Himalaya

2nd Edition

Complete Master Guide

GATE

Geology & Geophysics

21 Year's Solved Geology & Geophysics Papers 2016-1996

For

PSUs, BARC, GSI, CSIR, IISc, IITs, NITs, JRF, SRF & RA

Amaresh Singh

Jitendra Mishra

Himalaya Publishing House

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Complete Master Guide

GATE

Geology and Geophysics

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In the Loving Memory of
Late Shri Gangotri Singh
&
Late Shri Badri Vishal

Dedicated to
Our
Parents, Teachers, Seniors, Batchmates
&
Beloved Juniors

राष्ट्रीय पृथ्वी विज्ञान अध्ययन केन्द्र
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Director ***FNASc***

Dated: 14th October 2015

FOREWORD

The book 'Complete Master Guide GATE-2016 Geology and Geophysics' is a testimony of enthusiasm and talent of young students in the Indian Institutions and Universities. I congratulate the authors for their passionate efforts of timely bringing out this book. I am sure that the book will meet the student's target of qualifying the GATE examination in respective branch of Science.

Authors have very aptly presented the book in three sections. First two sections are devoted to the fundamentals of geology and geophysics and last section includes twenty one solved papers. Although the emphasis of this work is on GATE examination, yet it offers much more to the general reader and students – indeed to anyone interested in geology and geophysics.

Through this foreword, I celebrate the spirit and enthusiasm of two young boys below 25 years who have presented a tonic stimulant for GATE Exam aspirants.

V.M. Tiwari 14/10/15

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Committed to Our Earth Our Future
हमारे भविष्य हमारी पृथ्वि के लिऐ प्रतिबद्ध

PREFACE

We feel great pleasure to present the Second edition of the book "Complete Master Guide to GATE Geology and Geophysics" in your hands that will surely help GATE aspirants to face the exam with great confidence. We have made full efforts to consider all those points of Geology and Geophysics which we feel are important for the candidates appearing in the prestigious GATE exam.

GATE examination tests the in-depth knowledge of the students and demands comprehensive understanding of the various concepts. As previous years' questions and examination pattern are the only authentic source of information for the systematic preparation of GATE, the need for such a book has long been felt by students appearing in GATE examination. This greatly motivated us to write this book.

The content of the book has been organized in three sections namely Section-I, Section-II and Section-III. The first section contains a brief theory of all the topics in Geology included in the GATE syllabus. The second section deals with a concise theory of Geophysics and spans almost all the topics marked in GATE syllabus. The theory in each of these sections has been compiled taking help of the standard books in Geology and Geophysics. Care has also been taken to include all the important formulae and diagrams that are important from the competitive point of view. The third section contains last twenty one (1996-2016) solved papers of GATE – Geology and Geophysics. Solved papers help to familiarize the aspirants with the current trends of questions asked in GATE – Geology and Geophysics paper. The solutions to the problems have been presented in a comprehensive way. The questions have been solved with explanations and related concept and theories. As the Quantitative Aptitude section plays an important role in deciding the position of the candidates in the merit list of such examinations, Section-III also comprises of previous years' solved aptitude questions.

We wish to express our deep sense of gratitude to the faculty of the Department of Applied Geophysics and Applied Geology, ISM Dhanbad for extending their knowledge and encouragement in preparing this book. Special thanks to Prof. Shalivahan, Dr. Suresh Pandey, Avadhesh Kumar Shukla, Prakash Kumar Jha and Akanchha Dalania for their valuable contribution towards the completion of the book. Discussions with our colleagues have been useful, and we are thankful to them. Our sincere thanks to each and every individual, without whose contribution the book would not have been a success. Last but not the least, we wish to thank our friends and family, for the support and encouragement they provided us throughout different stages of our work.

We thank Sri Niraj Pandey, Himalaya Publishing House Pvt. Ltd., for their keen interest to bring out this revised edition of the book.

We will greatly appreciate if the users of this book communicate to us any errors, misprints or weaknesses that they may detect. These will be incorporated in the subsequent editions.

AMARESH SINGH
JITENDRA MISHRA

SYLLABUS – GG (Geology and Geophysics)

Common Section

Earth and Planetary system – size, shape, internal structure and composition of the earth; concept of isostasy; elements of seismology – body and surface waves, propagation of body waves in the earth's interior; Gravitational field of the Earth; geomagnetism and paleomagnetism; continental drift; plate tectonics – relationship with earthquakes, volcanism and mountain building; continental and oceanic crust – composition, structure and thickness.

Weathering and soil formation; landforms created by river, wind, glacier, ocean and volcanoes. Basic structural geology – stress, strain and material response; brittle and ductile deformation; nomenclature and classification of folds and faults.

Crystallography – basic crystal symmetry and concept of point groups. Mineralogy – silicate crystal structure and determinative mineralogy of common rock forming minerals.

Petrology – mineralogy and classification of common igneous, sedimentary and metamorphic rocks. Geological time scale – geochronology and absolute time. Stratigraphic principles; major stratigraphic divisions of India. Geological and geographical distribution of mineral, coal and petroleum resources of India. Introduction to remote sensing. Engineering properties of rocks and soils.

Ground water geology – Principles and applications of gravity, magnetic, electrical, electromagnetic, seismic and radiometric methods of prospecting for oil, mineral and ground water; introductory well logging.

Part – A: Geology

Geomorphic processes and agents; development and evolution of landforms; slope and drainage; processes in deep oceanic and near-shore regions; quantitative and applied geomorphology.

Mechanism of rock deformation; primary and secondary structures; geometry and genesis of folds, faults, joints and unconformities; cleavage, schistosity and lineation; methods of projection; tectonites and their significance; shear zones; superposed folding; basement-cover relationship.

Crystallography – symmetry, forms and twinning; crystal chemistry; optical mineralogy, classification of minerals, diagnostic physical and optical properties of rock – forming minerals.

Cosmic abundance of elements; meteorites; geochemical evolution of the earth; geochemical cycles; distribution of major, minor and trace elements in crust and mantle; elements of geochemical thermodynamics; isotope geochemistry; geochemistry of waters including solution equilibria and water-rock interaction.

Igneous rocks – classification, forms and textures; magmatic differentiation; binary and ternary phase diagrams; major and trace elements as monitors of partial melting and magma evolutionary processes. Sedimentary rocks – texture and structure; sedimentary processes and environments, sedimentary facies, provencance and basin analysis. Metamorphic rocks – structures and textures.

Physico-chemical conditions of metamorphism and concept of metamorphic facies, grade and baric types; metamorphism of pelitic, mafic and impure carbonate rocks; role of fluids in metamorphism; metamorphic P-T-t paths and their tectonic significance. Association of igneous, sedimentary and metamorphic rocks with tectonic setting. Igneous and metamorphic provinces and important sedimentary basins of India.

Morphology, classification and geological significance of important invertebrates, vertebrates, plant fossils and microfossils.

Principles of Stratigraphy and concepts of correlation – lithostratigraphy, biostratigraphy and chronostratigraphy. Indian stratigraphy – Pre-cambrian and Phanerozoic. Overview of Himalayan Geology.

Ore-mineralogy and optical properties of ore minerals; ore forming processes *vis-à-vis* ore-rock association (magmatic, hydrothermal, sedimentary, supergene and metamorphogenic ores); fluid inclusions as an ore genetic tool.

Coal and petroleum geology; marine mineral resources. Prospecting and exploration of economic mineral deposits – sampling, ore reserve estimation, geostatistics, mining methods. Ore dressing and mineral economics. Origin and distribution of mineral, fossil and nuclear fuel deposits in India.

Engineering properties of rocks and soils; rocks as construction materials; role of geology in the construction of engineering structures including dams, tunnels and excavation sites; natural hazards. Ground water geology – exploration, well hydraulics and water quality. Basic principles of remote sensing – energy sources and radiation principles, atmospheric absorption, interaction of energy with earth's surface, aerial-photo interpretation, multispectral remote sensing in visible, infrared, thermal IR and microwave regions, digital processing of satellite images. GIS – basic concepts, raster and vector mode operations.

Part – B: Geophysics

The earth as a planet; different motions of the earth; gravity field of the earth, Clairaut's theorem, size and shape of earth; geomagnetic field, palaeomagnetism; Geothermics and heat flow; seismology and interior of the earth; variation of density, velocity, pressure, temperature, electrical and magnetic properties of the earth; earthquakes – causes and measurements, magnitude and intensity, focal mechanisms, earthquake quantification, source characteristics, seismotectonics and seismic hazards; digital seismographs.

Scalar and vector potential fields; Laplace, Maxwell and Helmholtz equations for solution of different types of boundary value problems in Cartesian, cylindrical and spherical polar coordinates; Green's theorem; Image theory; integral equations in potential theory; Eikonal equation and Ray theory.

Absolute and relative gravity measurements; Gravimeters, Land, airborne, shipborne and borehole gravity surveys; various corrections for gravity data reduction – free air, Bouguer and isostatic anomalies; density estimates of rocks; regional and residual gravity separation; principle of equivalent stratum; data enhancement techniques, upward and downward continuation; derivative maps, wavelength filtering; preparation and analysis of gravity maps; gravity anomalies and their interpretation – anomalies due to geometrical and irregular shaped bodies, depth rules, calculation of mass.

Elements of Earth's magnetic field, units of measurement, magnetic susceptibility of rocks and measurements, magnetometers, Land, airborne and marine magnetic surveys, Various corrections applied to magnetic data, IGRF, Reduction to Pole transformation, Poisson's relation of gravity and magnetic potential field, preparation of magnetic maps, upward and downward continuation, magnetic anomalies – geometrical shaped bodies, depth estimates, Image processing concepts in processing of magnetic anomaly maps; Interpretation of processed magnetic anomaly data. Applications of gravity and magnetic methods for mineral and oil exploration.

Conduction of electricity through rocks, electrical conductivities of metals, non-metals, rock forming minerals and different rocks, concepts of D.C. resistivity measurement, various electrode configurations for resistivity sounding and profiling, applications of filter theory, Type-curves over multi-layered structures, Dar-Zarrouck parameters, reduction of layers, coefficient of anisotropy, interpretation of resistivity field data, equivalence and suppression, self-potential and its origin, field measurement, Induced polarization, time and frequency domain IP measurements; interpretation and applications of IP, groundwater exploration, mineral exploration, environmental and engineering applications.

Basic concept of EM induction in the earth, Skin-depth, elliptic polarization, inphase and quadrature components, Various EM methods, measurements in different source-receiver configurations, Earth's natural electromagnetic field, tellurics, magnetotellurics; geomagnetic depth sounding principles, electromagnetic profiling, Time-domain EM method, EM scale modeling, processing of EM data and interpretation. Geological applications including groundwater, mineral and hydrocarbon exploration.

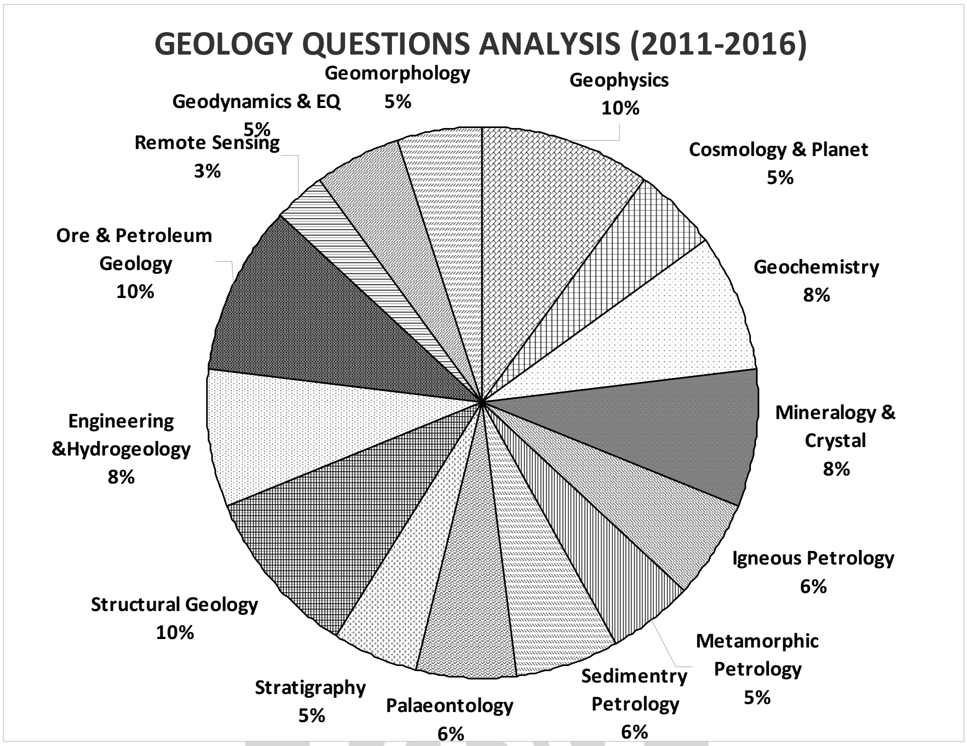
Seismic methods of prospecting; Elastic properties of earth materials; Reflection, refraction and CDP surveys; land and marine seismic sources, generation and propagation of elastic waves, velocity-depth models, geophones, hydrophones, recording instruments (DFS), digital formats, field layouts, seismic noises and noise profile analysis, optimum geophone grouping, noise cancellation by shot and geophone arrays, 2D and 3D seismic data acquisition, processing and interpretation; CDP stacking charts, binning, filtering, dip moveout, static and dynamic corrections, Digital seismic data processing, seismic deconvolution and migration methods, attribute analysis, bright and dim spots, seismic stratigraphy, high resolution seismics, VSP, AVO. Reservoir geophysics.

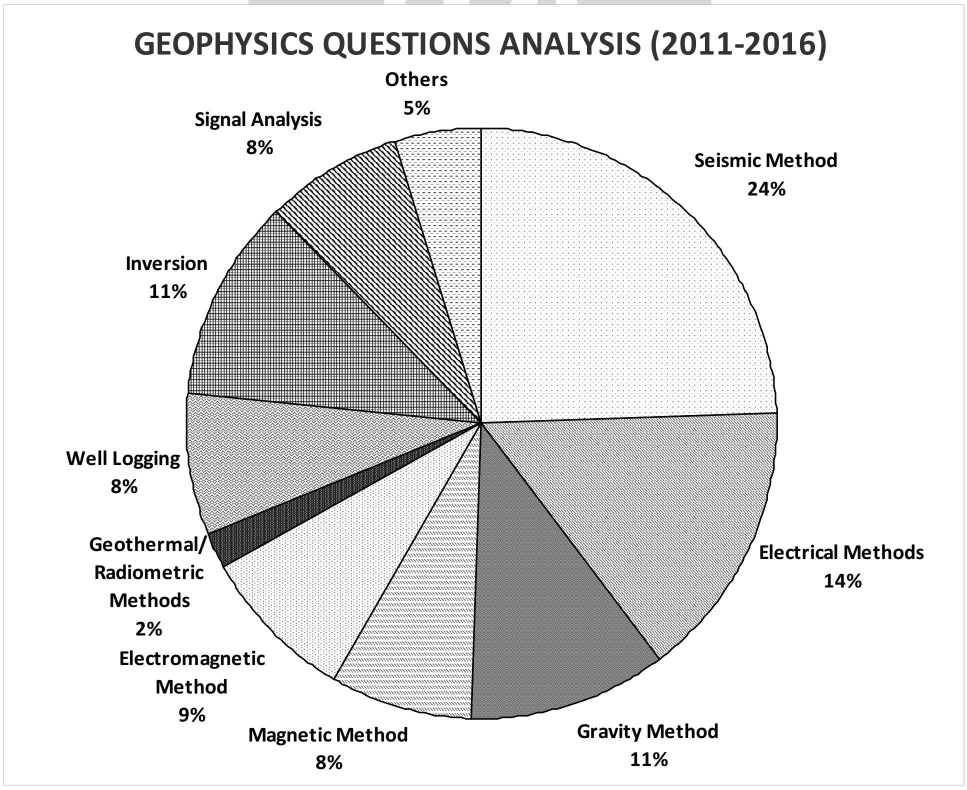
Geophysical signal processing, sampling theorem, aliasing, Nyquist frequency, Fourier series, periodic waveform, Fourier and Hilbert transform, Z-transform and wavelet transform; power spectrum, delta function, auto correlation, cross correlation, convolution, deconvolution, principles of digital filters, windows, poles and zeros.

Principles and techniques of geophysical well logging, SP, resistivity, induction, gamma ray, neutron, density, sonic, temperature, dip meter, caliper, nuclear magnetic, cement bond logging, micrologs. Quantitative evaluation of formations from well logs; well hydraulics and application of geophysical methods for groundwater study; application of bore hole geophysics in groundwater, mineral and oil exploration.

Radioactive methods of prospecting and assaying of mineral (radioactive and non-radioactive) deposits, half-life, decay constant, radioactive equilibrium, GM counter, scintillation detector, semiconductor devices, application of radiometric for exploration, assaying and radioactive waste disposal.

Basic concepts of forward and inverse problems, Ill-posedness of inverse problems, condition number, non-uniqueness and stability of solutions; L1, L2 and Lp norms, overdetermined, underdetermined and mixed determined inverse problems, quasi-linear and non-linear methods including Tikhonov's regularization method, Singular Value Decomposion, Backus-Gilbert method, simulated annealing, genetic algorithms and artificial neural network.


GEOLOGY QUESTIONS ANALYSIS (2011-2016)
Geomorphology 5%
Geophysics 10%
Geodynamics & EQ 5%
Remote Sensing 3%
Cosmology & Planet 5%
Ore & Petroleum Geology 10%
Geochemistry 8%
Engineering &Hydrogeology 8%
Mineralogy & Crystal 8%
Igneous Petrology 6%
Structural Geology 10%
Metamorphic Petrology 5%
Stratigraphy 5%
Palaeontology 6%
Sedimentry Petrology 6%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Others 5%
Signal Analysis 8%
Seismic Method 24%
Inversion 11%
Well Logging 8%
Geothermal/ Radiometric Methods 2%
Electrical Methods 14%
Electromagnetic Method 9%
Magnetic Method 8%
Gravity Method 11%

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GEOLOGY

SECTION – II
GEOPHYSICS

SECTION – III
SOLVED PAPERS

SOLAR SYSTEM EXPLORATION: THE PLANETS: ORBITS AND PHYSICAL CHARACTERISTICS

	Mercury	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune
Distance from the Sun (km) (Semi major axis of orbit)	5.7909227×10^7 (0 38709927 AU)	1.0820948×10^8 (7.2333566×10^{-1} AU)	$1. 4959826 \times 10^8$ (1.000 AU)	2.2794382×10^8 (1.523662 AU)	7.7834082×10^8 (5.2028870 AU)	1.4266664×10^9 (9.53667594 AU)	2.8706582×10^9 (1.9189165×10^1 AU)	4.4983964×10^9 (3.0069923×10^1AU)
Mean Equatorial Radius (km)	2.4397×10^3 (0.3829 × Earth)	6.0518×10^3 (0.9499 × Earth)	6.3710×10^3	3.3895×10^3 (0.5320 × Earth)	6.9911×10^4 (10.9733 × Earth)	5.8232×10^4 (9.1402 × Earth)	2.5362×10^4 (3.9809 × Earth)	2.4622×10^4 (3.8647 × Earth)
Volume (km^3)	6.08272×10^{10} (0.056 × Earth)	9.28415×10^{11} (0.857 × Earth)	1.08321×10^{11}	1.63116×10^{11} (0.151 × Earth)	1.43128×10^{11} (1321.337×Earth)	8.2713×10^{11} (763.594 × Earth)	6.83344×10^{11} (63.085 × Earth)	6.25257×10^{11} (57.723 × Earth)
Mass (kg)	3.3010×10^{23}	4.8673×10^{24}	5.9722×10^{24}	6.4169×10^{25}	1.8981×10^{27}	5.6832×10^{26}	8.6810×10^{25}	1.0241×10^{26}
Escape Velocity (km/k)	4.25×10^3	$1. 036 \times 10^3$	1.119×10^3	5.030×10^3	6.020×10^4	3.609×10^4	2.138×10^4	2.356×10^4
Rotation Period (Hours)	1407.5	5832.4	23.934	24.623	9.92496	10.656	17.23992	16.11000
Orbit Period (Earth days)	87.97	224.70	365.26	686.98	4,332.82	10,755.70	30,687.15	60190.03
Mean Orbit Velocity (m/s)	170,503	126,074	107,218	86,677	47,002	34,701	24,477	19,566
Orbit Eccentricity	0.20563593	0.00677672	0.01671123	0.0933941	0.04838624	0.05386179	0.04725744	0.00859048
Orbit Inclination to Ecliptic	7.0°	3.39°	0.00005°	1.85°	1.304°	2.49°	0.77°	1.77°
Inclination of Equator to Orbit	0°	177.3° (retrograde rotation)	23.4393°	25.2	3.1°	26.7°	97.8° (retrograde rotation)	28.3°
Minimum/Maximum Surface Temperature (K)	100/700	735	185/331 (min/max)	120 to 293				
Major Atmospheric Constituents		CO_2,N_2	N_2, O_2	CO_2,N_2,Ar	H_2,He	H_2,He	H_2,He,CH_4	H_2,He,CH_4
Moons	None	None	1 moon	2 moons	67 moons	62 moons	27 moons	14 moons
Rings	No	No	No	No	Yes	Yes	Yes	Yes

GEOLOGICAL TIME WITH MAJOR EVOLUTIONARY EVENTS IN THE FOSSIL RECORD

MYA	Eon	
0	PHANEROZOIC	Cenozoic
65		Mesozoic
251		Palaeozoic
542	PRE-CAMBRIAN	Proterozoic: Life begins in sea
2500		Archaean: Oldest rocks, Earth curst forms
4000		Hadean : Earth forms
4600		

MYA	Era	Period Major Events
0 1.8	CENOZOIC	Quaternary Tertiary Human evaluation Mammals diversify, Age of mammal
65	MESOZOIC	Cretaceous: Extinction of dinosaurs, First primates, First flowering plants
145		Jurassic: Age of dinosaurs, First birds, Dinosaurs diversify
199		Triassic: First mammals, first dinosaurs
251	PALEOZOIC	Permian: Major extinction, Reptiles diversify
299		Carboniferous: First reptiles, Trees, seed ferns
359		Devonian: First amphibians, Fish diversity
416		Silurain: First vascular plants
444		Ordovician: Graptolite Major diversification of animal life
488		Cambrian: First fish, First chordates (animal with backbone)
542		

SECTION - I

GEOLOGY

1

PHYSICAL GEOLOGY

WEATHERING AND SOILS

Weathering

Geologists recognize two categories of weathering processes

1. **Physical Weathering** – disintegration of rocks and minerals by a physical or mechanical process.
2. **Chemical Weathering** – chemical alteration or decomposition of rocks and minerals.

Although we separate these processes, as we will see, both work together to break down rocks and minerals to smaller fragments or to minerals more stable near the Earth's surface. Both types are a response to the low pressure, low temperature, and water and oxygen rich nature of the earth's surface.

Physical Weathering

The mechanical breakup or disintegration of rock doesn't change mineral makeup. It creates broken fragments or "detritus" which are classified by size:

- Coarse-grained – Boulders, Cobbles, and Pebbles.
- Medium-grained – Sand
- Fine-grained – Silt and clay (mud).

Physical weathering takes place by a variety of processes. Among them are:

- Development of Joints – Joints are regularly spaced fractures or cracks in rocks that show no offset across the fracture (fractures that show an offset are called faults).
- Joints form as a result of expansion due to cooling or relief of pressure as overlying rocks are removed by erosion.
- Igneous plutons crack in onion – Like "exfoliation" layers. These layers break off as sheets that slide off of a pluton. Over time, this process creates domed remnants.

Joints form free space in rock by which other agents of chemical or physical weathering can enter.

- **Crystal Growth** – As water percolates through fractures and pore spaces, it may contain ions that precipitate to form crystals. As these crystals grow, they may exert an outward force that can expand or weaken rocks.

- **Thermal Expansion** – Although daily heating and cooling of rocks do not seem to have an effect, sudden exposure to high temperature, such as in a forest or grass fire may cause expansion and eventual breakage of rock. E.g., Camp fire.
- **Root Wedging** – Plant roots can extend into fractures and grow, causing expansion of the fracture. Growth of plants can break rock – look at the sidewalks of New Orleans for example.
- **Animal Activity** – Animals burrowing or moving through cracks can break rock.
- **Frost Wedging** – Upon freezing, there is an increase in the volume of the water (that's why we use antifreeze in auto engines or why the pipes break in New Orleans during the rare freeze). As the water freezes, it expands and exerts a force on its surroundings. Frost wedging is more prevalent at high altitudes where there may be many freeze-thaw cycles.

Chemical Weathering

Since many rocks and minerals are formed under conditions present deep within the Earth, when they arrive near the surface as a result of uplift and erosion, they encounter conditions very different from those under which they originally formed. Among the conditions present near the Earth's surface that are different from those deep within the Earth are:

- Lower Temperature (near the surface T – 0-50°C)
- Lower Pressure (near the surface P = 1 to several hundred atmospheres)
- Higher free water (there is a lot of liquid water near the surface, compared with deep in the Earth)
- Higher free oxygen (although O_2 is the most abundant element in the crust, most of it is tied up bonded into silicate and oxide minerals – at the surface, there is much more free oxygen, particularly in the atmosphere).

Because of these differing conditions, minerals in rocks react with their new environment to produce new minerals that are stable under conditions near the surface. Minerals that are stable under P, T, H_2O, and O_2 conditions near the surface are, in order of most stable to least stable:

- Iron oxides, Aluminum oxides – such as hematite (Fe_2O_3) and gibbsite $Al(OH)_3$. The main agent responsible for chemical weathering reactions is water and weak acids formed in water.
- An acid is solution that has abundant free H^+ ions.
- The most common weak acid that occurs in surface waters is carbonic acid.
- Carbonic acid is produced in rainwater by reaction of the water with carbon dioxide (CO_2) gas in the atmosphere. H^+ is a small ion and can easily enter crystal structures, releasing other ions into the water.

Types of Chemical Weathering Reactions

- **Hydrolysis** – H^+ or OH^- replaces an ion in the mineral.
- **Leaching** – Ions are removed by dissolution into water.
- **Oxidation** – Since free oxygen (O_2) is more common near the Earth's surface, it may react with minerals to change the oxidation state of an ion. This is more common in Fe (iron) bearing minerals, since Fe can have several oxidation states, Fe, Fe^{+2} and Fe^{+3}. Deep in the Earth, the most common oxidation state of Fe is Fe^{+2}.
- **Dehydration** – Removal of H_2O or OH^- ion from a mineral.
- **Complete Dissolution** – All of the mineral is completely dissolved by the water.

- **Living Organisms** – Organisms like plants, fungi, lichen, and bacteria can secrete organic acids that can cause dissolution of minerals to extract nutrients. The role of micro organisms like bacteria has only recent been discovered.

STREAMS AND DRAINAGE SYSTEMS

Streams

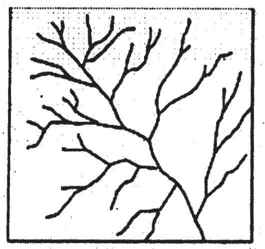
A stream is a body of water that carries rock particles and dissolved ions and flows down slope along a clearly defined path, called a channel. Thus, streams may vary in width from a few centimeters to several tens of kilometers. Streams are important for several reasons:

- Streams carry most of the water that goes from the land to the sea, and thus are an important part of the water cycle.
- Streams carry billions of tons of sediment to lower elevations, and thus are one of the main transporting mediums in the production of sedimentary rocks.
- Streams carry dissolved ions, the products of chemical weathering, into the oceans and thus make the sea salty.
- Streams are a major part of the erosional process, working in conjunction with weathering and mass wasting. Much of the surface landscape is controlled by stream erosion, evident to anyone looking out of an airplane window.
- Streams are a major source of water, waste disposal, and transportation for the world's human population. Most population centers are located next to streams.
- When stream channels fill with water, the excess flows onto the land as a flood. Floods are a common natural disaster.

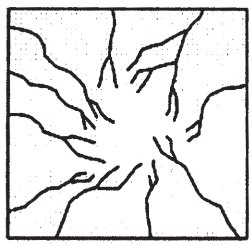
Drainage Systems

Drainage Patterns – Drainages tend to develop along zones where rock type and structure are most easily eroded. Thus, various types of drainage patterns develop in a region and these drainage patterns reflect the structure of the rock.

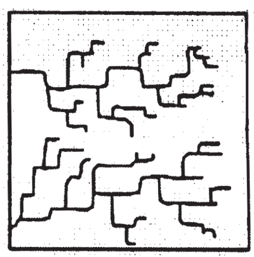
- Dendritic drainage patterns are most common. They develop on a land surface where the underlying rock is of uniform resistance to erosion.
- Radial drainage patterns develop surrounding areas of high topography where elevation drops from a central high area to surrounding low areas.
- Rectangular drainage patterns develop where linear zones of weakness, such as joints or faults cause the streams to cut down along the weak areas in the rock.
- Trellis drainage patterns develop where resistant rocks break up the landscape.



Dendritic Drainage



Radial Drainage



Rectangular Drainage

Drainage Basins – Each stream in a drainage system drains a certain area, called a drainage basin (also called a catchment or a watershed). In a single drainage basin, all water falling in the basin drains into the same stream. A drainage divide separates each drainage basin from other drainage basins. Drainage basins can range in size from a few km^2, for small streams, to extremely large areas, such as the Mississippi River drainage basin which covers about 40% of the contiguous United States.

Continental Divides – Continents can be divided into large drainage basins that empty into different ocean basins. For example: North America can be divided into several basins in the west of the Rocky Mountains that empty into the Pacific Ocean. Streams in the northern part of North America empty into the Arctic Ocean and Streams. East of the Rocky Mountains empty into the Atlantic Ocean or Gulf of Mexico. Lines separating these major drainage basins are termed drainage divide.

Continental Divides – Such divides usually run along high mountain crests that formed recently enough that they have not been eroded. Thus, major continental divides and the drainage patterns in the major basins reflect the recent geologic history of the continents.

Permanent Streams – Streams that flow all year are called permanent streams. Their surface is at or below the water table. They occur in humid or temperate climates where there is sufficient rainfall and low evaporation rates. Water levels rise and fall with the seasons, depending on the discharge.

Ephemeral Streams – Streams that only occasionally have water flowing are called ephemeral streams or dry washes. They are above the water table and occur in dry climates with low amounts of rainfall and high evaporation rates. They flow mostly during rare flash floods.

GEOMETRY AND DYNAMICS OF STREAM CHANNELS

Discharge

The stream channel is the conduit for water being carried by the stream. The stream can continually adjust its channel shape and path as the amount of water passing through the channel changes. The volume of water passing any point on a stream is called the discharge. Discharge is measured in units of volume/time (m^3/sec or ft^2/sec).

$$[Q = A \times V]$$

Discharge (m^3/sec) = Cross-sectional Area [width × average depth] (m^2) × Average Velocity (m/sec)

As the amount of water in a stream increases, the stream must adjust its velocity and cross-sectional area in order to form a balance. Discharge increases as more water is added through rainfall, tributary streams, or from groundwater seeping into the stream. As discharge increases, generally width, depth, and velocity of the stream also increase.

Velocity

A stream's velocity depends on position in the stream channel, irregularities in the stream channel caused by resistant rock, and stream gradient. Friction slows water along channel edges. Friction is greater in wider, shallower streams and less in narrower, deeper streams.

Erosion by Streams

Streams erode because they have the ability to pick up rock fragments and transport them to a new location. The size of the fragments that can be transported depends on the velocity of the stream and whether the flow is laminar or turbulent. Turbulent flow can keep fragments in suspension longer than laminar flow.

Sediment Transport and Deposition

- **Suspended Load** – Particles that are carried along with the water in the main part of the streams. The size of these particles depends on their density and the velocity of the stream. Higher velocity currents in the stream can carry larger and denser particles.
- **Bed Load** – Coarser and denser particles that remain on the bed of the stream most of the time but move by a process of saltation (jumping) as a result of collisions between particles, and turbulent eddies. Note that sediment can move between bed load and suspended load as the velocity of the stream changes.
- **Dissolved Load** – Ions that have been introduced into the water by chemical weathering of rocks. This load is invisible because the ions are dissolved in the water. The dissolved load consists mainly of HCO_3^{-2} (bicarbonate ions), Ca^{+2}, SO_4^{-2}, Cl^-, Na^{+2}, Mg^{+2} and K^+. These ions are eventually carried to the oceans and give the oceans their salty character. Streams that have a deep underground source generally have higher dissolved load than those whose source is on the Earth's surface.

The maximum size of particles that can be carried as suspended load by the stream is called stream competence. The maximum load carried by the stream is called stream capacity. Both competence and capacity increase with increasing discharge. At high discharge, boulder and cobble size material can move with the stream and are therefore transported. At low discharge, the larger fragments become stranded and only the smaller, sand, silt, and clay sized fragments move.

When flow velocity decreases, the competence is reduced and sediment drops out. Sediment grain sizes are sorted by the water. Sands are removed from gravels; muds from both. Gravels settle in channels. Sands drop out in near channel environments. Silts and clays drape floodplains away from channels.

Valleys and Canyons

Land far above base level is subject to downcutting by the stream. Rapid downcutting creates an eroded trough which can become either a valley or canyon. A valley has gently sloping sidewalls that show a V-shape in cross-section. A Canyon has steep sidewalls that form cliffs.

Whether or valley or canyon is formed depends on the rate of erosion and strength of the rocks. In general, slow downcutting and weak, easily erodible rocks results in valleys and rapid downcutting in stronger rocks results in canyons.

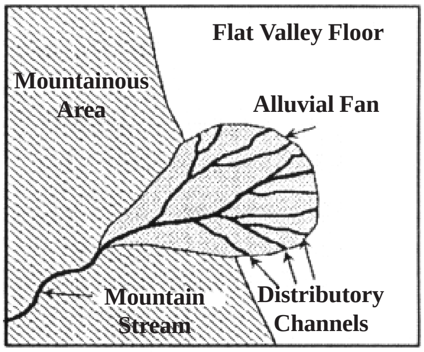
Rapids

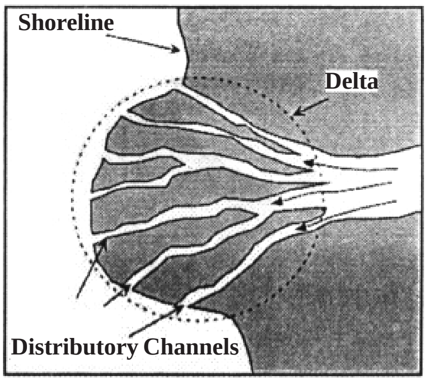
Rapids are turbulent water with a rough surface. Rapids occur where the stream gradient suddenly increases, where the stream flows over large clasts in the bed of the stream, or where there is an abrupt narrowing of the channel. Sudden change in gradient may occur where an active fault crosses the stream channel. Large clasts may be transported into the stream by a tributary stream resulting in rapids where the two streams join. Abrupt narrowing of the stream may occur if the stream encounters strong rock that is not easily subject to erosion.

Waterfalls

Waterfalls are temporary base levels caused by strong erosion resistant rocks. Upon reaching the strong rock, the stream then cascades or free falls down the steep slope to form a waterfalls. Because the rate of flow increases on this rapid change in gradient, erosion occurs at the base of the waterfall where a plunge pool forms. This can initiate rapid erosion at the base, resulting in undercutting of the cliff that caused the waterfall. When undercutting occurs, the cliff becomes subject to rockfalls or slides. This results in the waterfall retreating upstream and the stream eventually eroding through the cliff to remove the waterfall.

STREAM DEPOSITS





Floodplains and Levees – As a stream overtops its banks during a flood, the velocity of the flood will first be high, but will suddenly decrease as the water flows out over the gentle gradient of the floodplain. Because of the sudden decrease in velocity, the coarser grained suspended sediment will be deposited along the riverbank, eventually building up a natural levee. Natural levees provide some protection from flooding because with each flood the levee is built higher and therefore discharge must be higher for the next flood to occur.

Terraces – Terraces are exposed former floodplain deposits that result when the stream begins down cutting into its flood plain (this is usually caused by regional uplift or by lowering the regional base level, such as a drop in sea level).

Alluvial Fans – When a steep mountain stream enters a flat valley, there is a sudden decrease in gradient and velocity. Sediment transported in the stream will suddenly become deposited along the valley walls in an alluvial fan. As the velocity of the mountain stream slows, it becomes choked with sediment and breaks up into numerous distributory channels.

Deltas – When a stream enters a standing body of water such as a lake or ocean, again there is a sudden decrease in velocity and the stream deposits its sediment in a deposit called a delta. Deltas build outward from the coastline, but will only survive if the ocean currents are not strong enough to remove the sediment.

DRAINAGE EVOLUTION

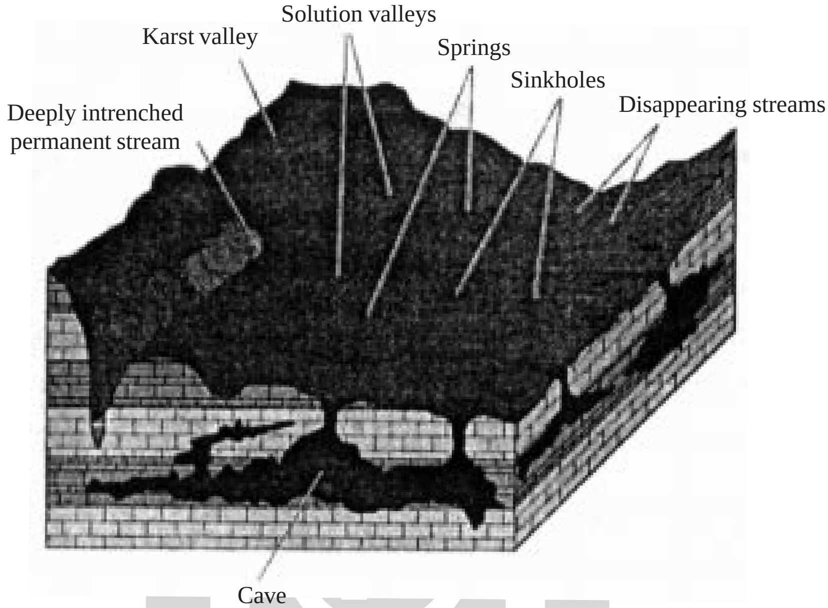
Stream Piracy

Stream piracy is where one stream erodes headward to capture the drainage of another stream. The stream with more vigorous erosion (steeper gradient), intercepts another stream and water from the captured stream flows into piercing stream.

GEOLOGIC ACTIVITY OF GROUNDWATER

- **Dissolution** – Water is the main agent of chemical weathering. Groundwater is an active weathering agent and can leach ions from rock, and, in the case of carbonate rocks like limestone, can completely dissolve the rock.
- **Chemical Cementation and Replacement** – Water is also the main agent acting during diagenesis. It carries in dissolved ions which can precipitate to form chemical cements that hold sedimentary rocks together. Groundwater can also replace other molecules in matter on a molecule by molecule basis, often preserving the original structure such as in fossilization or petrified wood.
- **Caves and Caverns** – If large areas of limestone underground are dissolved by the action of groundwater, these cavities can become caves or caverns (caves with many interconnected chambers) once the water table is lowered. Once a cave forms, it is open to the atmosphere and water percolating in can precipitate new material such as the common cave decorations like stalactites (hang from the ceiling), stalagmites (grow from the floor upward) dripstones, and flowstones.

- **Sinkholes** – If the roof of a cave or cavern collapses, this results in a sinkhole. Sinkholes, like caves, are common in areas underlain by limestones. For example, in Florida, which is underlain by limestones, a new sinkhole forms about once each year, gobbling up cars and houses in process.
- **Karst Landscapes** – In an area where the main type of weathering is dissolution (like in limestone terrains), die formation of caves and sinkholes, and their collapse and coalescence may result in a highly irregular topography called karst landscapes.



MASS MOVEMENTS

Gravity

Gravity is the main force responsible for mass movements.

The Role of Water

Although water is not always directly involved as the transporting medium in mass movement processes, it does play an important role.

Addition of water from rainfall or snow melt adds weight to the slope. Water can seep into the soil or rock and replace the air in the pore space or fractures. Since water is heavier than air, this increases the weight of the soil.

If the material becomes saturated with water, vibrations could cause liquifaction to occur, just like often happens during earthquakes.

Water can reduce the friction along a sliding surface.

Water has the ability to change the angle of repose (the slope angle which is the stable angle for the slope).

- Dry unconsolidated grains will form a pile with a slope angle determined by the angle of repose. The angle of repose is the steepest angle at which a pile of unconsolidated grains remains stable, and is controlled by the frictional contact between the grains. In general, for dry materials, the angle of repose increases with increasing grain size, but usually lies between about 30º and 45°.

- ✦ Coarser grained and angular particles have a steeper angle of repose than fine grained and rounded particles.
- ✦ Slightly wet unconsolidated materials exhibit a very high angle of repose because surface tension between the water and the grains tends to hold the grains in place.
- ✦ When the material becomes saturated with water, the angle of repose is reduced to very small values and the material tends to flow like a fluid. This is because the water gets between the grains and eliminates grain-to-grain frictional contact.

Mass Movement Processes

The down-slope movement of material, whether it be bedrock, regolith, or a mixture of these, is commonly referred to as a landslide. All of these processes generally grade into one another, so classification of mass movement processes is somewhat difficult. We will use a common classification of mass movements, which divides the processes into two broad categories and further subdivides these categories.

1. **Slope Failures** – a sudden failure of the slope resulting in transport of debris down hill by sliding, rolling, falling or slumping.
2. **Sediment Flows** – material flows down hill mixed with water or air.

Slope Failures

- ✦ **Slumps** – Types of slides wherein downward rotation of rock or regolith occurs along a curved surface. The upper surface of each slump block remains relatively undisturbed, as do the individual blocks. Slumps leave arcuate scars or depressions on the hill slope. Heavy rains or earthquakes usually trigger slumps.
- ✦ **Rock Falls and Debris Falls** – Rock falls occur when a piece of rock on a steep slope becomes dislodged and falls down the slope. Debris falls are similar, except they involve a mixture of soil, regolith and rocks. A rock fall may be a single rock or a mass of rocks and the falling rocks can dislodge other rocks as they collide with the cliff. At the base of most cliffs is an accumulation of fallen material termed talus. The slope of the talus is controlled by the angle of repose for the size of the material. Since talus results from the accumulation of large rocks or masses of debris, the angle of repose is usually greater than it would be for sand.
- ✦ **Rock Slides and Debris Slides** – Rock slides and debris slides result when rocks or debris slide down a pre-existing surface, such as a bedding plane or joint surface. Piles of talus are common at the base of a rock slide or debris slide.

Sediment Flows

Sediment flows occur when sufficient force is applied to rocks and regolith that they begin to flow down slope. A sediment flow is a mixture of rock, regolith with some water. They can be broken into two types depending on the amount of water present.

1. **Slurry Flows** – are sediment flows that contain between about 20% and 40% water. As the water content increases above about 40%, slurry flows grade into streams.
2. **Granular Flows** – are sediment flows that contain between 20% and 0% water. Note that granular flows are possible with little or no water. Fluid-like behavior is given to these flows by mixing with air.

Each of these classes of sediment flows can be further subdivided on the basis of the velocity at which flowage occurs.

- **Solifluction** – Flowage at rates measured in the order of centimeters per year of regolith containing water. Solifluction produces distinctive lobes on hill slope. These occur in areas where the soil remains frozen and then thawed for a short time to become saturated with water.
- **Debris Flows** – These occur at higher velocities than solifluction, and often result from heavy rains causing saturation of the soil and regolith with water. They sometimes start with slumps and then flow down hill forming lobes with an irregular surface consisting of ridges and furrows.
- **Mudflows** – A highly fluid, high velocity mixture of sediment and water that has a consistency of wet concrete. These usually result from heavy rains in areas where there is an abundance of unconsolidated sediment that can be picked up by streams. Thus, after a heavy rain, streams can turn into mudflows as they pick up more and more loose sediment. Mudflows can travel for long distances over gently sloping stream beds. Because of their high velocity and long distance of travel they are potentially very dangerous. Mudflows on volcanoes are called lahars.
- **Granular Flows** (low amounts of water).
- **Creep** – The very slow, usually continuous movement of regolith down slope. Creep occurs on almost all slopes, but the rates vary. Evidence for creep is often seen in bent trees, offsets in roads and fences, and inclined utility poles.
- **Earthflows** – Are usually associated with heavy rains and move at velocities between several cm/yr and 100s of m/day. They usually remain active for long periods of time. They generally tend to be narrow tongue-like features that begin at a scarp or small cliff. !
- **Grain Flows** – Usually form in relatively dry material, such as a sand dune, on a steep slope. A small disturbance sends the dry unconsolidated grains moving rapidly down slope.
- **Debris Avalanches** – These are very high velocity flows of large volume mixtures of rock and regolith that result from complete collapse of a mountainous slope. They move down slope and then can travel for considerable distances along relatively gentle slopes. They are often triggered by earthquakes and volcanic eruptions. Snow avalanches are similar, but usually involve only snow.

Mass Movements in Cold Climates

Mass movements in cold climates is governed by the fact that water is frozen as ice daring long periods of the year. Ice, although it is solid, does have the ability to flow, and freezing and thawing cycles can also contribute to movement.

Rock Glaciers – A lobe of ice-cemented rock debris (mostly rocks with ice between the blocks) that slowly moves downhill.

Subaqueous Mass Movement

Mass movements also occur on slopes in the ocean basins. Most slope failure can occur due to over-accumulation of sediment on slope or in a submarine canyon, or could occur as a result of a shock like an earthquake. 3 types can occur – (1) Submarine slumps – Coherent blocks break and slip, similar to slumps on land. (2) Submarine debris flows – Moving material breaks apart and flows, similar to debris flows on land. (3) Sediment moves as a turbulent cloud, called a turbidity current.

Gigantic submarine slope failures are widespread on the ocean floor, particularly around islands like Hawaii and off the east and gulf coasts of North America. They are much larger than land-based slope failures and are an important process sculpting adjacent land. When they occur, they create catastrophic tsunamis.

Triggering Events

A mass movement can occur any time a slope becomes unstable. Sometimes, as in the case of creep or solifluction, the slope is unstable all of the time and the process is continuous. But other times, triggering events can occur that cause a sudden instability to occur. Here, we discuss major triggering events, but it should be noted that if a slope is very close to instability, only a minor event may be necessary to cause a failure and disaster. This may be something as simple as an ant removing the single grain of sand that holds the slope in place.

- **Shocks and vibrations** – A sudden shock, such as an earthquake, may trigger slope instability. Minor shocks like heavy trucks rambling down the road, trees blowing in the wind, or human-made explosions can also trigger mass movement events.
- **Slope Modification** – Modification of a slope either by humans or by natural causes can result in changing the slope angle so that it is no longer at the angle of repose. A mass movement can then restore the slope to its angle of repose.
- **Undercutting** – Streams eroding their banks or surf action along a coast can undercut a slope making it unstable.
- **Changes in Hydrologic Characteristics** – Heavy rains can saturate regolith reducing grain-to-grain contact and reducing the angle of repose, thus triggering a mass movement. Heavy rains can also saturate rock and increase its weight. Changes in the groundwater system can increase or decrease fluid pressure in rock and also trigger mass movements.
- **Changes in Slope Strength** – Weathering creates weaker material, and thus leads to slope failure. Vegetation holds soil in place and slows the influx of water. Trees put down roots that hold the ground together and strengthen the slope. Removal of tress and vegetation either by humans or by a forest fire often results in slope failures in the next rainy season.
- **Volcanic Eruptions** – Produce shocks like explosions and earthquakes. They can also cause snow to melt or discharges from crater lakes, rapidly releasing large amounts of water that can be mixed with regolith to reduce grain-to-grain contact and result in debris flows, mudflows and landslides.

GLACIERS AND GLACIATION

Definition of a Glacier

A glacier is a permanent (on a human time scale, because nothing on the Earth is really permanent) body of ice, consisting largely of recrystallized snow, that shows evidence of downslope or outward movement due to the pull of gravity.

Types of Glaciers

Mountain Glaciers – Relatively small glaciers which occur at higher elevations in mountainous regions.

- Smallest of these occupy hollows or bowl-shaped depressions on sides of mountains (cirque glaciers).
- As cirque glaciers grow larger, they may spread into valleys and flow down the valleys as valley glaciers. Paths of these valley glaciers take are controlled by existing topography.
- If a valley glacier extends down to sea level, it may carve a narrow valley into the coastline. These are called fjord glaciers, and the narrow valleys they carve and later become filled with seawater after the ice has melted are fjords.

- ✦ If a valley glacier extends down a valley and then covers a gentle slope beyond the mountain range, it is called a piedmont glacier.
- ✦ If all of the valleys in a mountain range become filled with glaciers, and the glaciers cover entire mountain range, they are called ice caps.

Ice Sheets (Continental Glaciers) – Are the largest types of glaciers on Earth. They cover large areas of the land surface, including mountain areas. Modern ice sheets cover Greenland and Antarctica. These two ice sheets comprise about 95% of all glacial ice currently on Earth. They have an estimated volume of about 24 million km^3. If melted, they contain enough water to raise sea level about 66 m (216 ft.). This would cause serious problems for coastal cities (L.A., NY, Washington D.C., New Orleans, Miami, SF, etc.). The Greenland ice sheet is in some places over 3000 m (9800 ft) thick and the weight of ice has depressed much of the crust of Greenland below sea level. Antarctica is covered by two large ice sheets that meet in the central part along the Transantarctic Mountains. These are the only truly polar ice sheet on earth (North Pole lies in an ocean covered by thin layer of ice).

Ice Shelves – Ice shelves are sheets of ice floating on water and attached to land. They usually occupy coastal embayments, may extend hundreds of km from land and reach thickness of 1000 sm.

Glaciers can also be classified by their internal temperature.

- ✦ **Temperate glaciers** – Ice in a temperature glacier is at a temperature near its melting point.
- ✦ **Polar glaciers** – Ice in a polar glacier always maintains a temperature well below its melting point.

The Formation of Glacial Ice

Three conditions are necessary to form a glacier: (1) Cold local climate (polar latitudes or high elevation). (2) snow must be abundant; more snow must fall than melts, and (3) snow must not be removed by avalanches or wind.

Glaciers can only form at latitudes or elevations above the snowline, which is the elevation above which snow can form and remain present year round. The snowline, at present, lies at sea level in polar latitudes and rises up to 6000 m in tropical areas. Glaciers form in these areas if the snow becomes compacted, forcing out the air between the snowflakes. As compaction occurs, the weight of the overlying snow causes the snow to recrystallize and increase its grainsize, until it increases its density and becomes a solid block of ice. A glacier is actually a metamorphic rock.

Changes in Glacier Size

A glacier can change its size by accumulation, which occurs by addition of snowfall, compaction and recrystallization, and ablation, the loss of mass resulting from melting, usually at lower altitude, where temperatures may rise above freezing point in summer. Thus, depending on the balance between accumulation and ablation during a full season, the glacier can advance or retreat.

Movement of Glaciers

Glaciers move to lower elevations under the force of gravity by two different processes:

- ✦ **Internal Flow** – called creep, results from deformation of the ice crystal structure. The crystals slide over each other like deck of cards. This type of movement is the type that occurs in polar glaciers, but it also occurs in temperate glaciers.
- ✦ **Basal Sliding** – melt water at base of glacier reduces friction by lubricating the surface and allowing die glacier to slide across its bed. Polar glaciers are usually frozen to their bed and are thus too cold for this mechanism to occur.

The upper portions of glaciers are brittle, when the lower portion deforms by internal flow, the upper portions may fracture to form large cracks called crevasses. Crevasses occur where the lower portion of a glacier flows over sudden change in topography. The velocity of glacial ice changes throughout the glacier. The velocity is low next to the base of the glacier and where it is contact with valley walls. The velocity increases toward the center and upper parts of the glacier.

Glacial Erosion

Glaciers erode in several ways:

- ✦ **Abrasion** – Rock fragments carried by the glacier scrape against rock causing abrasion, like sandpaper.
- ✦ **Plucking** – Ice breaks off and removes bedrock fragments.

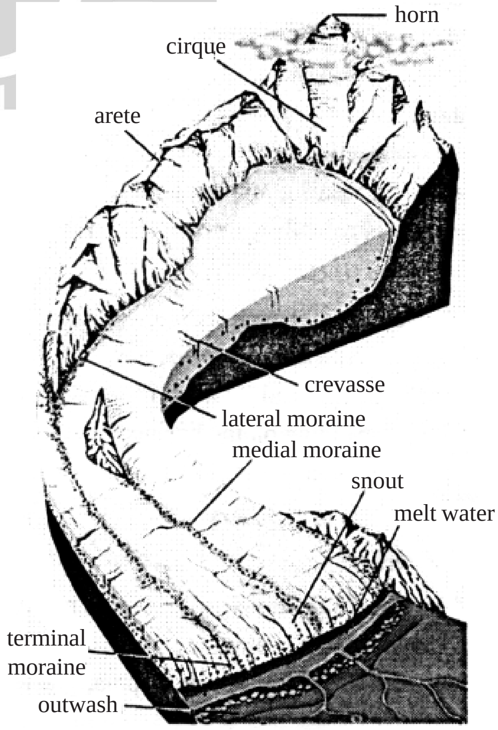
Ice melts by pressure against the up-ice side of an obstruction. Entering cracks in bedrock, this water re-freezes to the ice. Glacial movement plucks away bedrock chunks.

Small Scale Erosional Features

- ✦ **Glacial striations** – Long parallel scratches and grooves that are produced at the bottom of temperate glaciers by rocks embedded in the ice scraping against the rock underlying the glacier.
- ✦ **Glacial polish** – Rock that has a smooth surface produced as a result of fined grained material embedded in the glacier acting like sandpaper on the underlying surface.

Landforms Produced by Mountain Glaciers

- ✦ **Cirques** – Bowlshaped depressions that occur at the heads of mountain glaciers resulting from a combination of frost wedging, glacial plucking and abrasion. Sometimes, small lakes, called tarns, occur in the bottom of cirque.



- ✦ **Glacial Valleys** – Valleys that once contained glacial ice become eroded into a “U” shape in cross-section. Stream erosion, on the other hand, produces valleys that are “U” shaped in cross-section.
- ✦ **Aretes** – If two adjacent valleys are filled with glacial ice, the ridges between the valleys can be carved into a sharp knife-edge ridge, called an arete.
- ✦ **Horns** – Where three or more cirques are carved out of a mountain, they can produce a sharp peak called a horn.
- ✦ **Hanging Valleys** – When a glacier - occupying a smaller tributary valley meets the larger valley, the tributory glacier usually does not have the ability to erode its base to the floor of the main valley. Thus, when the glacial ice melts, the floor of the tributory valley hangs above the floor of the main valley and is called a hanging valley. Waterfalls generally occur where the hanging valley meets the main valley.

- **Fjords** – Fjords are narrow inlets along the sea coast that were once occupied by a valley glacier, called a fjord glacier.

Landforms Produced by Ice Caps and Ice Sheets

- **Abrasional features** – The same small-scale abrasional features such as striations and glacial polish can occur beneath ice caps and ice sheets, particularly in temperate environments.
- **Streamlined forms** – The land surface beneath a moving continental ice sheet can be molded into smooth elongated forms called drumlins.

  Other elongated hills carved into bedrock by plucking and abrasion are called roche mountones.

Glacial Deposition and Deposits

Since glaciers are solid. They can transport all sizes of sediment, from huge house-sized boulders to fine-grained clay sized material. The glacier can carry this material on its surface or embedded within it. Thus, sediment transportation in a glacier is very much different than that in a stream. Thus, sediments deposited directly from melting of a glacial can range from very poorly sorted to better sorted, depending on how much water transport takes place after the ice melts. All sediments deposited as a result of glacial erosion is called Glacial Drift.

Ice Laid Deposits

- **Till** – Non-sorted glacial drift deposited directly from ice. Till consists of a random mixture of different sized fragments of angular rocks in a matrix of fine grained, sand to clay-sized fragments that were produced by abrasion within the glacier. This fine-grained material is often called rock flour because it is really ground up rock. A till that has undergone diagenesis and has turned into a rock is called a tillite.
- **Erratics** – A glacially deposited rock or fragment that now rests on a surface made of different rock. Erratics are often found many kilometers from their source, and by mapping the distribution pattern of erratics, geologists can often determine the flow directions of the ice that carried them to their present locations.
- **Moraines** – These are deposits of till that have a form different from the underlying bedrock. Depending on where it formed in relation to the glacier moraines can be.
- **Ground Moraines** – these are deposited beneath the glacier and result in a hummocky topography with lots of enclosed small basins.
- **End Moraines and Terminal Moraines** are deposited at the low elevation end of a Lateral Moraines. These are deposits of till that were deposited along the sides of mountain glaciers.
- **Medial Moraines** – When two valley glaciers meet to form a larger glacier, the rock debris along the sides of both glaciers merge to form a medial moraine. These black streaks in an active glacier, as well as the deposits left behind after the ice melts are called medial moraines.
- **Glacial Marine Drift** – Glaciers that reach the oceans or even lakes, may calve off into large icebergs which then float on the water surface until they melt. Upon melting, the rock debris that they contain becomes immediately deposited on the sea floor or lake bed as an unsorted chaotic deposit. Sometimes, single large rock fragments fall out on the floor of the water body, and these are called dropstones.
- **Stratified Drift** – Glacial drift can be picked up and moved by meltwater streams which can then deposit that material as stratified drift.

- **Outwash Plains** – Streams running off the end of a melting glacier are usually choked with sediment and form braided streams, which deposit poorly sorted stratified sediment in an outwash plain. These deposits are often referred to as outwash.
- **Kettle Lakes** – If depressions form underneath a glacier and remain after the glacier is melted, then water filling these depressions become small lakes where fine-grained sediment is deposited. The state of Minnesota is called the land of ten thousand lakes, most of which are kettle lakes.
- **Kames and Kame Terraces** – Streams and lakes forming on top of or on the sides of stagnant ice may deposit stratified sediment on top of the glacier. When the glacier melts, these deposits are set down on the ground surface and become kames.
- **Eskers** – Eskers are long sinuous ridges of sediment deposited by streams that run under or within a glacier. The sediment deposited by these streams becomes an esker after the ice has melted.
- **Meltwater Lakes** – Depressions created by glacial erosion and deposition collect water released by melting glaciers. Sediment that collected in the bottom on the lakes is often finely layered with coarser grained layers formed during times of warmer temperatures and fine-grained layers formed during cold times when no new sediment is entering the lake. Such finely layered strata are termed varves.

Other Consequences of Glaciation

Ice Loading and Glacial Rebound

The weight of glacial ice sheets depress the lithosphere into the mantle causing the crust to subside. After the ice melts, the depressed lithosphere rebounds. The rebound process is still taking place today.

Sea Level Changes

- During glacial periods, much sea water was tied up in glaciers. So, sea level was lower.
- During interglacial periods, sea level was higher due to melting of the ice.

Glacial Ages:

The last glaciation ended about 11,000 years ago. But the period between 11,000 years ago and 2 million years ago (the Pleistocene epoch) was a time of many glacial and interglacial ages.

Based on evidence from glacial deposits and glacial erosion features, geologists have been able to document at least 4 glaciations during the Pleistocene, two of which are poorly documented. But recent studies of deep-sea sediments and dating of these deposits suggest that there were at least 30 glaciations that occurred during the Pleistocene. This evidence comes from studies of fossils found in deep-sea sediment cores, and what they tell us about ocean surface temperatures in the past. The results come from studies of the isotopes of oxygen.

Oxygen has two major isotopes, ^{18}O, which is considered heavy, and ^{16}O, which is considered light. Both of these isotopes are stable and non-radiogenic, so their ratio is constant through time.

- Because ^{16}O is lighter, it is preferentially evaporated with sea water from the oceans, and thus gets concentrated in the water that eventually falls on the continents as rain or snow. Because of this, ^{18}O gets concentrated in ocean water. During constant climatic conditions, the ^{16}O lost to evaporation returns to the oceans by rain and streams, so that the ratio of ^{18}O to ^{16}O (^{18}O / ^{16}O) is constant.
- But, during a glaciation, some of the ^{16}O gets tied up in glacial ice and does not return to the oceans. Thus, during glaciation the ^{18}O / ^{16}O ratio of sea water increases.

- During an interglaciation, on the other hand, the ^{16}O that was tied up in glacial ice returns to the oceans causing a decrease in the ^{18}O / ^{16}O ratio of seawater.

Thus, we expect that during glaciations, the ^{18}O / ^{16}O ratio in seawater will be high, and during interglaciations, the ^{18}O / ^{16}O ratio in seawater will be low. Since organisms that live in the oceans extract oxygen from seawater to form their carbonate (CO_3^{-2}) shells, measuring the ^{18}O / ^{16}O ratio in the shells of dead organisms gives a record of past ocean temperatures.

During the last 1 million years, it appears that each glacial – interglacial cycle has lasted about 100,000 years, but earlier cycles were about 40,000 years long.

Other periods of glaciation are known from the geologic record, mainly from preserved glacial striations and tillites (consolidated till). The earliest recognized glaciation occurred about 2.3 billion years ago, but at least 50 other glaciations are recognized to have occurred during the Paleozoic era.

Causes of Glacial Ages

In order to understand what causes these cycles of glacial-interglacial episodes we need a much better understanding of what causes global climate changes. Because human history is so short compared to the time scales on which global climate change occurs, we do not completely understand the causes. However, we can suggest a few reasons why climates fluctuate.

- Long-term variations in climate (tens of millions of years) on a single continent are likely caused by drifting continents. If a continent drifts toward the equator, the climate will become warmer. If the continent drifts toward the poles, glaciations can occur on that continent.
- Short-term variations in climate are likely controlled by the amount of solar radiation reaching the Earth. Among these are astronomical factors and atmospheric factors.

Astronomical Factors

- Variation in the eccentricity of the Earth's orbit around the sun has periods of about 400,000 years and 100,000 years.
- Variation in the tilt of the Earth's axis has a period of about 41,000 years.
- Variation in the way the Earth wobbles on its axis, called precession, has a period of about 23,000 years.
- The combined effects of these astronomical variations results in periodicities (called Milankovitch Cycles) similar to those observed for glacial-interglacial cycles.
- **Atmospheric Factors –** The composition of the Earth's atmosphere can be gleaned from air bubbles trapped in ice in the polar ice sheets. Studying drill core samples of such glacial ice and their contained air bubbles reveals the following:.
- During past glaciations, the amount of CO_2 and methane, both greenhouse gasses that tend to cause global warming, were lower than during interglacial episodes.
- During past glaciations, the amount of dust in the atmosphere was higher than during interglacial periods, thus more heat was likely reflected from the Earth's atmosphere back into space.
- The problem in unraveling what this means comes from not being able to understand if low greenhouse gas concentration and high dust content in the atmosphere caused the ice ages or if these conditions were caused by the ice ages.

Changes in Oceanic Circulation – Small changes in ocean circulation can amplify small changes in temperature variation produced by astronomical factors and other factors:

- The energy output from the sun may fluctuate.
- Large explosive volcanic eruptions can add significant quantities of dust to the atmosphere reflecting solar radiation and resulting in global cooling.
- Impacts of large asteroids with the Earth can cause extensive amounts of dust and soot to be placed in the atmosphere. Dust and soot would block incoming solar radiation and cause a cooling effect for as long as the dust remains in the atmosphere.

DESERTS

Deserts are areas where rainfall is less than 250 mm (10 in.)/year, or where evaporation exceeds precipitation. Thus, deserts are areas that we think of as arid. They may be hot or cold. They are characterized by specialized ecosystems and low human populations.

Because of their dryness, unique geologic processes operate in deserts.

Origin of Deserts

Deserts originated by several different mechanisms may result in five types of deserts.

1. Subtropical deserts
2. Rain shadow deserts
3. Coastal deserts
4. Continental interior deserts
5. Polar deserts.

Subtropical Deserts – The general atmospheric circulation brings dry, subtropical air into mid-latitudes. ***Examples:*** Sahara of Northern Africa, Kalahari of Southern Africa, and the Great Australian Desert.

Rainshadow Deserts – Areas where mountainous regions cause air to rise and condense, dropping its moisture as it passes over the mountains. ***Examples:*** East of the Sierra Nevada Mountains, California and Nevada, East of the Cascades of Oregon and Washington, and East of the Andes Mountains in South America.

Coastal Deserts – Areas where cold upwelling seawater cools the air and decreases its ability to hold moisture. ***Examples:*** Atacama Desert of coastal Peru and Namib Desert of coastal South Africa.

Continental Interior Deserts – Areas in the continental interiors, far from source of moisture where hot summers and cold winters prevail. ***Example:*** Gobi, Mongolia.

Polar Deserts – Cold polar regions where cold dry air prevails and moisture available remains frozen throughout the entire year. ***Examples:*** Northern Greenland, and ice-free areas of Antarctica.

SURFACE PROCESSES IN DESERTS

The same geologic processes operate in deserts as in other more humid climates. The difference is the intensity to which the processes act.

Weathering and Mass Movements

- Deserts have little soil because moisture is so low and the rate of chemical weathering is slow. Chemical weathering is responsible for the formation of soils. Bedrock commonly occurs at the surface. Exposed rock surfaces develop desert, dark reddish brown surface coating of iron and manganese oxides. This forms very slowly by bacterial activity, dust and water.

- Little plant life develops because of lack of soils and water. Plants tend to hold soil and fine-grained rock fragments in place. So, without plants, erosional processes can remove the thin desert soils.
- Desert soils are usually colored like the bedrock nearby. Trace elements in the soils bring out wide color variations.
- The desert surface is dominated by mechanical weathering processes. Rock fragments tend to be angular, rather than rounded. If we compare the surface features of deserts with those in humid regions, we find that:

  Deserts are dominated by rock falls, rock slides, and the accumulation of coarse grained material, and generally have steeper slopes.
- Humid regions have soil and fine-grained regolith covering slopes, with creep being the dominant mass movement process, resulting in curved gentle slopes.
- Cliffs of solid rock are common in desert regions. If the rock making up the cliff has numerous vertical joints and they are underlain by more easily eroded rocks like shales, erosion and mechanical weathering will eventually cause rock falls. This results in cliff retreat.

If the cliff forming rocks have horizontal bedding planes, continued cliff retreat and stream erosion eventually form flat-tipped hills called mesas (mesa is Spanish for table) with areas of several square kilometers. Small flat topped hills that become isolated from the mesas are called buttes.

If the cliff forming rocks have bedding planes that dip, then an asymmetrical ridge, caned a cuesta will form. The steep cliff forms on one side and a gentle slope parallel to the bedding planes forms on the other side. This gentle slope is referred to as dip slope, because it is has the same angle as the dip of the bedding planes.

Streams and Fluvial Landforms

- **Alluvial Fans and Bajadas** – An alluvial fan forms where a mountain stream enters a broad flat valley and deposits sediment as its velocity decreases on entering the flatter valley. When a linear mountain range has several closely spaced valleys, the alluvial fans may coalesce to form a gentle undulated slope on the sides of the bounding lowlands.

  Such coalesced alluvial fans are known as **Bajadas**.
- **Pediments** – A pediment is broad bedrock surface with a gentle slope away from highlands. With distance away from the highlands, the pediment passes beneath a thin cover of alluvial sediment derived from erosion of the pediment. The highlands remain as residual hills as the pediment matures.
- **Playa Lakes** – Lakes that do form during the rare periods of rainfall, quickly evaporate, leaving a dry lake bed behind. Playa Lakes (also called dry lakes) are formed in basins of internal drainage. The lake beds often consist of salts (evaporates) that were carried in by streams and precipitated during evaporation. These precipitated salts give the dry lakebed a white color resembling a beach (playa means beach in Spanish).

Wind Erosion and Deposition

Wind is common in arid desert regions because:

1. Air near the surface is heated and rises, cooler air comes in to replace hot rising air and this movement of air results in winds.

2. Arid regions have little or no soil moisture to hold rock and mineral fragments.
3. Wind has the ability to transport, erode and deposit sediment.

Sediment Transportation by Wind – Wind transports sediment near the surface by saltation. Just as in the bed load of streams, saltation refers to short jumps of grains dislodged from the surface and jumping a short distance. As the grains fall back to the surface, they may dislodge other grains then get carried by wind until they collide with ground to dislodge other particles. Smaller particles can become suspended in the wind and may travel for longer distances.

Sand Ripples – Occur as a result of larger grains accumulating as smaller grains are transported away. Ripples form in lines perpendicular to wind direction. These are similar to, but much smaller than dunes.

Wind Erosion – Wind can be effective agent of erosion anywhere that it is strong enough to act. Wind can erode by deflation and abrasion.

✦ **Deflation** is the lowering of the land surface due to removal of fine-grained particles by the wind. Deflation concentrates the coarser grained particles at the surface, eventually resulting in a surface composed only of the coarser grained fragments that cannot be transported by the wind: Such a surface is called desert pavement.
✦ **Ventifacts** are any bedrock surface or stone that has been abraded or shaped by wind-blown sediment in a process similar to sand blasting.
✦ **Yardangs** are streamlined wind-eroded ridges commonly found in deserts.

Wind Deposits

Wind can deposit sediment when its velocity decreases to the point where the particles can no longer be transported. This can happen when topographic barriers slow the wind velocity on both the upwind and downwind side of the barrier. As the air moves over the top of the barrier, streamlines converge and the velocity increases.

After passing over the barrier, the streamlines diverge and the velocity decreases. As the velocity decreases, some of the sediment in suspension can no longer be held in suspension, and thus drops out to form a deposit.

Topographic barriers can be such things as rocks, vegetation, and human-made structures that protrude above the land surface.

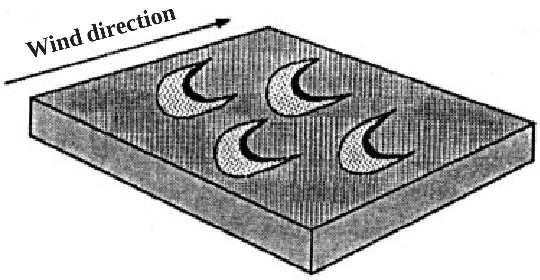
Sand Dunes

Sand dunes form when there is: (1) a ready supply of sand, (2) a steady wind, and (3) some kind of obstacle such as vegetation, rocks, or fences, to trap some of the sand. Sand dunes form when moving air slows down on the downwind side of an obstacle. The sand grains drop out and form a mound that becomes a dune.

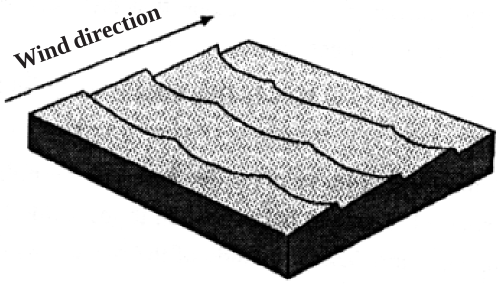
✦ Sand dunes are asymmetrical mounds with a gentle slope in the upwind direction and steep slope called a slip face on the downwind side. Dunes migrate by erosion of sand by wind (saltation) on the gentle upwind slope, and deposition and sliding on the slip face, and thus are cross-bedded deposits.
✦ Dunes may cover large areas and reach heights up to 500 m.

Types of Sand Dunes

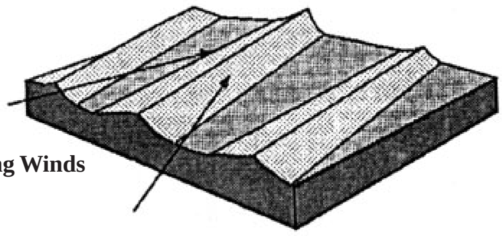
Barchan Dunes – Are crescent-shaped dunes with the points of the crescents pointing in the downwind direction, and a curved slip face on the downwind side of the dune. They form in areas where there is a hard ground surface, a moderate supply of sand, and a constant wind direction.



Transverse Dunes – Are large fields of dunes that resemble sand ripples on a large scale. They consist of ridges of sand with a steep face in the downwind side, and form in areas where there is mere abundant supply of sand and a constant wind direction. Barchan dunes merge into transverse dunes if the supply of sand increases.



Longitudinal Dunes (also called Sief Dunes) – Are long straight dunes that form in areas with a limited sand supply and converging wind directions.



Parabolic (also called blowout) Dunes – Are "U" shaped dunes with an open end facing upwind. They are usually stabilized by vegetation, and occur where there is abundant vegetation, a constant wind direction, and an abundant sand supply. They are common in coastal areas.