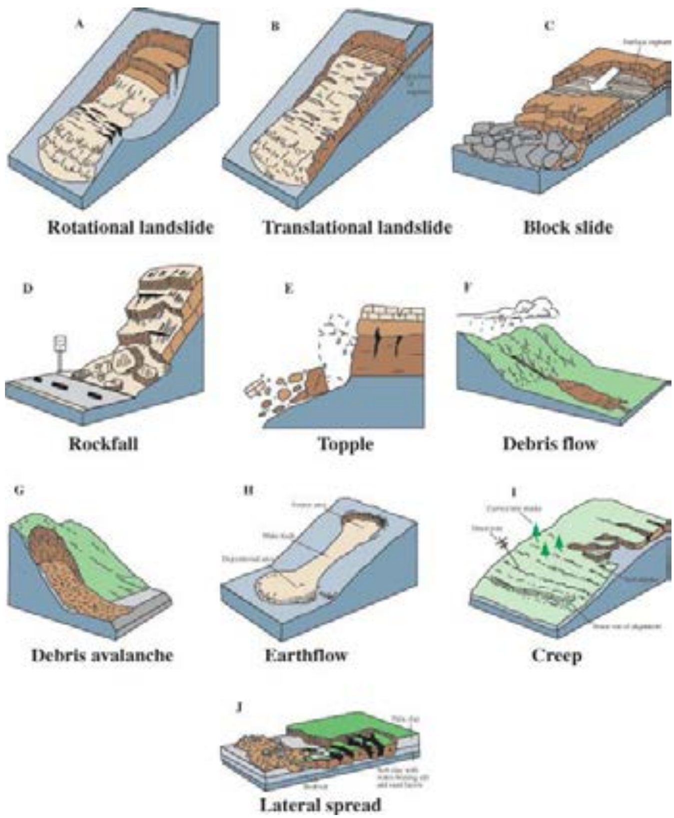


Figure 4. Landslide Types (United States Geological Survey, Fact Sheet 2004-3072, 2004)

LANDSLIDES IN LADAKH

In Ladakh a number of these landslide types are particularly common and important. They include rockfalls (**Figure 4D**) and debris flows (**Figure 4F**). The large landslide that impacted Leh in 2010 is an example of a debris flow.

2.2. FORCES IN A SLOPE

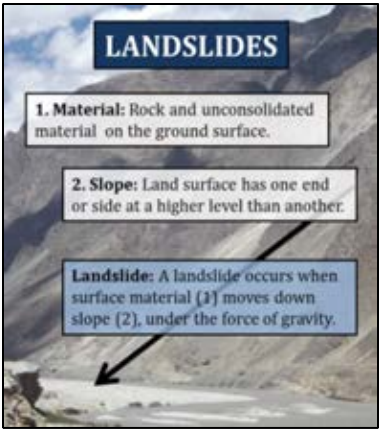


Figure 5. A landslide occurs when surface material moves down slope under the force of gravity.

As previously noted, a landslide is a general term for the downwards movement of surface materials due to forces of gravity.

This helps us to understand two key factors needed for a landslide to occur: (i) **surface material**, (ii) **variation in slope** (**Figure 5**).

We do not see landslides on every slope, at all times. This is because there are a number of other factors that influence whether a landslide will occur or not. These factors can be both natural (e.g., rainfall) and human (e.g., deforestation).

If one or a number of these factors change, this can increase or decrease how likely it is that a landslide will occur (or how stable the slope is).

SLOPE STABILITY

Assessing the stability of a slope involves analysing the forces acting on the slope. Forces can either be:

Driving Forces: These are the forces that promote the movement of material downslope. *An increase in these forces will make a landslide more likely.*

Resisting Forces: These are the forces that resist downwards movement. *An increase in these forces makes a landslide less likely.*

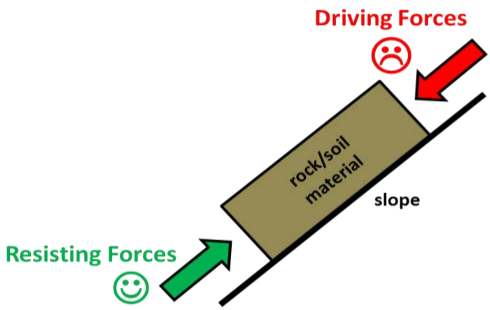


Figure 6. A landslide occurs when driving forces are greater than resisting forces.

If **driving forces are greater than resisting forces**, a slope is unstable and landslides more likely to occur (the slope is more **susceptible** to landslides occurring). If **driving forces are less than resisting forces**, the slope will be stable and landslides less likely to occur (the slope is less susceptible to landslides occurring).

Through understanding the driving and resisting forces, and the natural and human processes that may cause them to change, we can better understand how slopes become more or less susceptible to landslides. In the following pages we look in detail at some of these factors and their effects.

2.3. FACTORS INFLUENCING LANDSLIDE OCCURRENCE

NATURAL FACTORS

A range of natural factors can affect the landslide occurrence, through changing the driving and resisting forces. These include slope angle, rock/soil type, weathering, water and vegetation.

A) Slope Angle: Changes in the steepness of a slope (or angle) can change the driving or resisting forces.

- If a slope is shallow or gentle (**Figure 7-left**), driving forces are reduced and resisting forces are increased. This means a landslide is less likely.
- If a slope is steep (**Figure 7b-right**), driving forces are increased and the resisting forces are reduced. This means a landslide is more likely.

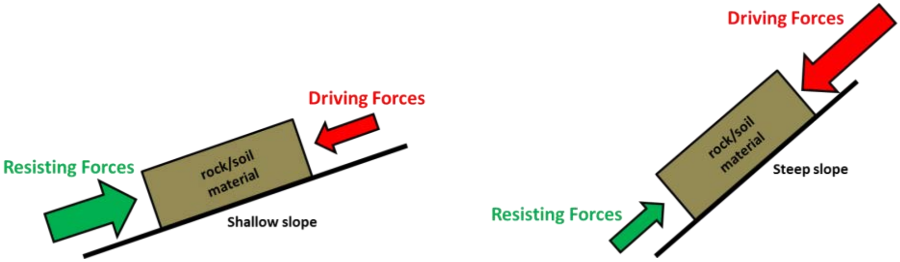


Figure 7. Changes in the slope steepness will change the distribution of resisting and driving forces.

B) Rock/Soil Type: Slope geology (type of rock and soil material) can be very important in understanding how susceptible it is to landslide activity. Some rock types are weak (e.g., chalk) and others are relatively strong (e.g., basalt, granite). In general landslides are more common in weaker rocks.

Different rock types also have different structures. Some have lots of fractures that can reduce the strength of the rock. In **Figure 8** we see two rock specimens, one with a few fractures and one with many fractures. The rock with many fractures is likely to be weaker due to the number and density of these fractures.

Other factors, such as the fracture width, orientation, roughness, and whether they are open or filled will also have an impact on the strength of the rock.

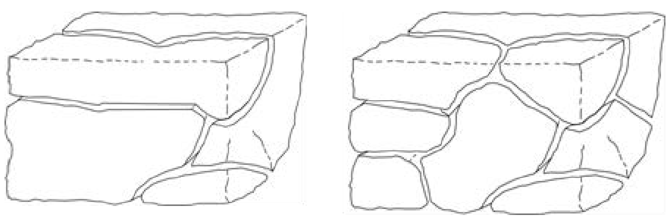


Figure 8. Fractures in the rock can reduce its strength.

C) Weathering: Weathering is a process where changes in temperature or water can change a material (by either physical or chemical processes) into another material. For example a rock such as granite can be changed by chemical processes into clay. The main effects of weathering are to (i) change rock composition, normally making it weaker, and (ii) increase the number of fractures, altering rock strength.

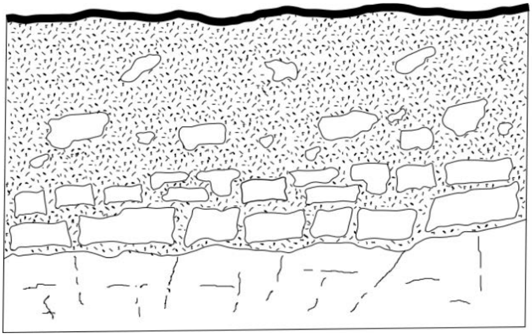


Figure 9. A typical rock weathering profile, showing loose, weak unconsolidated material at the top and stronger, solid rock at the base.

In **Figure 9** we observe a cartoon showing how weathering may affect the structure of the ground. Weathering is likely to change solid rock (seen at the bottom of the diagram) into soil and loose rock (seen at the top of the diagram). Such processes often increase the number of fractures in a rock. Weakened weathered rock is more susceptible to landslide events.

D) Water: Water is very important when considering factors that influence landslides. It acts in a number of ways to increase driving forces and reduce resisting forces.

The first way is through **erosion**. Rivers or streams at the base of slopes can cause erosion of the slope base (**Figure 10**). This undercutting can change the forces acting on the slope so as to make landslides more likely.

Figure 10. Rivers at the base of slopes can remove material, changing stability

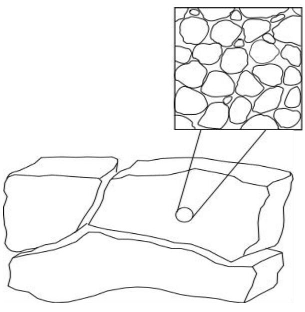


Figure 11. Fractures and Pore Space

The second way that water can influence landslide occurrence is by **reducing the material strength**. Increases in water can occur due to heavy rain or the melting of snow. Water enters rock and soil material, filling fractures in rocks and any small gaps between particles (known as pore space). Examples of both are shown in **Figure 11**.

As fractures and pore space are filled with water, the forces that help keep a material solid and rigid (called *effective stress*) decrease. When these forces are reduced, the overall resisting forces decrease and landslides are more likely to occur.

An important case study of heavy rain triggering a landslide is now discussed.

CASE STUDY: LEH CLOUD BURST

Background: On 6 August 2010 very heavy rain impacted the town of Leh in Ladakh. This event, commonly called a **'cloudburst'** resulted in rainfall ranging from 150-250 mm/hour. This intense precipitation across the slopes around Leh triggered mud and debris flows.

Causes: Heavy rainfall resulted in large amounts of water entering soil and rock material covering slopes. As the amount of water in the soil/rock increased, the effective stress decreased (**Figure 12**). As we discussed earlier, this results in a material losing its ability to stay rigid and solid, therefore reducing resistive forces. As these resistive forces were reduced further, slopes collapsed forming deadly debris and mud flows.

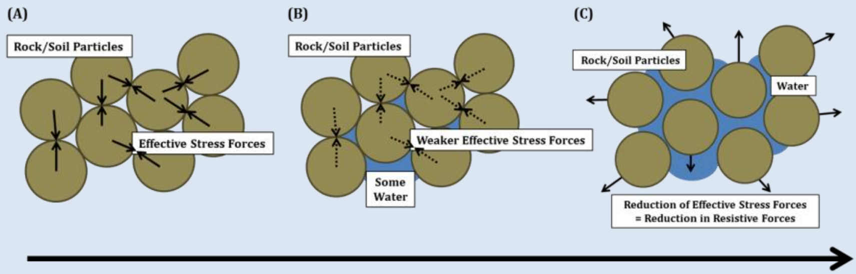


Figure 12. (A) Effective stress forces help a material to stay strong and rigid, (B) Increased water reduces the effective stress, weakening the material, (C) Further water reduces effective stress forces, resistive forces are reduced and a landslide triggered.

Impacts: Over 200 people died in the event. Debris flows also destroyed homes, roads, bridges, a hospital, drinking water canals, farmland and lines of communication.

E) Vegetation: Vegetation, including trees and plants, is very good at helping a slope stay strong. Roots infiltrate the soil and act as anchors, giving the slope additional strength. This strength means that there is an increase in the resisting forces and so the slope is less susceptible to landslides.

Plants/trees also help to remove water from the soil.

Figure 13. Vegetation acts as an anchor, increasing the strength of the slope.

F) Seismic Shaking: During an earthquake the ground undergoes a variety of movements (see **Section 3**). In slopes these seismic movements change the load due to gravity, increasing the driving forces. In mountainous areas the shape of the land makes these ground movements greater, especially in the peaks of hills.

HUMAN FACTORS

In addition to natural factors influencing the likelihood of a landslide, it is very important to recognise that **human actions can also change the driving or resisting forces**. As humans change or interact with a slope, they also change its properties, either making the slope weaker or stronger. In this section we outline some of the ways in which individuals and communities influence slopes so as to increase the likelihood of a landslide.

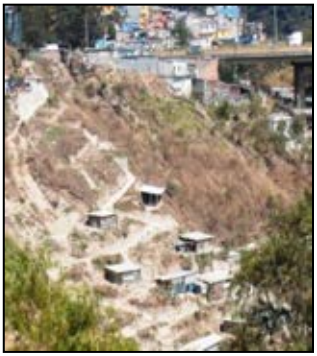


Figure 14. Construction of houses changes the forces within this slope.

A. Construction: If a house is built on a slope (**Figure 14**) it can change the slope properties. The house could be built at the base of the slope, removing material that is giving the slope its strength. This is an example of human activity increasing driving forces and reducing resistive forces.

The house may also be built on the slope itself, adding extra weight to the slope. This would also increase the driving forces within the slope, making the slope more susceptible to landslides.

Figure 15. Road construction in Guatemala.

B. Road Building: In the same way as removing material to build a house will increase driving forces and reduce resistive forces – removing material to construct a road will have the same effect. Not only will the whole slope be more susceptible to landslides, but often a new vertical cut slope is created. These slopes, if not managed carefully, can be unstable and the sources of rockfalls or landslides.

C. Deforestation: As we have noted previously, vegetation can help increase the stability of a slope, through increasing the resistive forces and removing water from the system.

Vegetation removal (i.e., deforestation) can therefore reduce resistive forces and increase the amount of water in the system. This combination of factors can result in a slope that is more susceptible to landslides.

Figure 16. Deforestation in Guatemala.

2.4. IMPACTS OF LANDSLIDES

IMPACTS ON COMMUNITIES AND INFRASTRUCTURE

Examples of possible impacts include:

Fatalities: Landslides can result in fatalities ranging from 0-1000s, depending on the size of the event, number of people exposed and their vulnerability. This is traumatic for relatives and friends of those who die, and may also then impact their long-term physical and mental health.

Injuries: Landslides can result in serious and minor injuries to those living in the area. These can be a direct result of the landslide (e.g., a rock falling on a leg) or indirect (e.g., an accident whilst trying to evacuate).

Property Damage/Destruction: Landslides can damage and destroy property, including houses, farms and businesses.

Loss of Income/Livelihoods: Fatalities, injuries and property destruction can result in individuals unable to generate income. This can increase poverty and vulnerability to future occurrences of a hazardous event.

Infrastructure Damage/Destruction: Landslides can damage infrastructure such as schools and hospitals. They can also damage roads and transportation networks, resulting in communities being isolated

Diverted Resources: Disaster events will result in financial resources being used for rescue, recovery and reconstruction. These resources could otherwise have been used to improve education, healthcare and infrastructure.

SECONDARY AND TERTIARY NATURAL HAZARDS

As well as directly impacting individuals, communities and infrastructure, landslides can also trigger other natural hazards, especially floods.

A. Landslide Dams: When a landslide blocks a river, it can create a natural dam. The water in the river is prevented from flowing downstream; instead it builds up behind the natural dam. This results in land being flooded.

This situation can be very dangerous, as the dam is often not stable. If these dams (made of loose soil, rock and debris) collapse, very large amounts of water can be released very suddenly. This water moves downstream rapidly and can result in catastrophic flooding events.

B. Sediment Increase: An increase to sediment in a river, caused by landslides, can change the behaviour of a river. It can lead to a reduction in storage capacity and therefore increase flooding. It can also increase erosion of river banks, creating a positive feedback loop (more sediment results in flooding and greater erosion, this erosion results in further landslides if the river is at a slope base).

2.5. MANAGING LANDSLIDE RISK

In Section 1.3 we introduced the idea that **we can reduce the number of disasters that occur or minimise the impacts of these disasters**. This can be done by attempting to (i) reduce, manage or better understand the hazard itself (i.e. stop the slope from collapsing), (ii) reduce the exposure (i.e. minimise the number of people who live in areas where landslides could occur) or (iii) reduce the vulnerability of individuals/groups (i.e. strengthening the ability of communities to anticipate, cope with, resist and recover from a landslide event).

RISK = HAZARD x EXPOSURE x VULNERABILITY

If we are able to tackle one, two or all three of these factors, we are able to reduce the overall risk of a disaster event.

MANAGING AND REDUCING THE NATURAL HAZARD (LANDSLIDE)

With many natural hazards (e.g., earthquakes) we are not able to reduce the hazard itself. Instead we aim to better understand the hazard through scientific research, so as to improve forecasting. For landslides, however, there are ways in which we can both increase our knowledge of the hazard (through **undertaking scientific research**) and **change the forces acting on the slope** so as to make the likelihood of a landslide less likely.

A. Scientific Research

Scientific research into landslides (an important responsibility of geologists and geoscientists) aims to better understand the processes behind landslide triggering and the likely spatial and temporal distribution of landslides in a given region. The spatial distribution of landslides is *where* they are likely to occur. The temporal distribution of landslides is *when* or *how often* they are likely to occur.

To understand the likely spatial and temporal distribution of future landslides, a study of the land surface is important, to identify where landslides have occurred in the past. It is possible that these landslides will be remobilised (start moving again). **Geological** and **topographical maps** are also important, as they give us an indication of rock type and slope angle – both important factors that influence the driving and resisting forces within a slope.

This range of information can be used to produce a **hazard map** or **landslide susceptibility map** that shows which parts of a region will have a high susceptibility or likelihood of landslides occurring and which areas have a low susceptibility of likelihood of landslides occurring. Hazard maps are very important, but do not normally contain information about exposure or vulnerability.

B. Changing the Forces Acting On a Slope

Humans can take deliberate actions to either increase the resistive forces or reduce the driving forces acting on a slope, with the aim of reducing the likelihood of landslides.

In **Section 2.3** we examined a number of factors that can influence whether a landslide is triggered or not. Three important factors were:

- **Slope Angle** – A high angle (or steep slope) is more susceptible to landslides.
- **Water** – Water reduces the material strength and makes a slope more susceptible to landslides
- **Vegetation** – Vegetation acts as an anchor, therefore increasing resistive forces and making a slope less susceptible to landslides

Humans can use this information to take deliberate actions that reduce the likelihood of a landslide.

- **Slope Angle** – Ensuring that artificial slopes (e.g., for roads) are not too steep.
- **Water** – Building drainage channels in a slope to take away water and stop it filling fractures and pore-space in the rock and soil.
- **Vegetation** – Preventing deforestation, and planting more trees on slopes that are susceptible to landslides to increase the resistive forces.

Figure 17. Slope protection methods in China, aiming to reduce the susceptibility of the slope to landslides

We can also use a number of other techniques to increase the strength and stability of slopes, by reducing the driving forces or increasing the resistive forces. These include:

Toe Support: The toe is the base of the slope. If additional weight is placed here it will increase the resistive forces, making landslides less likely to occur.

Anchors: Material such as concrete and metal can be used to reinforce the slope, acting as rigid anchors. This increases the resistive forces.

A slope in China using both a **toe support** and **anchors** can be seen in **Figure 17**.

A further method is to **reduce the load** on the top of the susceptible slope by removing material. This will reduce the driving forces.

MANAGING AND REDUCING THE EXPOSURE

In order to reduce exposure, we need to use the information generated in research related to the natural hazard. This information can be used to assess how many people, or what proportion of assets are exposed to a particular hazard.

Reducing exposure then requires moving these people or assets from areas of high hazard potential to areas of low hazard potential. Although this sounds simple, it can be very expensive to relocate people. Furthermore, many people do not want to move location because of strong cultural connections to their land and surroundings.

For this reason, efforts are often made to reduce the vulnerability of those people exposed to the hazard instead.

MANAGING AND REDUCING THE VULNERABILITY

A further way to reduce the risk of a landslide disaster is to reduce the vulnerability of people and their property. Efforts can be made that increase and improve the ability of a community to anticipate, cope with and recover from the occurrence of a landslide. Methods include:

Better Education: If communities understand more about landslides (what they are, how they are triggered, what makes them more likely), they will be able to respond in a better way. Education helps people to know how best to evacuate and stay safe.

Planning: Families and wider communities, as well as governments, can help to reduce vulnerability by developing an evacuation and response plan. For a family this may include preparing an emergency bag and knowing where to go if there is very heavy rain. For a government this may include planning how to evacuate people from their town, or ensuring emergency food/medical equipment is ready.

Risk Maps: A landslide hazard map can be combined with maps of population to generate a risk map. These maps can be used to design effective evacuation plans as well as improve planning. A good risk map can help prevent new schools, hospitals or houses being built in dangerous, high-risk places.

Provision of Insurance: Many people are reluctant to evacuate because they are worried about losing their house, land and resources. Provision of insurance means that people can have confidence that they will be compensated for the loss of their house/land and start to rebuild their lives again soon.

Targeting Corruption: Corruption increases the vulnerability of a community, as it diverts money away from research into the hazards and the development of safer infrastructure. Reducing corruption will reduce vulnerability, helping a community have a stronger capability to recover.

3. EARTHQUAKES

In this chapter we will explore the following questions:

- What is an earthquake
- Where do earthquakes happen
- What are seismic waves
- How do we measure earthquakes

3.1. WHAT IS AN EARTHQUAKE?

In ancient times earthquakes were thought to be caused by restless gods or giant creatures slumbering beneath the Earth.

Figure 18. In Japanese history, people thought earthquakes were caused by a monster catfish (Namazu) that lived under Japan. In this picture people are punishing the catfish for causing a large earthquake in 1855.

The early Greek philosophers developed a theory that earthquakes were caused by movements of gases trying to escape from underground. Up until the 18th century western scientists (including Sir Isaac Newton) thought they were caused by explosions of flammable material deep underground.

In 1760 Rev J.Mitchell proposed that earthquakes were caused by rock movements and related the shaking to the propagation of elastic waves within the Earth.

Figure 19. photo shows a fence offset by 2.5 m by the earthquake

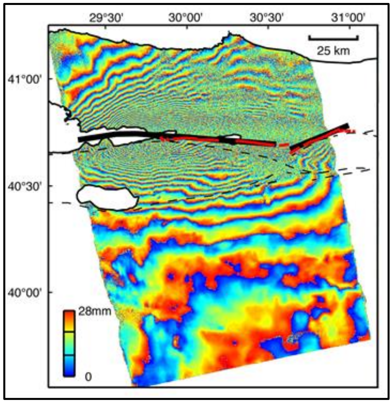


Figure 20. Interferogram of the area around the 1999 M7.3 earthquake in Izmit, Turkey

By examination of the displacement of the ground surface caused by the 1906 San Francisco earthquake, (**Figure 19**) Henry Fielding Reid, Professor of Geology at Johns Hopkins University, concluded that the earthquake must have involved an 'elastic rebound' of previously stored elastic stress.

Scientists can now measure how the movement caused by an earthquake is distributed in space. By comparing two radar satellite images before and after a large earthquake we can determine how much each pixel has moved. In this interferogram of the area around the 1999 M7.3 earthquake in Izmit, Turkey, each colour band (red-blue) represents a movement of 28 mm (one radar wavelength) (**Figure 20**).

3.2. ELASTIC REBOUND

The mechanisms and processes involved when earthquakes occur are extremely complex. However some of the characteristics of earthquakes can be explained by using a simple elastic rebound theory.

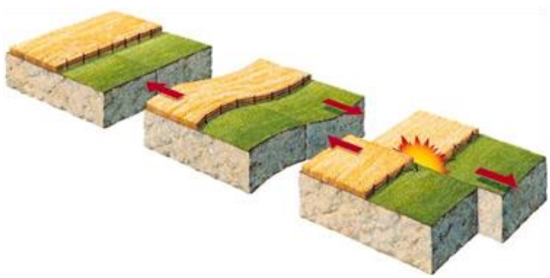


Figure 21. stress build up and release in earthquake cycle

• Over time stresses in the Earth build up (often caused by the slow movements of tectonic plates) (**Figure 21**).

• At some point stresses become so great that the Earth breaks… an earthquake rupture occurs and relieves some of the stresses (but generally not all).

In earthquakes these ruptures generally happen along fault planes, or lines of weakness in the Earth's crust. There are three basic types of fault (**Figure 22**).

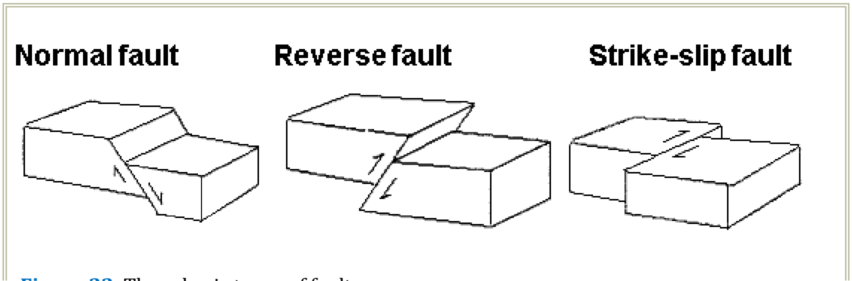


Figure 22. Three basic types of fault

Earthquake rupture occurs in three stages:
1) Initiation of sliding along a small portion of the fault,
2) Growth of the slip surface and
3) Termination of the slip.

Slip amount will vary in different places along the fault, growing with time.

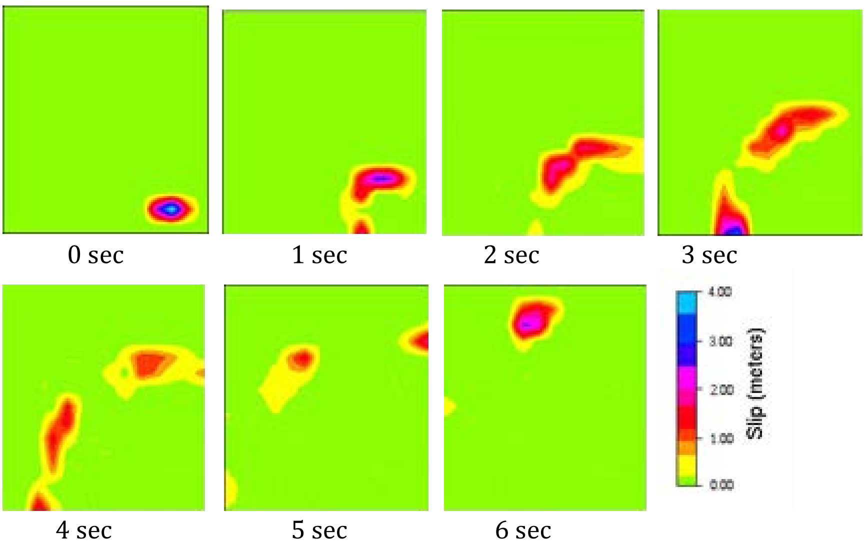


Figure 23. This sequence of images shows the growth of an earthquake rupture, modelled using data from the 1994 M6.7 Northridge earthquake in California (a movie of this process can be found at www.data.scec.org/Module/links/northrup.html images used with permission of David Wald) The size of the fault plane in these images is 18 km wide and 14 km deep.

3.3. WHERE DO EARTHQUAKES HAPPEN?

The rigid outer shell of the Earth is called the lithosphere. The lithosphere is broken into a series of moving plates (Figure 24). The lithosphere is composed of the crust, and some of the upper mantle. Mature oceanic plate is approximately 80-100 km thick, of which, the upper 5-7 km is oceanic crust. Continental plate is somewhat thicker, perhaps 150-200 km thick, and includes continental crust, which varies from 5 to 70 km in thickness. A single plate may be part oceanic and part continental. In that case, the boundary between ocean crust and continental crust is not a plate boundary. The mobile part of the mantle under the lithosphere is called the asthenosphere.

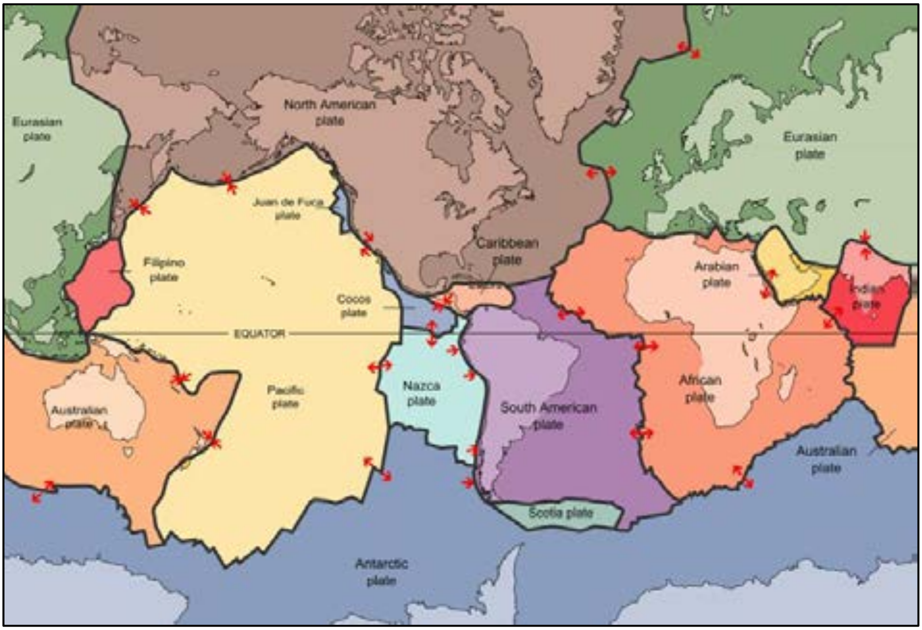


Figure 24. Major tectonic plate boundaries

Plate boundaries are most readily identified by seismicity, the location of significant earthquake activity (**Figure 25**). About 95% of the world's earthquakes occur on plate boundaries, and all earthquakes occur in the lithosphere.

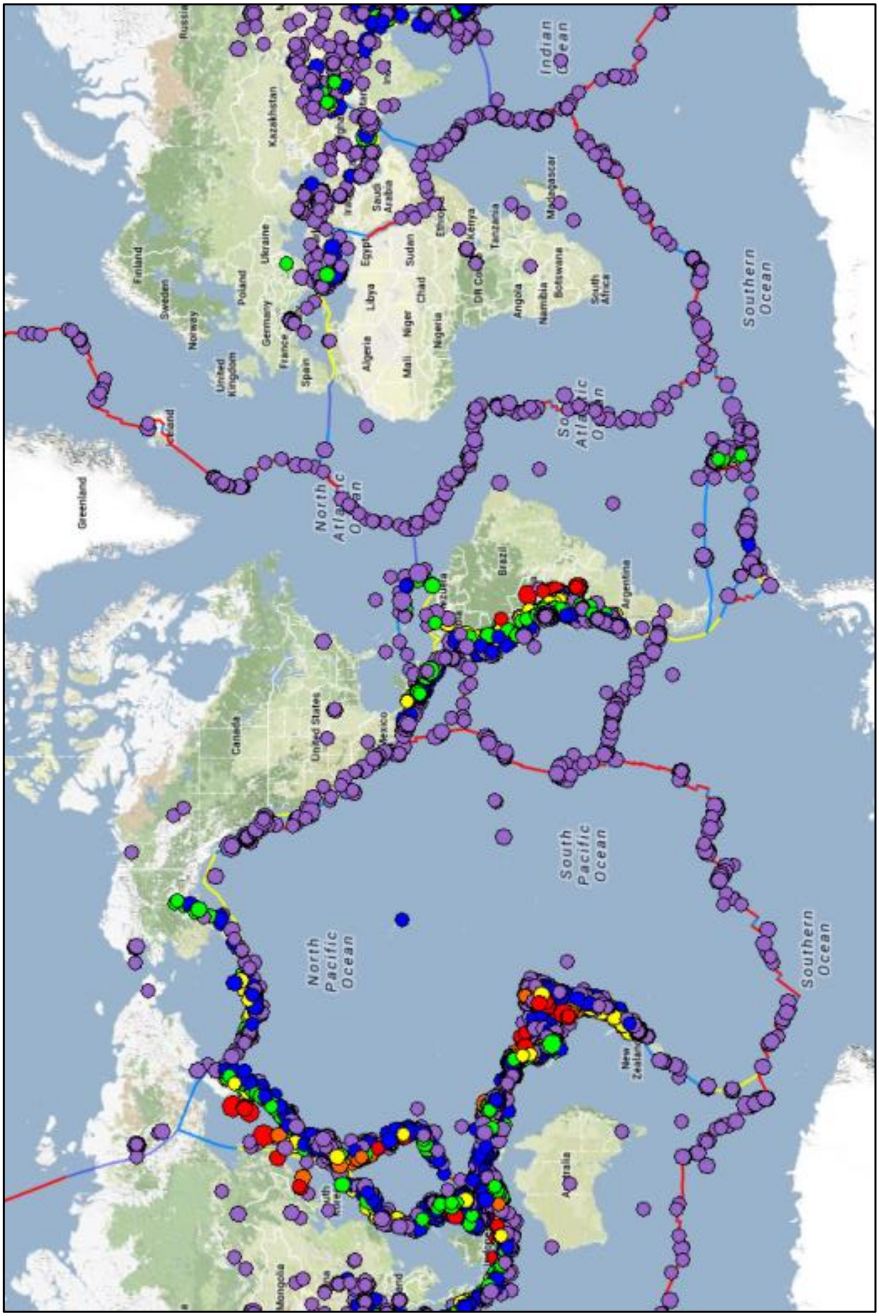
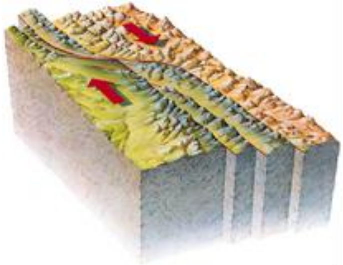
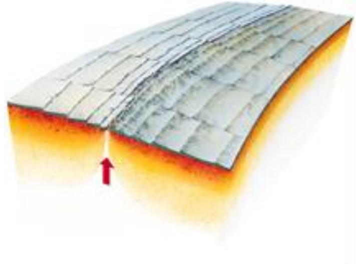


Figure 25. Major tectonic plate boundaries highlighted by seismic activity. Each purple dot is an earthquake event

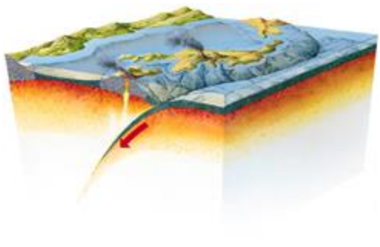
Tectonic plate boundaries occur as four main types:



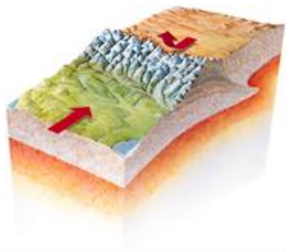
(A) Transform Boundaries: Plates sliding past each other (e.g., California)



(B) Divergent Boundaries: New crust created by undersea volcanoes (e.g., Mid-Atlantic Ridge)

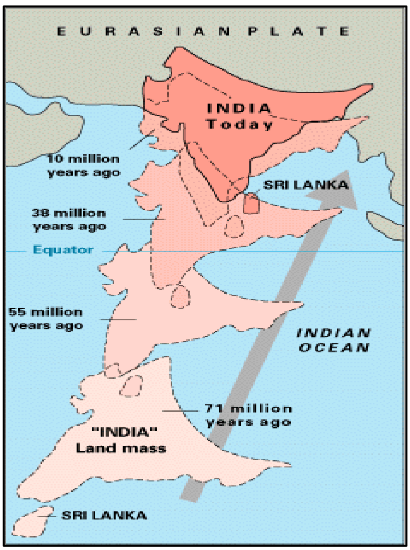


(C) Convergent (Subduction) Boundaries: Ocean crust being pushed down (e.g., Chile or Sumatra)



(D) Convergent (Diffuse) Boundaries: Continental collision (e.g., Himalayas)

Figure 26. Tectonic plate boundary types



Tectonic plates move at a rate of a few cm per year. The Indian Plate broke free from where it used to be joined with what is now Africa and started moving towards Eurasia over 90 million years ago.

India started colliding with the Eurasian plate approximately 50 million years ago creating the Himalaya mountains and the Tibetan plateau. Today India is still moving northwards into Asia at a rate of about 3cm per year (this is about the same rate that your fingernails grow).

Figure 27. India's collision with mainland Asia

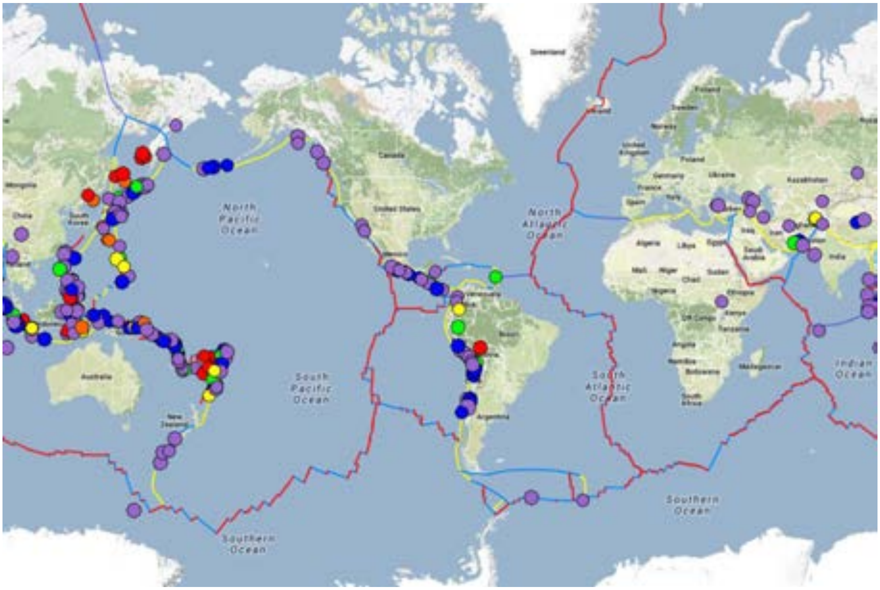


Figure 28. Tectonic plate boundary types and earthquakes. Red Lines are 'Divergent,' Blue Lines are 'Transform' and Yellow Lines are 'Convergent.' Coloured dots represent earthquakes.

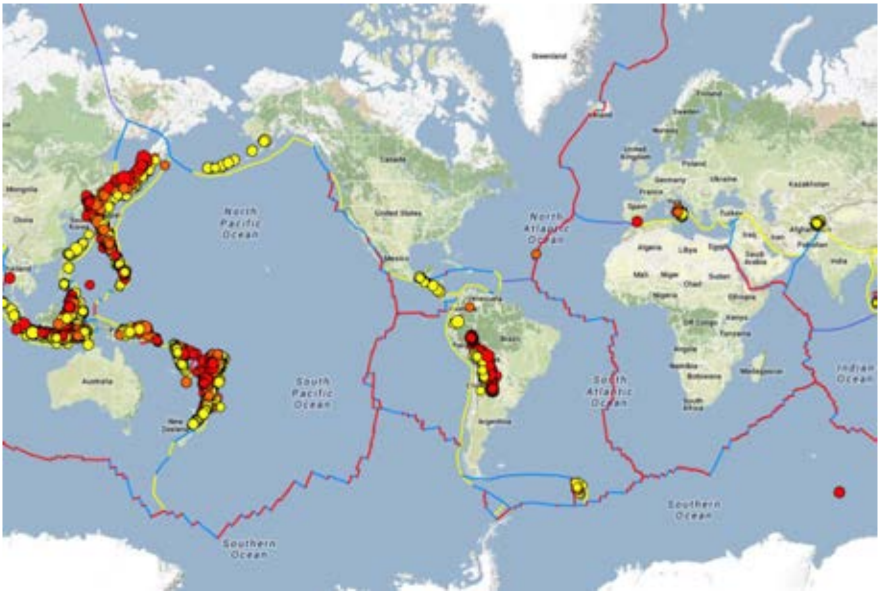


Figure 29. Large earthquakes (greater than M7.0) are very rare on divergent plate boundaries (red lines).

Deep earthquakes (deeper than 200 km) generally only occur where oceanic tectonic plates are being subducted (pushed down) into the mantle

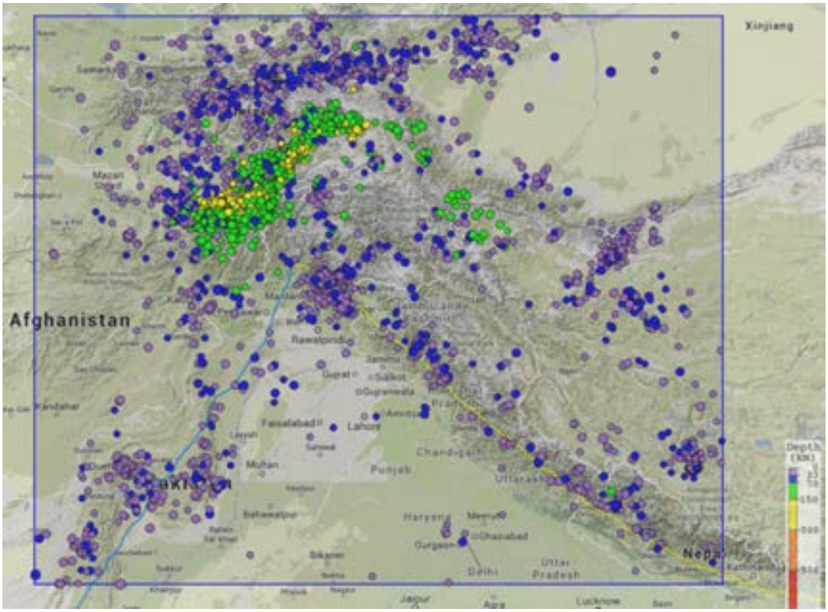


Figure 30. Earthquake events in the Himalayas. Different colours represent different

Within this region of the Himalaya on average 400 earthquakes larger than magnitude 4 occur each year. Of these 35 each year are greater than Magnitude 5.0 and 2 are greater than Magnitude 6.0.

3.4. SIMPLE PROBABILITY

If we assume that the timing of earthquakes is random then we can say that the chance of an earthquake of greater than Magnitude 6.0 happening this month is 2/12 or 0.166 *(Note this simple approach only works if the probability of two earthquakes happening on the same day is very small. For other situations you have to consider the probability distribution of events.)*

To calculate how long we would have to wait before a >M6.0 event it is easier to consider the probability of such an event not occurring, which is 10/12 in any one month or about 0.83. Using the multiplication rule for probabilities we can calculate that the probability of an event not happening for two consecutive months is 0.83*0.83 =0.69

Month	1	2	3	4	5	6	7	8	9	10	11	12
Probability	0.83	0.69	0.58	0.48	0.40	0.33	0.28	0.23	0.19	0.16	0.13	0.11

After 4 months the probability of an event in this region >M6.0 is greater than 0.5 (or 50%).

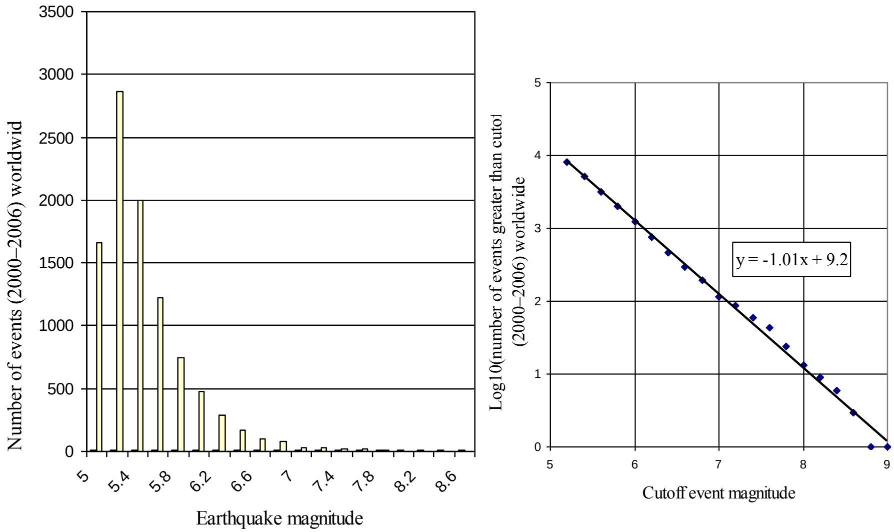


Figure 31. Histogram (left) and log plot (Right) of all earthquakes measured worldwide over the past 6 years shows small events happen much more frequently than large events

A histogram of all the earthquakes measured worldwide over a 6 year period shows large events are far less frequent than smaller ones.

This is more usually plotted as a cumulative plot on a log axis. This way the data plots as a straight line. **Y= ax +b**

This is referred to as the Gutenberg-Richter relationship after Charles Richter (1900–1985) and Beno Gutenberg (1889–1960) who both worked at the California Institute of Technology (CALTECH).

The slope of the line is approximately -1 for all earthquakes (because this is a Log 10 graph that means that for each increase in magnitude there are 10 x fewer events). This relationship holds true even when you consider earthquakes in smaller areas.

3.5. SEISMIC WAVES

When an earthquake occurs deep underground, a crack will start to open on a pre-existing line of weakness in the Earth's brittle crust. This crack will then grow larger and larger, relieving built up stress as it goes. The speed at which the crack grows is 2–3 km/s. Eventually the rupture will cease to grow and will slow down and stop. The size or magnitude of the earthquake depends upon how much the fault has ruptured (the slip) and also the area over which the rupture has occurred.

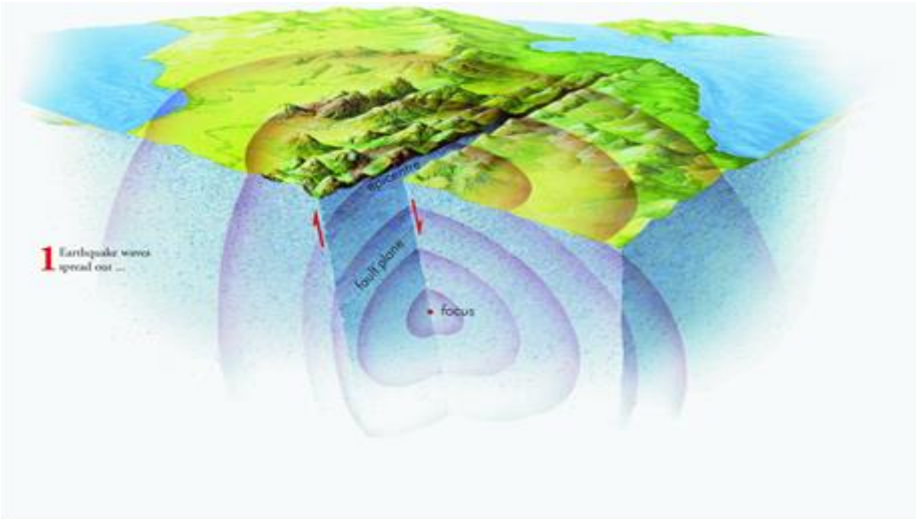


Figure 32. Rupturing at the Earth surface

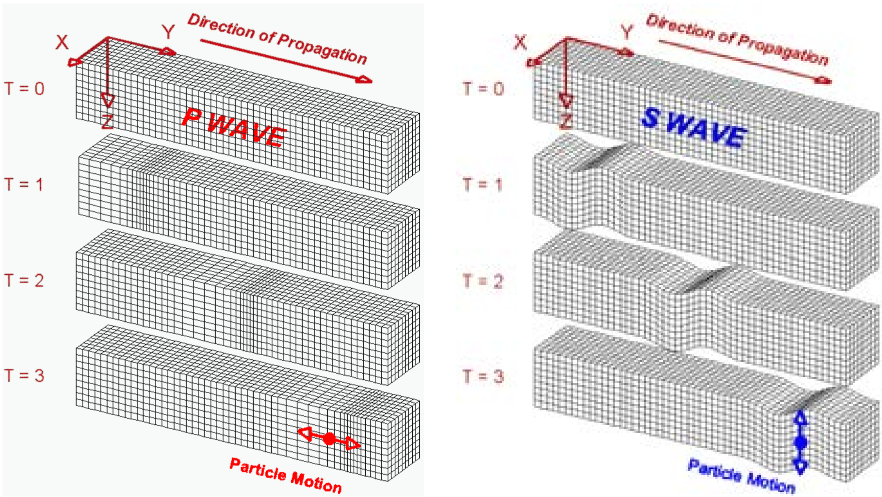
This rupturing process creates elastic waves (called seismic waves) in the Earth which travel away from the rupture front at a much faster speed than the rupture grows, the exact speed depends upon the nature of the wave (a longitudinal or P wave is faster than a transverse or S wave), and on the elastic properties of the Earth. As you go deeper into the Earth, the density and pressure increases and so do the velocities of seismic waves. Seismic waves are fundamentally of two types, compressional, longitudinal waves or shear, transverse waves. Through the body of the Earth these are called P waves (for primary because they are fastest) and S waves (for secondary since they are slower). However where a free surface is present (like the Earth–air interface) these two types of motion can combine to form complex surface waves. Although often ignored in introductory texts, surface waves are very important since they propagate along the surface of the Earth (where all the buildings and people are) and usually have much higher amplitudes than the P waves and S waves.

Seismic waves, like all waves, transfer energy from one place to another without moving material.

Properties of Seismic Waves

Name	Particle Motion	Typical Velocity	Other characteristics
P (Primary Longitudinal)	Alternating compressions ('pushes') and dilations ('pulls') in the same direction as the wave is propagating	**5 – 7 km/s in crust :** >~ 8 km/s in mantle 1.5 km/s in water; 0.3 km/s in air	P motion travels fastest in materials, so the P-wave is the first-arriving energy on a seismogram. Generally smaller and higher frequency than the S and surface waves. P waves in a liquid or gas are pressure waves, including sound waves.
S (Secondary Transverse)	Alternating transverse motions perpendicular to the direction of propagation.	**3 – 4 km/s in crust :** >~ 4.5 km/s in mantle;	S-waves do not travel through fluids, so do not exist in Earth's liquid outer core or in air or water or molten rock (magma). S waves travel slower than P waves in a solid and, therefore, arrive after the P wave.
Surface waves	Complex	2.0 - 4.5 km/s depending on frequency	Surface waves exist because of the Earth's surface. They are largest at the surface and decrease in amplitude with depth. Their wave velocity is dependent on frequency, with low frequencies propagating at higher velocity.

Primary or P waves are a compression followed by a dilatation. The particle motion is in the direction of propagation. Sound waves are P-waves in air. Secondary or S-waves have an up motion followed by a down motion. The particle motion is perpendicular to the direction of propagation.



P-waves are a compression followed by a dilatation. The particle motion is in the direction of propagation. Sound waves are P-waves.

S-waves have an up motion followed by a down motion The particle motion is perpendicular to the direction of propagation.

"© L Braile. 2000-2006"

Figure 33. P and S wave motion

Wave propagation through a grid through a grid representing a volume of material. The directions X and Y are parallel to the Earth's surface and the Z direction is depth. T = 0 through T = 3 indicate successive times. The material returns to its original shape after the wave has passed.

Animations of these images can be found at

http://web.ics.purdue.edu/~braile/edumod/waves/WaveDemo.htm

P waves travel through solids and liquids and can travel through the liquid outer core of the Earth. S waves can only travel through solids, they pass through the solid mantle of the Earth but do not penetrate the liquid outer core (**Figure 34**).

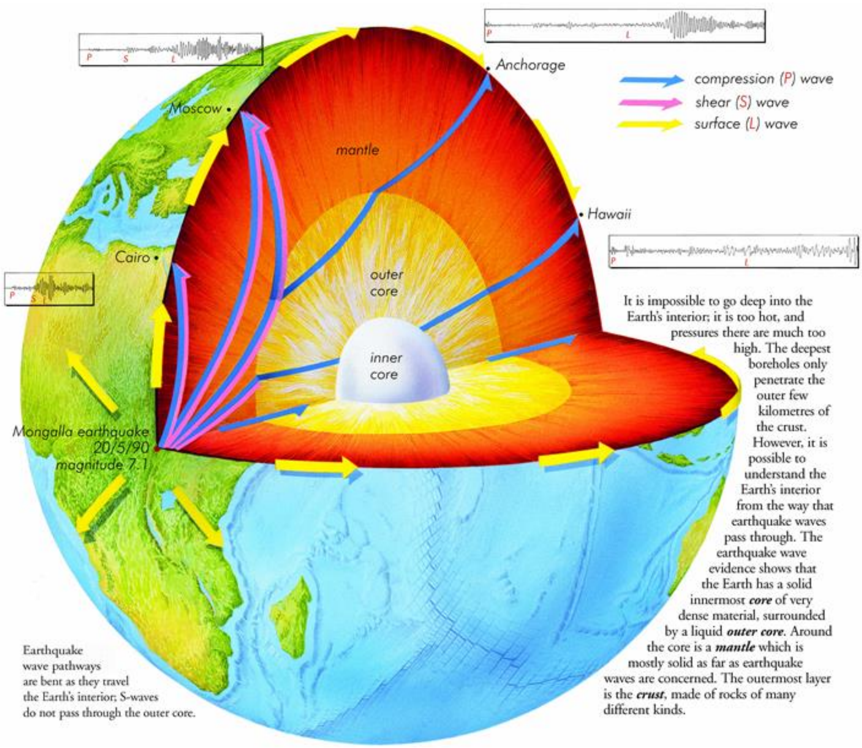


Figure 34. Waves travelling through the Earth

3.6. MEASURING EARTHQUAKES

Seismic waves can be detected with seismometers (**Figure 35**). These devices contain a mass which is loosely connected to the solid ground so that it is relatively free to move. When the ground moves due to a seismic wave passing by the mass will tend to stay still (because it has Inertia). The resulting relative motion between the ground and the mass can be converted to a seismograph trace. Originally this was done on paper; nowadays it is done on a computer.

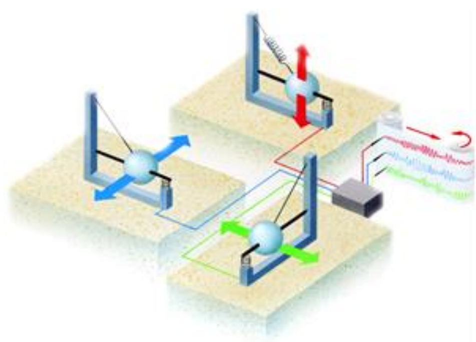


Figure 35. Equipment to measure earthquakes

The ground can move in three directions (up-down, east-west or north-south) so seismologists usually use three seismometers together to capture the full ground motion.

In **Figure 36** we see seismograms recorded in the UK from the 2013 M7.7 Pakistan earthquake. The vertical component (top) shows most of the P wave energy and the two horizontal components show most of the S wave energy.

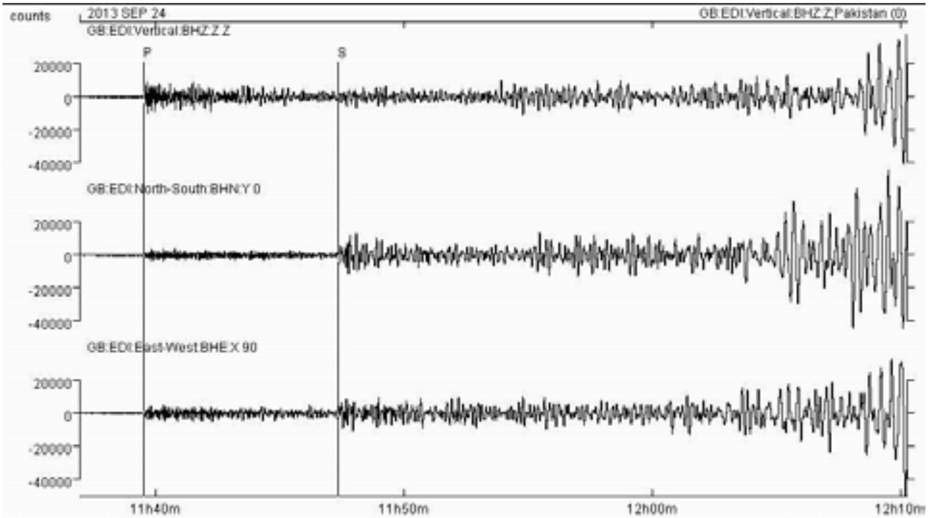


Figure 36. Seismogram readings from an earthquake

3. 7. LOCATING EARTHQUAKES

At some distance from an earthquake the P waves will arrive before the S waves because they travel faster. By measuring the time delay between the arrival of the P waves and the S waves it is possible to determine how far away the earthquake happened.

If we determine the distance to an event from three or more points it is possible to estimate the location of the event by intersecting circles (a process called triangulation).

Figure 37. Locating an earthquake using the intersection of two circles

In this example we look at data recorded by seismograph stations in the UK from a magnitude 3.5 earthquake in the Midlands.

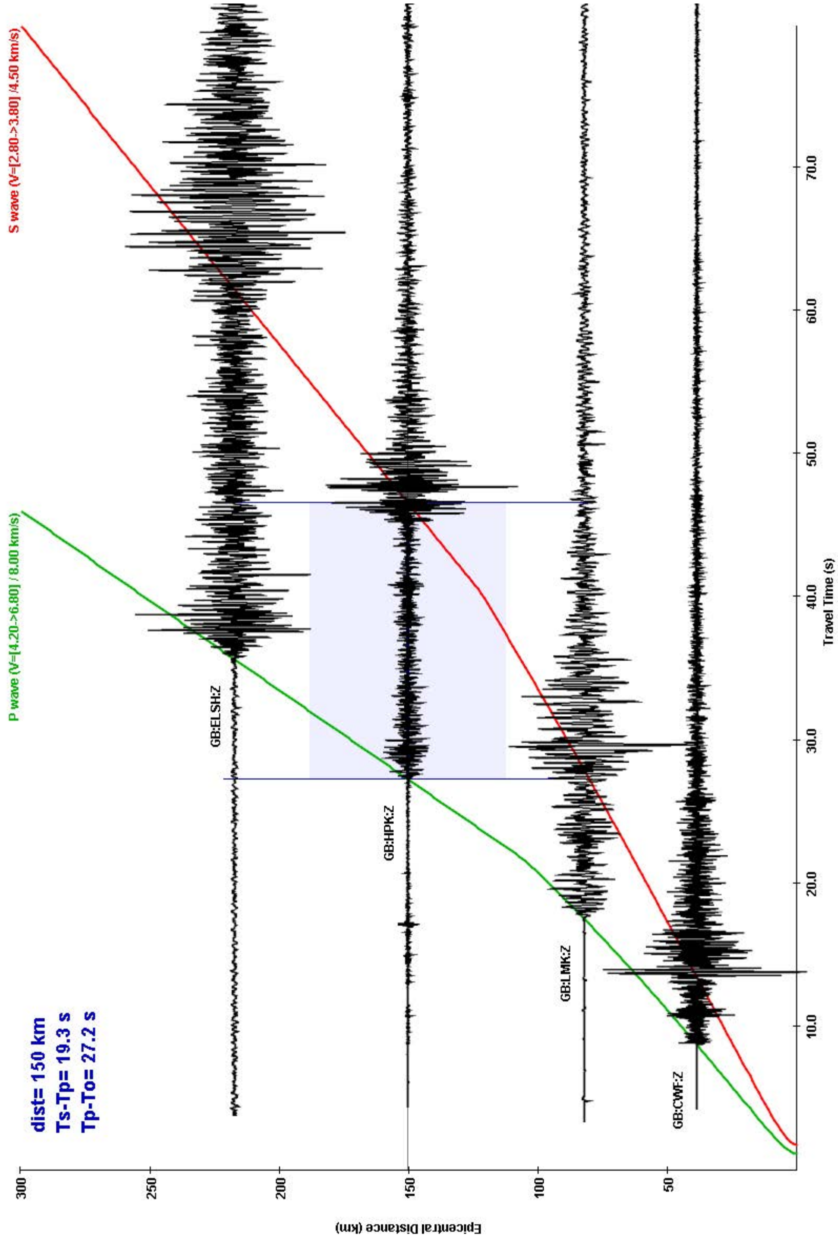


Figure 38. Seismogram readings from an earthquake in the UK.

3.8. EARTHQUAKE MAGNITUDES

The magnitude of an earthquake is a number that relates to the size of the earthquake. Earthquake magnitude scales are logarithmic (i.e. a 1 unit increase in magnitude corresponds to a 10 fold increase in ground motion). Scientists can only estimate the true magnitude of an earthquake by measuring its effects, this leads to earthquakes appearing to have different magnitudes depending on what method is used for estimating the magnitude and which datasets have been used to make this estimate.

Richter magnitude (Local Magnitude ML)

The first earthquake magnitude scale was devised by Charles Richter and was based on the amplitude of ground motion displacement as measured by a standard seismograph with a correction for distance to the event.

ML = logA + 2.56logD - 1.67

Where A is the measured ground motion (in micrometers) and D is the distance from the event (in km). This is still used for measuring the magnitude of shallow events at distances less than 600 km (today called the Local Magnitude). For events larger than magnitude 8 this scale saturates and gives magnitude estimates that are too small.

Moment magnitude

For the largest earthquakes a more useful scale relates magnitude to actual fault rupture properties.

Seismic moment (Mo) = μ* rupture area * slip length

where μ is the shear modulus of the crust (approx. 3x1010 N/m)

Moment magnitude (Mw) = 2/3log(Mo) - 6.06

Nowadays the moment magnitude scale is the one used by seismologists to measure large earthquakes. The historic Richter magnitude is calculated by measuring the deflection on a seismometer corrected for distance from the event. Richter magnitudes underestimate the size of large events and are no longer used. However the constants used in the definition of Moment magnitude (Mw) were chosen so that the magnitude numbers for Richter and Moment magnitudes match for smaller events. For the largest events (the Mw 9.3 event on Dec 26th 2004) the rupture area can be 1200 km long by 100 km deep with a slip length of up to 15 m (it had a seismic moment of 1.1x1023 Nm)

How is energy related to magnitude?

Seismologists have determined that the energy radiated by an earthquake is a function of both the amplitude of the waves and the duration of the earthquake. A very small earthquake is over in less than a second while for the largest events the fault may continue to slip for more than 5 minutes.
For each unit increase in magnitude M, the amplitude increases by a factor of 10.
Empirical studies have found that:

Energy is proportional to $10^{(1.5M)}$

Consider the energy (E1) from a magnitude M and from (E2) from magnitude M+1

$E2/E1 = (10^{(1.5M + 1.5)})/(10^{1.5M})$ $E2/E1 = 10^{1.5} = 32$

Thus, for each unit increase in magnitude, the energy increases by a factor of 32.
For two units of magnitude, the energy increase is a factor of 10^3 or one thousand.

3.9. SEISMIC ENERGY

Both the magnitude and the seismic moment are related to the amount of energy that is radiated by an earthquake. Richter, working with Dr. Beno Gutenberg, early on developed a relationship between magnitude and energy. Their relationship is:

$$\log E = 4.8 + 1.5M$$

giving the energy E in joules from the magnitude M.

Note that E is not the total 'intrinsic' energy of the earthquake, transferred from sources such as gravitational energy or to sinks such as heat energy. It is only the amount radiated from the earthquake as seismic waves, which ought to be a small fraction of the total energy transferred during the earthquake process.

Earthquake energy as a function of magnitude

Magnitude	Energy in joules	Notes
-3.0	2	1 kg dropped 20 cm
-2.0	63	
-1.0	2000	100 kg person jumps down 2 m
0.0	6.3×10^{4}	
1.0	2.0×10^{6}	
2.0	6.3×10^{7}	Only felt nearby
3.0	2.0×10^{9}	Energy from 50 litres of petrol
4.0	6.3×10^{10}	Often felt up to 10's of miles away
5.0	2.0×10^{12}	Energy from 50 000 litres of petrol
6.0	6.3×10^{13}	3.3 Hiroshima-size A bombs
7.0	2.0×10^{15}	
8.0	6.3×10^{16}	1–2 earthquakes this size each year
9.0	2.0×10^{18}	Total annual energy use of UK

FURTHER READING

HAZARDS AND DISASTERS

- The official disaster management plan for Leh district is available here: **www.cdrn.org.in/show.detail.asp?id=22815**
- Ekbal Hussain (Booklet Contributor) runs a blog 'Climate and Geohazards': **http://climateandgeohazards.wordpress.com/**

LANDSLIDES

- Landslide information from the British Geological Survey (BGS): **www.bgs.ac.uk/discoveringGeology/hazards/landslides**
- Professor Dave Petley, a landslide expert, runs a blog where he writes about recent landslide events around the world: **www.blogs.agu.org/landslideblog**
- The Canadian government give tips on how to prepare for a landslide: **www.getprepared.gc.ca/cnt/hzd/lndslds-bfr-eng.aspx**
- Landslide Educational Resources (LAMPRE Project) **www.lampre-project.eu/**

EARTHQUAKES

- The United States Geological Survey earthquake information site: **http://earthquake.usgs.gov/earthquakes**
- The UK School Seismology Project (part of the BGS): **www.bgs.ac.uk/schoolseismology**

SUSTAINABLE RESOURCE DEVELOPMENT IN THE HIMALAYA

This booklet is intended to give a useful introduction to the topics of natural hazards (earthquakes and landslides), vulnerability and disaster risk reduction. It was designed as part of the '*Sustainable Resource Development in the Himalaya'* Conference taking place in Leh, India (June 2014). The conference is co-organised by the Geological Society of London and Institute of Energy Research and Training (University of Jammu). As part of this conference, an interactive students' programme is being organised, engaging schools in Leh and Puga (Ladakh, India) with important geoscience topics (including energy resources, climate change, and natural hazards).

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ABOUT US

Geology for Global Development (GfGD) is a not-for-profit organisation, established to raise the profile of international development within the geoscience community, fight poverty and improve lives. For more information, visit: **www.gfgd.org**

The *Institute for Risk and Disaster Reduction* exists within University College London to lead research, knowledge exchange with industry and humanitarian agencies and advanced teaching, in the area of risk and disaster reduction, visit: **www.ucl.ac.uk/rdr**

The *British Geological Survey* is the world's oldest national geological survey and the UK's premier centre for earth science information and expertise. The UK School Seismology Project enables schools to detect signals from large earthquakes happening anywhere in the world. For more information visit: **www.bgs.ac.uk/schoolseismology**

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