Surface Processes


Spheroidal weathering of granite that was beneath soil, California.


Waterfall retreat that has left Niagara Falls at the head of a gorge.


Collapse of a California marine arch that has left a sea stack.


Glacier retreat that has left moraines around a frozen lake, Nepal.


Dry salt flat with crystal growth along desiccation cracks, Bolivia.


Flood damage left after Hurricane Katrina hit New Orleans.


Barchan sand dunes, migrating towards the left, Egypt.

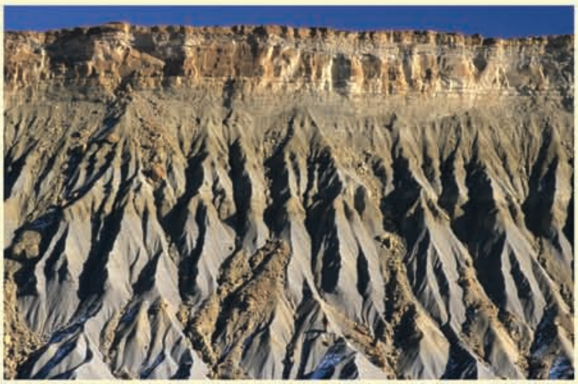

Gabion wall protecting a road from river erosion in Scotland.


Houses under water on the active floodplain through York.


Waves breaking onto coastal defences, Sidmouth, Devon.


Pleistocene glacial striae on gneiss in Central Park, New York.


Converging glaciers with lateral and medial moraines, Alaska.


Gully erosion of shale slope below sandstone plateau, Colorado.


Oil pipeline on refrigerated piles across permafrost, Alaska.


Shingle spit across mouth of the River Axe at Seaton, Devon.


Very large cave passage in Brazil.

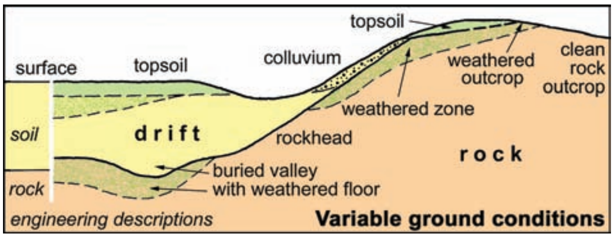

Braided river on floodplain, Zanskar, India.


Fluvial slot canyon in sandstone, Utah.

13 Weathering and Soils

GROUND CONDITIONS

Top few metres of the ground profile generally consist of soil, drift and weathered rock, with engineering properties very different from those of the underlying bedrock.
Soil: mixture of weathered mineral debris and plant material, usually <1 m thick; may divide into plant-rich topsoil and clay-rich subsoil.
Weathering: the natural decay and breakdown of rock, or drift, that is in contact with air and water; generally to depths of less than 10 m.
Drift: transported, superficial sediment deposited on top of the bedrock; mostly unconsolidated clay, sand and coarser clastic debris; generally Quaternary age, hence too young to be consolidated; varies in total thickness from 0 to >50 m.
Colluvium: slope debris, moved downslope largely by gravity alone; so relative extent of sediment transport is drift $>$ colluvium $>$ soil; it includes debris from creep and sheetwash, also head and scree. Sheetwash by surface water increases greatly with loss of vegetation.
Rockhead: the buried drift/rock interface; commonly a conspicuous boundary between weak soils and drift and the underlying strong rock; may be less well defined in deep profile of weathered rock; formed as erosion surface before drift deposition so its topography may be totally unrelated to modern surface.
Engineering soil: weak material (UCS <600 kPa) that can be excavated without ripping or blasting, therefore including soil, drift, weak rocks and weathered rocks.



Variable ground conditions

ROCK WEATHERING

Physical and chemical breakdown of rocks at or near the surface. Subsequent removal causes surface lowering:

• Weathering + Transport = Erosion •

Weathering processes depend on contact with air and/or water, so are strongly influenced by climate.

- Frost shattering is important in cooler latitudes and at higher altitudes.
- Salt crystallization is only significant in deserts with high evaporation.
- All chemical processes accelerate in hot wet climates, and are further increased by organic acids from dense plant cover.
- The most important chemical process is the production of clay minerals from other silicates.
- Temperate weathering produces illite as the dominant clay mineral.
- Hot wet weathering of igneous rocks produces the unstable smectite.
- Laterite: red soil, high iron and aluminium, low silica, formed in tropics.
- Saprolite: totally decomposed rock retaining ghosts of original structure.
- Spheroidal weathering: forms rounded boulders or corestones from angular joint blocks weathered more at edges and corners.

DEPTH OF WEATHERING

Scale and depth of weathering depends on the time scale, the rock type and the present and past climates.
Rocks only exposed for 10,000 years (i.e. since last glaciation) are less deeply weathered than those exposed for a million years in unglaciated areas.
Shales, porous sandstones and weak limestones weather to greater depths than do granites and compact metamorphic rocks.
Deepest weathering occurs in regions of climatic extremes, either with periglacial frost action or beneath equatorial rainforest.

Top of zone II is effectively rockhead, but is not sharply defined; it is usually about 1–5 m deep in Britain; but zone I fresh rock may only be found at depths >20 m in quarries that demand the best quality of rock.
In tropical areas, soils of zone IV may reach depths of 5–20 m. Decomposed granite of weathering grade III commonly reaches >30 m deep in Hong Kong.

This road cutting in Hawaii shows an almost complete weathering sequence in basalt lavas.
Grade III material is not seen in this sequence, because a change of rock type is more significant than the weathering state – a layer of weak, rubbly, scoriaceous lava has weathered much more completely than the solid lava above it.
Grade I fresh rock only occurs at greater depths, below this cut face. For engineering purposes, sound rock is found near the top of zone II, about 4m below the surface at this site.

Physical Weathering

Unloading joints:	stress relief fractures, due to overburden removal.
Thermal expansion:	fracturing, due to daily temperature changes.
Frost shatter:	fracturing, as fissure water or porewater freezes and expands.
Wetting and drying:	movement, due to loss or gain of water in clays.
Root action:	tree root expansion in fissures, and rootlet growth in pores.
Crystallization:	growth of salt crystals, where groundwater evaporates.

Chemical Weathering

Solution:	mainly of calcite and gypsum, in sandstone cement, veins and limestone.
Leaching:	selective removal of solutes or specific elements.
Oxidation:	notably rusting and breakdown of iron.
Hydrolosis:	most silicates react with water to form clay minerals.

ENGINEERING CLASSIFICATION OF WEATHERED ROCK

Grade	*Description*	*Lithology*	*Excavation*	*Foundations*
VI	Soil	Some organic content, no original structure	May need to save and re-use	Unsuitable
V	Completely weathered	Decomposed soil, some remnant structure	Scrape	Assess by soil testing
IV	Highly weathered	Partly changed to soil, soil > rock	Scrape *nb* corestones	Variable and unreliable
III	Moderately weathered	Partly changed to soil, rock > soil	Rip	Good for most small structures
II	Slightly weathered	Increased fractures, and mineral staining	Blast	Good for anything except large dams
I	Fresh rock	Clean rock	Blast	Sound

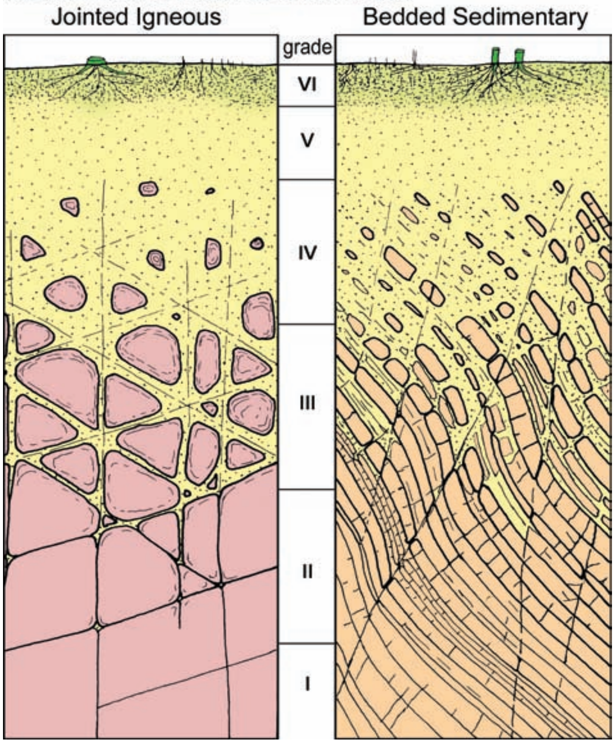
(More complex schemes, for description of non-uniform and mixed rock masses, are given in BS 5930.)

WEATHERING GRADE AND ROCK PROPERTIES

Some representative values for selected materials to demonstrate physical changes in weathered rock

Grade of weathering		I	II	III	IV	V
Granite: unconfined compressive strength	MPa	250	150	5–100	2–15	<1
Triassic sandstone: unconfined compressive strength	MPa	30	15	5	2	0
Carboniferous sandstone: rock quality designation	%	80	70	50	20	<15
Chalk: standard penetration test	N value	>35	30	22	17	75
Chalk: safe bearing pressure	kPa	1000	750	400	200	
Triassic mudstone: safe bearing pressure	kPa	400	250	150	50	
Triassic mudstone: clay particle fraction	%	10–35		10–35	30–50	
Typical depth in Britain	metres		5–30	1–5	1–2	

WEATHERING PROFILES IN ROCK



WEATHERING OF LIMESTONE

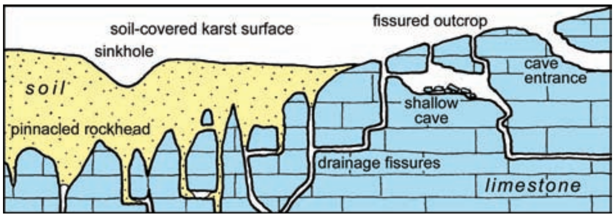
Limestone is unique because it is a physically strong rock that can be totally removed by natural dissolution during weathering.

Rainwater and soil water weather the limestone surface, and also dissolve away the rock where they seep down fractures and bedding planes, thereby creating wider fissures and caves.

This process forms very uneven ground with strong rock between large voids.

Pinnacled rockhead has deep fissures, mostly filled with soil, between weathered limestone pinnacles, all beneath soil or drift cover; it creates difficult foundation conditions prone to sinkhole subsidence (*section 29*). Limestone pavements with large flat rock surfaces are the result of recent glacial scouring which removed the weathered and dissected surface rock.

Karst is a landscape, normally on limestone, that is characterized by underground drainage, caves, sinkholes, dry valleys, thin soils and bare rock outcrops.



DRIFT DEPOSITS AND CLIMATE

The nature, extent, structure and properties of drift deposits are closely related to the processes by which they were deposited.

These deposition processes are, or were, determined largely by climate.

Fluvial processes – the action of rivers and flowing water – are dominant in all climatic regimes except for the permanently frozen zone beneath glaciers and the very arid zones in deserts.

Ice Ages: During the Quaternary, the Pleistocene period was marked by phases of world-wide cooling – the Ice Ages – when ice sheets covered large parts of the northern continents, and climates were severely modified across the rest of the world. The last ice sheets retreated only about 10,000 years ago.

Many drift deposits were formed in environments very different from those of today. They are therefore best understood by distinguishing them on the basis of process and climate.

14 Floodplains and Alluvium

WATER EROSION

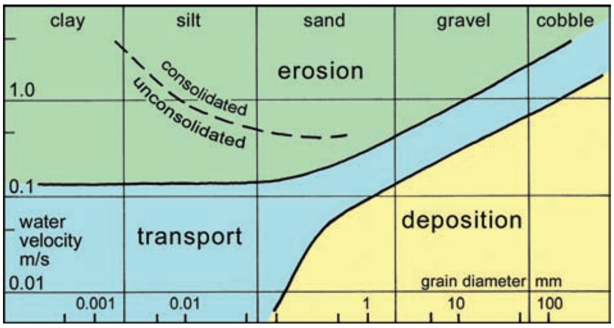
Water is the main agent of erosion; its power increases greatly with velocity.

Rivers erode by downcutting, and sides degrade to form valleys with V profiles.

On low gradients, downcutting reduces, so lateral erosion dominates, notably on the outside of river bends.

Sediment is transported as rolled bed-load and in suspension; particle size increases with velocity.

Deposition is due to velocity loss, on gradient loss and inside bends, so sediment is sorted by size.



ALLUVIAL DEPOSITS

Alluvium: river-deposited sediment; sorted and bedded, but any grain size from clay to boulders; laterally and vertically variable, with wide range of engineering properties.

Floodplain: zone of alluvial deposition along valley floor, subject to periodic flooding. The alluvium builds up over time, much of it formed as over-bank flood deposits, which are mostly fine grained and horizontally bedded.

Meander scrolls: cross-bedded, crescentic lenses of sediment, mostly sand or gravel, left on insides of migrating river bends or meanders.

Channel fills: abandoned river channels filled with sediment, commonly clay or peat.

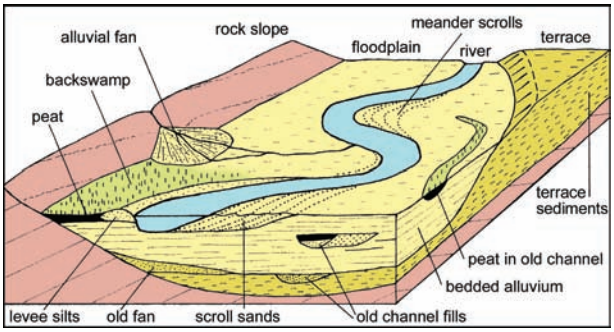
Alluvial fans: coarser, poorly sorted sediment (including fanglomerate) on steeper slopes and at mouths of hillside gullies and tributary streams.

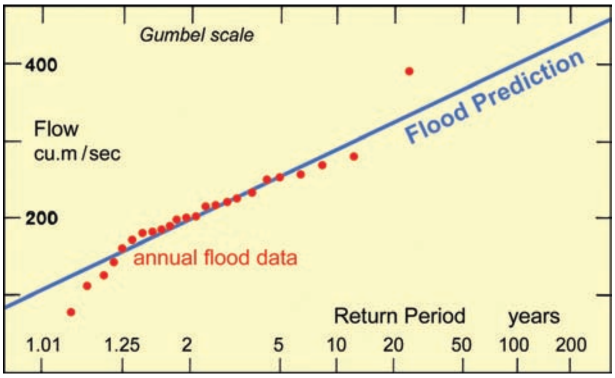
River terraces: remnants of any older, higher floodplains, abandoned when river cut to lower level; formed of alluvium, though may be rock-cored; eroded away as modern floodplain enlarges.

Tufa and **travertine**: weak, porous calcite deposit, forming thin layer or cementing a gravel; may overlie uncemented alluvium and can be confused with rockhead. Les Cheurfas dam, Algeria, was built in 1885 on tufa crust, and failed by piping on first impoundment.

Peat: black organic soil, formed in small lenses or large areas of upland bog or lowland fen; extremely weak and compressible (*section 27*).

Lake deposits: similar to fine alluvium (*section 15*).





Maximum annual flood flows on a river over 24 years; return period = (number of records –1) / (rank).

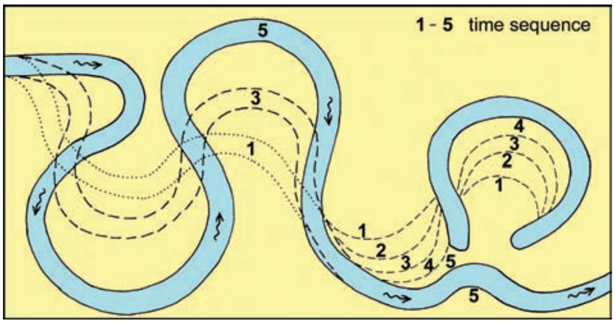
FLOODPLAINS

Flooding is natural and inevitable on floodplains.

Flood size (expressed as flow, stage, height or area) is described by its statistical return period, e.g. a 50 year flood, which has 2% chance of occurring in any year.

From existing data, plot of flow against return time (based on rank) gives straight line (often except for the highest flood), which allows predictions of rarer events; so flood zones can be identified and avoided, and channel sizes can be designed.

Floodplain hydrology may be changed unintentionally; urbanization, deforestation and levee construction all raise height of flood peaks.



Development of river meanders.

CONSTRUCTION ON ALLUVIUM

Alluvium thickness may vary 1–>100 m; difficult to predict but generally compatible with local hill relief.

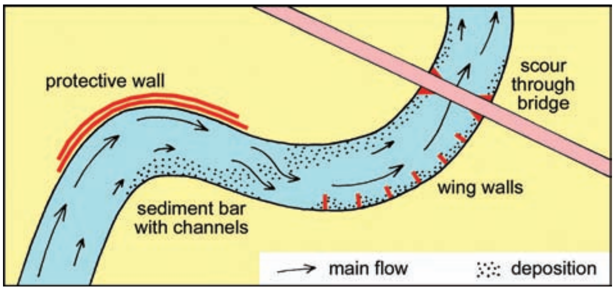
Some alluvium is laterally uniform. Other has channel fills, scrolls and fans, making site investigation and borehole correlation difficult.

Non-cohesive sand alluvium has SBP = 100–600 kPa, depending on density; quick or running sands form with high water pressures or seepage flows in loose material.

Cohesive clay alluvium generally has SBP = 0–200 kPa, depending largely on consolidation history (*section 26*).

Bearing capacity of unconsolidated alluvium can normally be increased by effective drainage and consequent accelerated consolidation.

Heavy structures on soft alluvium may require end-bearing piles to rockhead, or friction piles in thicker sequences. Each phase of Yorkshire's Drax power station required over 12,000 end-bearing, pre-cast concrete piles, each 22 m long, driven through clay and silt alluvium and into sandstone bedrock or a dense alluvial sand just above rockhead.



FLOOD CONTROL MEASURES

Levees are linear ridges alongside river channels.

Natural levees are formed by bank overflow and rapid deposition, and may build up to channel a river at a level above the main floodplain; China's Yellow River is 6 m above its floodplain for over 500 km.

Artificial levees are earth (or concrete faced) embankments built to prevent floodplain inundation. They must be continuous – roads must go over them or through floodgates; the Mississippi levees are 10 m high and more than 1000 km long.

Canalization can shorten a river course, creating a new steeper gradient to transmit flood peaks more effectively. Levees and canals prevent a river flooding its natural floodplain, and so artificially increase flood peaks downstream. Flood control dams can capture floodwater and act as a substitute for lost floodplain storage.

Floodways are zones of undeveloped land between levees designed to transmit floodwater when required.

CONSTRUCTION ON FLOODPLAINS

Protection by levees permits wider use of floodplains.

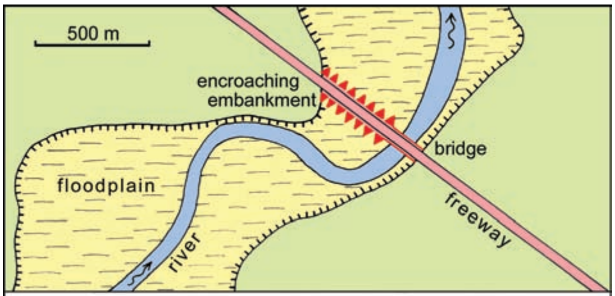
On undefended floodplains, construction is normally avoided inside the 100 year flood zone (in Britain, the 1947 flood limit provides a useful guideline) – but flood frequencies will change with any global warming.

The flood of 1972 in Rapid City, South Dakota, cost 237 lives; all the destroyed buildings were on the floodplain, recognizable on existing maps as the area of alluvium; reconstruction has left the floodplain as a park.

Encroachment is construction on the floodplain which hinders flood flows; it causes upstream ponding, and increased flows and scour round the structures, which are therefore self-destructive and must be avoided.

Parkland and buildings with unenclosed ground floor carparks do not encroach, and are acceptable on active floodplains and in floodways.

Transport routes need to cross floodplains; bridges must have extra flood arches to avoid encroachment; flat bridges with no parapets can survive overflooding with no damage and only short-term loss of use.



Freeway bridge over Schoharie Creek, New York, failed in 1987; approach embankment had encroached on floodplain and thereby increased flood flow beneath bridge, so extra scour undermined pad foundations on gravel.

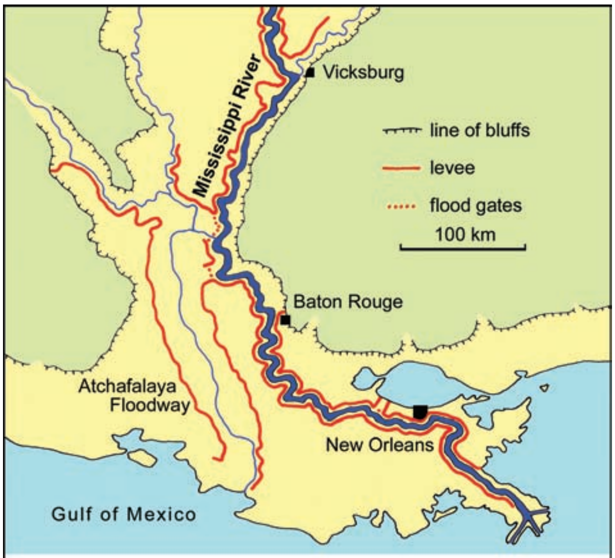
RIVER CHANNEL ENGINEERING

The natural processes of river flow include:

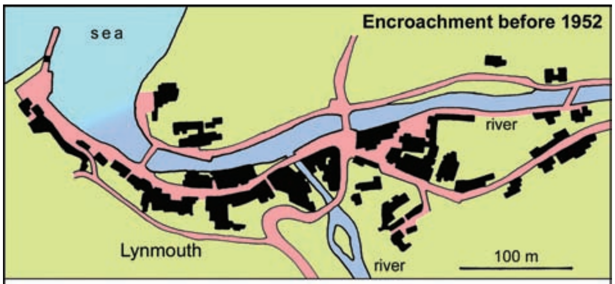
- Erosion on the outside of bends;
- Channel migration due to bend erosion;
- Bed scour between encroaching bridge piers;
- Sediment deposition in slack water, notably inside bends and downstream of obstacles;
- Catastrophic channel re-routing across floodplains, during rare flood events that overtop levees.

Bank erosion may exceed 1 m per year, and protection may be essential, using walls of concrete or gabions (loose rock in wire baskets), and wing dams to trap sediment.

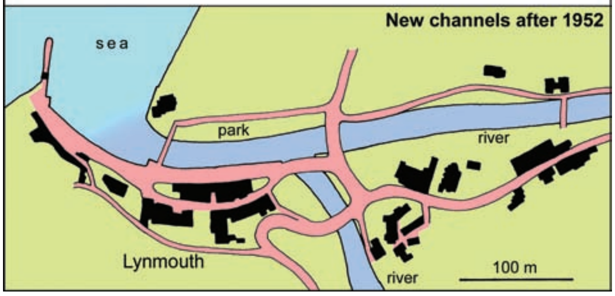
Repeated dredging may be needed to counter mid-channel deposition, notably on oblique bars.



Mississippi River has continuous levees to protect New Orleans and other cities. Floodway sluices can be opened to take flood peaks that threaten to overtop the levees. The 1993 flood overtopped the 100 year levees. Since then, more farmland has been left unprotected – a limit to sustainable economic floodplain development is now recognized. River levees were not overtopped in 2005, when the flooding of New Orleans was by seawater surge caused by Hurricane Katrina.



Lynmouth, Devon, flood disaster in 1952 was due to encroachment by bridges and buildings that diverted floodwater down the streets and through the village. New larger channel has longer bridges and floodway park.



15 Glacial Deposits

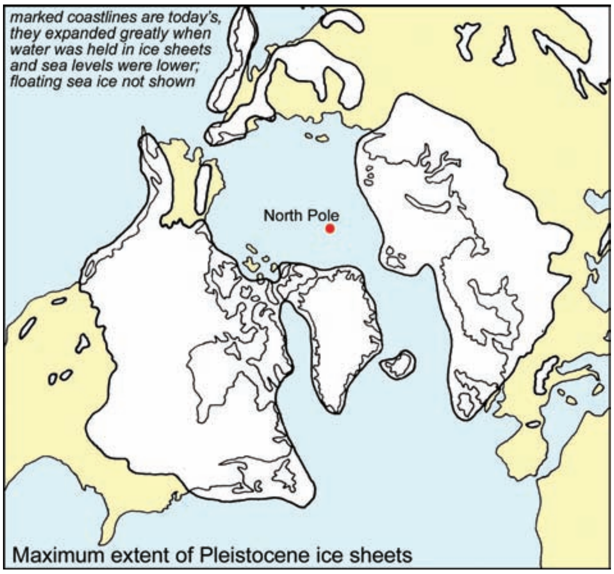
Pleistocene Ice Ages

Ice Ages were created by a series of phases of worldwide cooling, when average temperatures fell 8°C.

In each Ice Age, the largest ice sheets centred over Canada (reaching into USA) and Scandinavia (extending over most of Britain). Smaller ice caps formed on most high mountain ranges. Glaciated landforms and deposits still remain over these very large areas.

Last Ice Age ended about 15,000 years ago; known as Promit Devensian in Britain and Wisconsin in USA; features dominate mountain landscapes today, and it left extensive deposits on glaciated lowlands.

Earlier Ice Ages had ice sheets more extensive than during the last Ice Age, leaving lowland deposits in parts of Britain and USA.



GLACIAL EROSION

Glaciers form where winter snowfall exceeds summer melt; snow layers accumulate, compressed lower zones recrystallize and these are squeezed out as flowing ice.

Erosion is largely by entrained rock debris scraped over the surface, locally leaving glacial striae (scratches).

Most glaciers move about a metre per day.

Pleistocene glaciated areas are most easily recognized by erosional landforms.

Alpine glaciation: valley glaciers in mountain areas of high relief; ice further deepens U-shape valleys between high uneroded arête ridges.

Sheet glaciation: thick ice moves over entire landscape; greater erosion of high ground reduces relief; ice can erode while moving uphill, to create irregular topography with over-deepened rock basins.

GLACIOFLUVIAL DEPOSITS

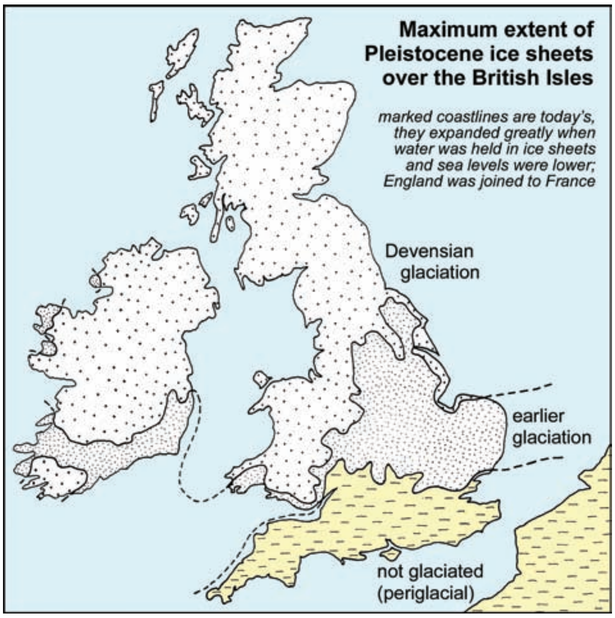
Meltwater occurs on, in, beneath and downstream of all glaciers; it erodes transports and deposits various types of glaciofluvial sediments.

Sediment is mostly sand and gravel, with moderate sorting and bedding; fines have generally been washed out; commonly non-cohesive and highly permeable, with good bearing capacity and low settlement.

Outwash: tracts of alluvial sand and gravel deposited by meltwater downstream of glacier snouts.

Kames and **eskers:** hills and ridges that were sediment fills in glacier caves; may be buried inside till.

Glaciofluvial sediments are also known as stratified till, or glacial sand and gravel.



Ice Ages had other far-reaching effects.

Periglacial conditions extended over large areas, including all of southern Britain and the USA as far south as Oregon, Wyoming and Tennessee.

World sea levels fell 150 m as water was locked in ice sheets; Britain was joined to France, Alaska to Siberia. Weight of ice caused crustal sag beneath ice-sheets, followed by slow isostatic uplift after ice melted.

GLACIAL DEPOSITION

Debris of all sizes is picked up and transported by glaciers, and then dumped at glacier edges, along their bases, or mostly in terminal melt zones.

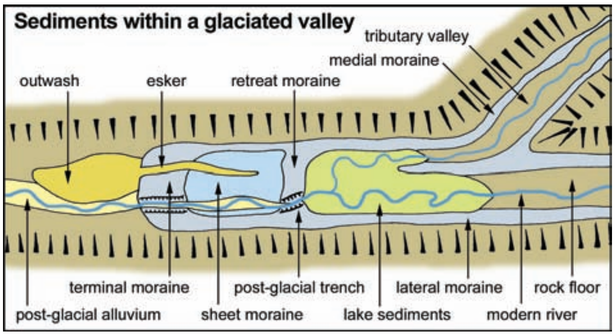
Till or **boulder clay**: general terms for glacial debris.

Moraines: morphological units of glacial till – layers, mounds, ridges or any shape of deposit that is on, or was left behind by, a glacier.

Sheet moraines: extensive till blankets of variable thickness; typically hummocky surfaces may be streamlined into drumlin landscapes.

Valley moraines: till ridges along or across glaciers or left behind in glaciated valleys:

- lateral moraines: along glacier edges, fed by debris from higher slopes;
- medial moraines: coalesced lateral moraines where glaciers converge (not so common);
- terminal, end or retreat moraines: till banks across valleys where ice melting reaches maximum at the glacier snouts; a sequence may be left up a valley by a glacier retreating irregularly.



BURIED TOPOGRAPHY

Rockhead relief: features of an eroded landscape that are buried beneath drift.
Burial is consequence of deposition after erosion – common with Pleistocene climatic changes.
Topography of old buried landscape (rockhead) may not relate to modern landscape.
Depth to rockhead may be variable and irregular; greatest and least predictable under post-glacial drift in over-deepened glaciated valleys and where subglacial meltwater channels entrenched bedrock beneath ice.
Buried valleys have drift of locally greater or unknown thickness, causing added costs and potential hazard for foundations designed to bear on rockhead. May lie beneath, or be unrelated to, modern valleys. Irregular subglacial channels in rockhead commonly have very steep sides; often known as tunnel valleys.

GLACIAL TILL

Till is unsorted and unstratified glacial sediment consisting of a mixture of any or all of clay, silt, sand, gravel, cobbles and boulders.
Composition relates to the rocks which were eroded by glacier before deposition.
Also known as boulder clay, but this term can be misleading as a till with a sandy matrix may have no clay component.

- Lodgement till: carried and deposited at base of ice; generally over-consolidated by overriding glacier, and with clay content of 10–40%.
- Ablation till: deposited as ice melted from beneath it; poorly consolidated, commonly with clay content of $<10\%$, as fines removed by meltwater.

All till may be locally variable, with lenses or zones of soft clay, running sand or large boulders. Terminal moraines may be structurally complex where glacial readvance has pushed till into ridges.

Bearing capacity may vary from 400 kPa for old, stiff lodgement till to <100 kPa for ablation till.
Compressibility is generally low except for clay-rich ablation till.

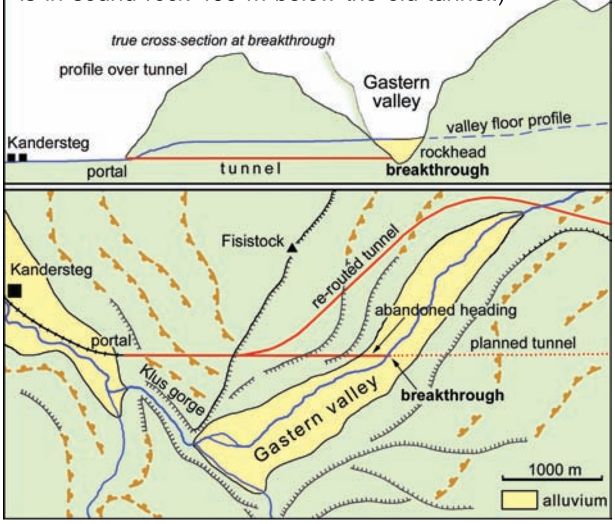
- Excavation costs on St Lawrence Seaway, on USA-Canada border, doubled when dense lodgement till was found instead of loose ablation till (which was at outcrop and wrongly expected at depth).

Temporary cut faces may be vertical in cohesive lodgement till, but need support in sandy ablation till.
Permeability is generally low but variable, related to matrix. Eigiau Dam in North Wales failed in 1925 due to piping through a sandy zone in foundation till.
Erratics: isolated large boulders; may exceed 10 m diameter; may be confused with rockhead in site investigation. Test bores for Silent Valley Reservoir, Ireland, stopped at rock at –15 m, but all had hit erratics; rockhead was –60 m. Driven piles and sheet piling cannot be used in till with erratics.

Glacial till in a Derbyshire quarry.

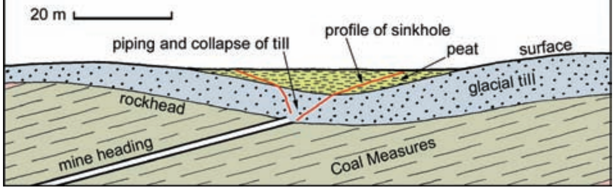
LÖTSCHBERG TUNNEL DISASTER, 1908

Swiss tunnel heading drove through rockhead into saturated gravels 185 m below valley floor, after false assumption of sediment depth. No allowance had been made for any reverse gradient on rock floor of glaciated valley beneath alluvial fill. In reality, prediction of rock profile was impossible without boreholes. Horizontal probes ahead of tunnel face would have given warning. Inrush of water and gravel killed 25 men; tunnel was re-routed to avoid buried valley. (The 2007 base tunnel is in sound rock 400 m below the old tunnel.)



KNOCKSHINNOCH MINE DISASTER, 1950

Scottish mine heading broke through rockhead into glacial till beneath hollow filled with saturated peat on hummocky sheet moraine. Piping failure of till allowed peat inrush to mine, leaving surface sinkhole 100 m across. Flat area on ground profile indicated some sort of fill – and potentially a hazard; should have been checked before heading was advanced to rockhead.



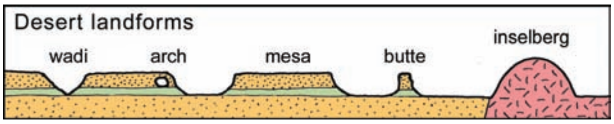
LAKE SEDIMENTS

Most lakes are created by glacial processes – damming behind terminal moraines, or post-glacial flooding of ice-scoured rock basins, over-deepened glaciated valleys and hollows on sheet moraines.
Lakes of English Lake District are in glaciated valleys with end moraines. Great Lakes of America are in ice scoured basins, partly dammed by moraines and ponded by post-glacial isostatic uplift of outlets.
Rivers destroy lakes – by sediment infill and through draining by erosional lowering of outlet. Thousands of lakes left at end of Pleistocene have since been filled and/or drained, leaving areas of lake sediments.
Lake (lacustrine) sediments are like alluvium with more silts and clays, and less gravels, so commonly have lower bearing capacity with higher settlements.
Often recognize lake sediments by flat ground.
Small ponds in sheet moraine were commonly filled with mosses to form peat.
Sensitive clays were deposited in inland seas along Pleistocene ice margins in Scandinavia and eastern Canada (*section 34*).

16 Climatic Variants

Semi-Arid Environments

Deserts have low rainfall, less than potential evaporation; may be hot or cold. With little surface water, wind erosion and transport are effective, but periodic water erosion is still dominant process, except in rare, totally arid deserts.
Wadis, or arroyos, are desert valleys, normally dry but subject to flash floods from isolated rainstorms.
Roads across wadi floors that only rarely flood can be designed to be over-flooded; reinforced concrete or gabions are essential on downstream side, where scour and undercutting are most destructive.
Selective erosion is by slow weathering, wind transport and rare flood events; leaves residual inselberg mountains, flat-topped mesas and pillar buttes in bedded rocks, and natural arches where weathering breaches thin rock ribs.



Desertification is slow loss of vegetation and expansion of desert, as in African Sahel. Due to any or all of climate change, deforestation, over-cropping, over-grazing, and soil salt increase by evaporation of irrigation water.

DESERT SEDIMENTS

Alluvial fans: banks of flood sediment and debris flows from mountain wadis. May coalesce into bajada, forming the mountain footslope with a sediment apron over a sloping bedrock pediment. Sediments are deposited rapidly, so are unsorted and poorly consolidated.
Alluvial plains: extensive lower reaches of fans; mainly sand and gravel in shallow, braided wadi channels; coarse cobble beds remain from wet Pleistocene climates.
Playas: flat floors of inland basins with fine, soft, weak silts and clays, often thixotropic. Salt and gypsum form in temporary evaporating lakes.
Sabkha: similar, but with limestones, in coastal zones.
Salt: may form thick beds in playas and sabkhas; also left by evaporation in clastic sediments. Capillary rise in fine soils may lift salt 3 m above water table, into roads and built structures. Salt crystal growth is major form of desert weathering of rocks and concrete. Impermeable dense concrete suffers less from salt breakdown.
Duricrusts: surface layers of cemented sediment, mostly sand or gravel; mineral cement deposited by evaporating groundwater. Most common duricrust is calcrete, or caliche, cemented by calcite, about 1 m thick, over unconsolidated sediment; should not be confused with rockhead as bearing capacity is low.
Loess: structureless, yellowish, calcareous silt, of grain size 0·02–0.06 mm, common in interiors of the northern continents; much was derived by wind deflation from Pleistocene glacial outwash plains. Dry or moist loess will stand in a vertical face; but it is easily gullied and piped by running water, and it disaggregates and collapses on saturation – hydrocompaction (*section 27*).

CLIMATE CHANGE

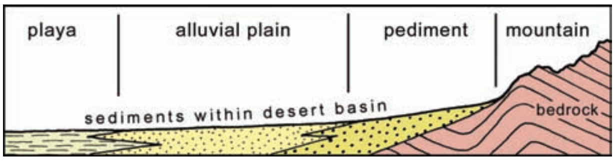
World-wide climatic variations include large cycles that caused the Ice Ages, and also smaller oscillations.
Natural global warming has been almost continuous for the last 300 years, since the end of the ‘Little Ice Age’ (when English rivers froze each winter).
Man-made global warming is largely due to increased atmospheric carbon dioxide, created by burning wood and fossil fuels (coal and oil), but the scale of this artificial increase remains open to debate.
Global warming, both natural and artificial, causes rise in sea levels, shifted climatic zones, more extremes of weather, and increased scale and frequency of floods.

BLOWN SAND

Wind moves dry sand by sliding, rolling or bouncing (saltation). Sand abrasion undercuts rocks and structures close to ground level. Deflation removes sand, leaving desert pavements of polished pebbles.
Dunes are built by deposition in slack air, in eddies and in the lee of obstacles; they may be longitudinal (seif) or transverse to prevailing wind, irregular in shape or crescentic barchans. Active, depositional slopes of dunes have loose sand at angle of repose of 32–34°, while the flatter sides are eroded by the wind in firm dense sand.
Stabilization of migrating dunes may be achieved by trapping the sand with induced vegetation cover, or with fences and shelter belts; but impractical if sand supply is too large. Sand accumulates downwind of structures, while exposed areas are cleared by the wind; roads that slope gently down towards the prevailing wind are more exposed and therefore become self-clearing.

Corrugations (or washboarding) on dirt roads develop on dry, well-sorted sands; worst are dune sands. Damp, well-graded soils are stable; tills and glaciofluvial sands are best because clay content fills pore spaces.

Corrugated road on dune sand in Australia.



Profile through the typical zones of desert landforms.

ARID LANDFORM ZONES

	zone	slope	width	process	sediments	drainage	hazards
1	Mountain	>12°		erosion	(rock)	gorges	flash floods
2	Pediment	2–12°	1–2 km	steep fans	coarse unsorted	entrenched wadis	hydrocompaction
3	Alluvial plain	0.5–2°	1–>10 km	gentle fans	sand, gravel, fines	shallow wadis	and blown sand
4	Playa	<0.5°		basin flat	silt, mud, salt	temporary lakes	salt, blown sand

Periglacial Environments

Cold climates with limited snowfall and with no ice cover are periglacial; locally peripheral to glaciers. Winter snowfall is matched by summer melt, and vegetation is sparse, open tundra.

Today, much of Alaska, Arctic Canada and Siberia is periglacial; in Pleistocene, conditions extended over southern Britain, central Europe and central USA, south of the ice sheets, leaving periglacial structures that are found in the ground today.

Climate causes increased frost shatter and mechanical weathering, and reduced chemical weathering.

Permafrost: permanently frozen ground, to depths of 10–$>$200 m; deeper freezing is prevented by geothermal heat; if permafrost $<$50 m thick, it may be discontinuous; may include lenses of pure ice within soil and rock.

Active layer: zone of summer thawing and winter refreezing, generally 0·3–5.0 m deep; permanently frozen ground beneath prevents drainage, leaving it saturated and unstable in summer, causing widespread slope failure and subsidence.

STRUCTURES AND SEDIMENTS

Landslides and solifluction are common in active layer.

Camber folding, valley bulging increase (*section 06*).

Ice heave and collapse forms irregular cryoturbated ground, sediment-filled ice wedges, patterned ground with stone polygons; all create disturbed and vertical boundaries in soil active layer. Deeper drift-filled hollows in London Clay relate to freezing around artesian groundwater flows.

Frost shatter is extensive, commonly to 10 m deep in chalk of southern England.

Scree, or talus, is coarse, angular slope debris, with angle of repose equal to 37°, masking cliff foot profile. Many fossil Pleistocene screes are inactive in modern climate and so gain vegetation cover.

Lowland periglacial sediments include outwash gravels, alluvial and blown sand, and extensive loess.

Clay with flints is soliflucted mixture of residual soils and Tertiary clastics, widespread but generally thin on English chalk outcrops.

SOLIFLUCTION

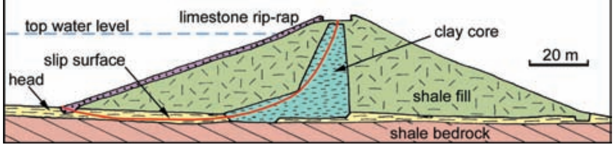
This is the downslope movement of saturated debris – a type of wet soil creep moving about 1 metre per year. It can occur on any saturated slope, but is most common in the summer-thawed active layer of periglacial slopes which cannot drain through the deeper permafrost.

Head is unsorted, soliflucted debris; it may appear similar to glacial till, but is formed entirely of local upslope material. Head can flow by plastic deformation, but is typically well sheared, with basal, intermediate and circular slip surfaces. The shears reduce the strength to low residual values.

Head forms most easily on slopes of shale, mudstone, clay and chalk; coombe rock is chalk head. Most slopes in Britain, steeper than 5° on these rocks and outside the Devensian ice limits, can be expected to have a veneer of sheared, unstable head.

Solifluction flows, up to 1000 m long, may move on slopes as low as 2°; commonly 2–4 m thick, but may accumulate in layers to depths of $>$15 m on concave slopes and as valley infills.

Carsington Dam, an earth embankment in Derbyshire, failed in 1984 before the reservoir was filled. A slip surface developed through both the weak clay core (which was of an unusual shape) and a layer of head that had been left in place over the shale bedrock, beneath the dam's shale fill. The head had been wrongly interpreted as *in situ* weathered shale, and the design assumed an undisturbed angle of friction $\phi = 20^\circ$, but shear surfaces within it reduced its strength to a residual $\phi = 12^\circ$. This mistake, and the rebuild, cost £20M, yet periglacial head is widespread on the shale outcrops of Derbyshire and could have been expected.



PERMAFROST ENGINEERING

Subsidence, flow and heave occur on poorly drained silts and clays when ground ice is melted; sands and gravels are generally thaw-stable.

Conservation of the permafrost is generally the best means of ensuring ground stability for built structures. Any disturbance of the natural insulation (provided by the soil and vegetation) increases summer thaw, and depresses permafrost beneath buildings and roads.

Block supports for heated buildings, with clear airspace beneath, can be stable on gravel active layer over preserved permafrost.

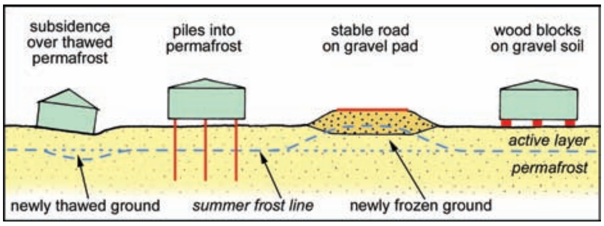
Piles into stable frozen ground generally need to reach depths around 10 m.

Utilidors are pile-supported conduits built in streets for heated services pipelines and cables.

Trans-Alaska oil pipeline rests on piled trestles, each with internal circulating coolant and heat fins on top to dissipate stray heat from the oil; it is a giant utilidor.

Gravel pads or embankments, a few metres thick, can be enough to provide insulation and let the permafrost expand into them, stabilizing the compacted old active layer. Internal cold air ducting or insulation layers of peat or wood chips further improve conservation of the permafrost and protection of the structure.

Subsided houses on permafrost in Dawson, Canada.



17 Coastal Processes

Wave action is the dominant mechanism in both erosion and deposition along coastlines.

Waves are powerful due to their pounding action but are also very selective in etching out rock weaknesses and controlling sediment deposition.

The largest and most powerful waves are those which have travelled furthest, i.e. have the greatest fetch.

Large storm waves are powerful and destructive.

Tidal surges cause damage when waves reach new heights; they occur on high spring tides, aided by strong onshore winds and low atmospheric pressure, as in the North Sea, 1953, and in Burma, 2008.

CLIFF EROSION

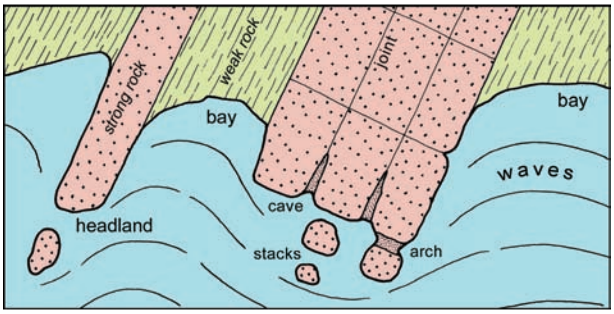
Coastal erosion is by wave action at beach level.

This creates a wave notch, which advances, leaving a wave-cut platform and undercut cliffs – which retreat by series of rock falls (or larger landslides in weak material).

Selective wave erosion of strong rock cliffs etches out faults, joints and weaknesses to form sea caves, arches and inlets that retreat between headlands and stacks.

Coastal equilibrium has slowly eroding headlands between bays in soft rocks protected by beaches.

Marine erosion is relentless; artificial control by coastal defences may be uneconomic outside urban areas, so the inevitable long-term loss of land is now being more widely accepted by government agencies.



SHORELINE BUDGET

Main sources of beach sediment are eroding cliffs of soft Pleistocene material, and also river delta deposition.

On any shoreline, erosion and the production, transport and deposition of sediments are all finely balanced; any disturbance of the budget prompts renewed erosion or deposition to recover the equilibrium.

Longshore drift budget is easily disturbed by coastal engineering works, most notably where sediment is trapped or deflected into deeper water, so that beach starvation down-drift causes renewed erosion.

Similarly, any disturbance of a beach profile prompts natural processes that oppose the change in order to restore a stable form.

Coast erosion at Holderness, eastern England.

SEDIMENT TRANSPORT

Clastic sediment is mostly rolled along the seabed where it is reached by wave motion in shallow water.

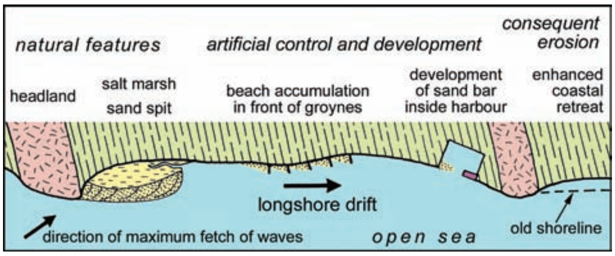
Beaches are formed by sand deposition where wave upwash (swash) is greater than the backwash due to water soaking down into the porous sand.

Shingle storm beach forms higher up by larger waves.

Coastal dunes are of beach sand blown inland by wind.

Sediment washed into deeper water is deposited below wave influence, as wave-built terrace or offshore bar.

Longshore drift is due to oblique upwash of impacting waves, then backwash directly down beach slope – always away from waves arriving with greatest fetch.



Deposition occurs in the lee of any obstacle, where sand is drifted into deep or slack water; a spit forms down-drift of a headland, and may extend into a bar across a bay or river mouth; a tombolo may form a sand link between an island and the main shore.

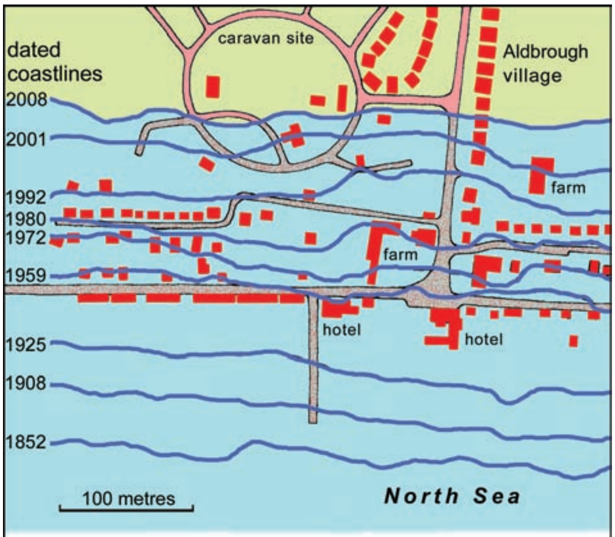
Salt marsh develops on mud held behind spits, storm beaches or coastal dunes.

Barrier islands, as on east coast of USA, may evolve from extended spits or emergent offshore bars.

Carbonate sediments in shallow water create varied and difficult ground conditions for coastal and off-shore structures. Strengths of shell sands and coral reefs vary greatly with type and cementation history.

Western Australia off-shore oil platforms required piles through more than 110 m of loose shell sands.

Sabkha sediments include gypsum and carbonate, both weakened by karstic solution cavities, interbedded with muds; formed in lagoons along arid coastlines.



Coastal retreat is most rapid where soft rock cliffs are eroded and longshore drift leaves no protective beach. On the east coast of England, the glacial till cliffs of Holderness retreat by about 2 m/year, by successive landslides that destroy houses, farms and roads.

Coastal Engineering

EROSION DEFENCES

A wide sand beach is the best means of preventing coastal erosion and retreat. Sea walls may prevent erosion, but wave action is relentless, and even the largest structure is only a short-term defence unless there is effective beach sediment control.

Efficient sea defence is porous to absorb wave energy; made of armour stone (blocks of >2 tonnes), concrete tetrapods, or massive wall faced with cellular concrete. Reflected waves off solid face may induce scour.

Sea walls may cost £5M/km. Economical alternative on long eroding coast (e.g. Holderness) is to create hard points – short sections of stable, fully defended shore – with intervening coast left unprotected. Down-drift of each hard point, erosion creates a shallow bay, which traps beach sediment. Eventually, a crenulated coast should become stable, but compensation is needed for short-term accelerated land loss between hard points.

BEACH CONTROL

Groynes are timber, concrete or steel barriers across beach, which prevent or reduce longshore drift by trapping sediment. Groyne spacing should be double their length to effectively stabilize beach.

Offshore breakwater, parallel to shore, absorbs wave energy and causes beach accumulation in its lee – similar to a natural tombolo.

Beach may be stabilized or expanded by pumping sea-water from a buried porous pipeline. Wave upwash adds sand to foreshore, but a drained beach absorbs and reduces backwash – so sand is not swept back out to sea.

Active spits, bars and barrier islands migrate inland mainly by wave overwash. Any development, with erosion defences on the exposed outer face, causes thinning due to continued sediment loss from the inner face. The Spurn Head spit, England, and the Carolina barrier islands, USA, are now precariously thin; they should be allowed to break up and reform at a stable site further inland, as artificial defences will become increasingly expensive.

CHANNELS AND HARBOURS

Harbours, cut into the coastline or built out between breakwaters, are stable on a coast which is an erosional source area of overall sediment losses.

Harbour mouths may develop obstructing sand bars if longshore drift is strong. Jetties deflect sediment drift; they may develop spits off their ends and cause down-drift beach starvation.

Natural clearance of harbour and lagoon channels relies on tidal scour, which must exceed deposition by beach drift; larger tidal volumes and flow velocities improve scour clearance, so larger lagoons and narrow channels are better kept clear.

Tsunamis are large waves generated by seabed earthquake movements; they form in series of 1–6 waves. In the open ocean they are long and low, but their fronts slow down in shallow water, and can build up to >10 m high approaching a shoreline; they reach maximum heights in tapering inlets.

Best defence is warning and coastal evacuation. They take up to 24 hours to travel from the earthquake source to distant shores. Pacific Ocean has most tsunamis, so has an international warning system.

There are fewer tsunamis in the Indian Ocean, so there is no warning system, but the 2004 tsunami killed 228,000 people, mostly in Sumatra and Sri Lanka.

BEACH STARVATION

Sediment input and output, by longshore drift, must be in balance to maintain a stable beach. Many artificial measures – trapping drift on a groyned beach, reducing erosion with a sea wall, deflecting sediment at a harbour mouth – reduce onward drift, and therefore cause beach starvation at down-drift sites.

This may cause beach loss or renewed erosion (as at Folkestone Warren, *section 36*) at new sites down-drift of engineered sections. Beach nourishment by artificial input of sediment is an expensive alternative to down-drift extensions of the initial control measures.

Hallsands village stood on a rock platform with a protective beach in front of it, on the Devon coast. In 1897, off-shore shingle dredging steepened the seabed sediment profile. Natural response was lowering and removal of beach within five years; so houses were exposed to waves, and destroyed in a storm in 1917.

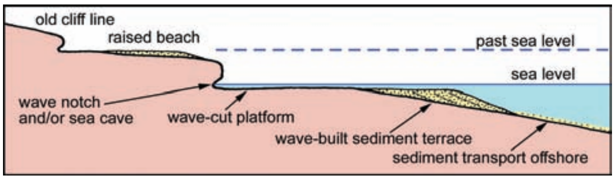
SEA LEVEL CHANGES

Pleistocene sea levels fell by about 150 m when water was trapped in continental ice sheets, and some land areas were depressed as much as 50 m by ice weight.

Drowned valleys (rias) were flooded by sea level rise at the Ice Age end, after having been cut by rivers draining to the lower sea levels; some now form natural harbours, as at Milford Haven and Plymouth; others have sediment fills, leaving deep coastal buried valleys.

Raised beaches have abandoned cliffs, dry sea caves and fossil beach sediments; many were cut in ice-depressed coastlines at end of Ice Age after sea level had risen but before land rose with isostatic rebound; Scotland's raised beaches are due to the rapid loss of its Pleistocene ice burden. Those in California are due to tectomic uplift close to the plate boundary.

Unconsolidated raised beach sediments may be clays, sands and/or gravels, typically with lateral variation.



Modern sea level rise is about 2 mm per year world-wide, due to thermal expansion of seawater (and also to glacier melting); this rate may double with any increased rate of global warming (whether caused by nature or by man's activities). Local tectonic movements may greatly increase or reduce the local effect.

Rising sea levels, and/or ground subsidence, accelerate coastal erosion, cliff retreat, coastal flooding, beach losses and barrier island migration. Greatest effect is on low eastern coastlines of both Britain and the USA.

18 Groundwater

Rainfall (precipitation) is the ultimate source of all fresh water, and when it lands on the ground surface it is dispersed in three ways.

- **Evapotranspiration**: combination of evaporation from open water and transpiration by plants, both returning water to the atmosphere; in temperate climates, it may vary from 20% of the rainfall on open hills, to 70% from wooded lowland.
- **Runoff**: surface water flow into streams and rivers; increases with low rock permeability, steep slopes, intense rainfall and urbanization.
- **Infiltration**: seepage into the ground to become groundwater; important on permeable rocks, and where runoff is slow.

Groundwater is all water flowing through or stored within the ground, in both rocks and soils; it is derived from infiltration; it is lost by flow to surface springs, and by seepage out through the sea bed.

Water budget is the balance of flows for any part or the whole of a combined groundwater and surface water system; a natural budget is easily disturbed by man's activities, notably where land drainage or urbanization reduces infiltration and groundwater recharge.

PERMEABILITY OF ROCKS

Permeability is the ability of a rock to transmit water through its interconnected voids.

Aquifer: rock with significant permeability, suitable for groundwater abstraction, e.g. sandstone.

Aquiclude: impermeable rock with static water held in poorly connected voids, e.g. clay.

Aquifuge: impermeable rock with no voids, e.g. unfractured granite.

Aquitard: rock with very low permeability, unsuitable for abstraction but significant in regional water budgets, e.g. siltstone.

Permeability (= hydraulic conductivity = coefficient of permeability = K) = flow through unit area of a material in unit time with unit hydraulic head. K is expressed as a velocity, correctly as metres/second, more conveniently as metres/day (or in America as Meinzer units = gallons/day/square foot = 0·0408 m/day).

Intrinsic permeability (k), expressed in darcys, is also a function of viscosity, only significant in considering oil and gas flows through rock.

Groundwater velocities are normally much lower than the K values because natural hydraulic gradients are far less than the 1 in 1 of the coefficient definition. Typical groundwater flow rates vary from 1m/day to 1m/year, but are far higher through limestone caves.

Porosity: % volume of voids or pore spaces in a rock.

Specific yield: % volume of water that can drain freely from a rock; it must be less than the porosity, by a factor related to the permeability, and indicates the groundwater resource value of an aquifer.

Hydrological values typical for rocks

	Permeability m/day	*Porosity %*	*Sp.Yield %*
Granite	0·0001	1	0·5
Shale	0.0001	3	1
Clay	0.0002	50	3
Sandstone (fractured)	5	15	8
Sand	20	30	28
Gravel	300	25	22
Limestone (cavernous)	erratic	5	4
Chalk	20	20	4
Fracture zone	50	10	

K < 0·01 m/day = impermeable rock
K > 1m/day = exploitable aquifer rock

AQUIFER CONDITIONS

Water table (= groundwater surface) is the level in the rocks below which all voids are water-filled; it generally follows the surface topography, but with less relief, and meets the ground surface at lakes and most rivers.

Vadose water drains under gravity within an aerated aquifer above the water table.

Phreatic water flows laterally under hydrostatic pressure beneath the water table; it is the resource for all high-yield wells; there is less at greater depths and pressures, and most rocks are dry at depths >3 km.

Capillary water rises above the water table by surface tension, by very little in gravels, by up to 10 m in clays.

Hydraulic gradient is slope of the water table, created by pressure gradient required to overcome frictional resistance and drive phreatic flow through aquifer rock. Water table is steeper where permeability is low or flow is high; typical gradient is 1:100 in good aquifer.

Groundwater flow is in direction of water table slope, identified in wells that are not pumped.

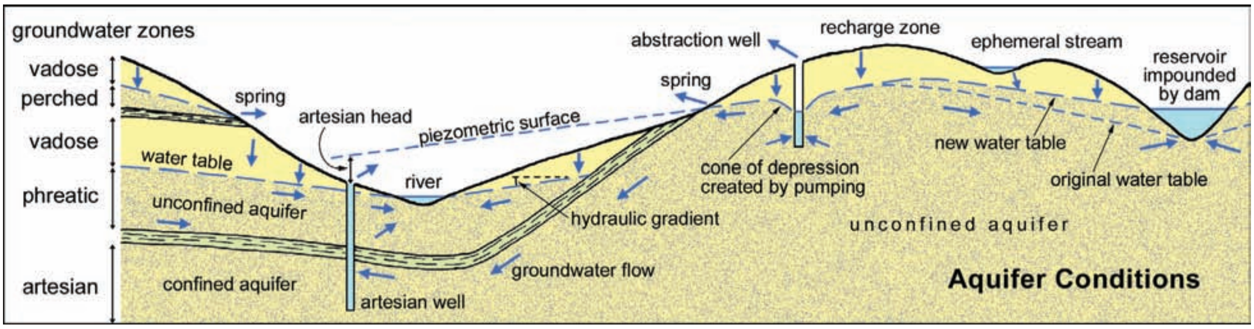
Rivers normally have water table sloping towards them, with groundwater flow into them. Ephemeral rivers lie above water table, and leak into the aquifer.

Perched aquifer lies above the regional water table.

Unconfined aquifer has vadose zone in upper part.

Confined aquifer has artesian water held beneath an overlying aquiclude, with a head of artesian pressure to drive the water above the aquifer, perhaps to rise to ground level; artesian water is common in sand/clay alluvial sequences, and in complex landslides.

Groundwater flow − Q = Kbwi
where K = permeability, b = aquifer thickness, w = aquifer width and i = hydraulic gradient. This is Darcy's law, easily calculated for a simple geological structure or as a rough guide for flow through a cut face; the maths is more complex for convergent flow to a well or spring where the water table steepens to compensate for the decreasing cross-sectional area of the aquifer.



TYPES OF PERMEABILITY

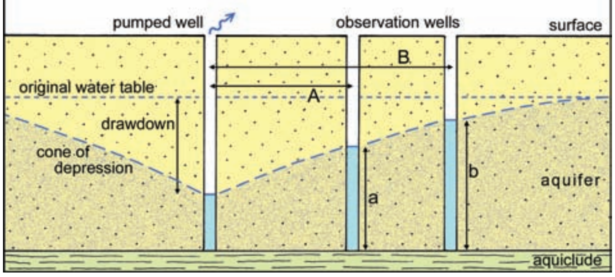
Intergranular: diffuse flow, between grains, in sands and gravels, poorly cemented sandstones and young porous limestones.
Fracture: through joints, in nearly all rocks; erratic flow in fault zones, but dense joint systems provide diffuse flow in sandstones, chalk and young basalts; most fractures are tight at depths of >100 m.
Secondary: groundwater flow increases permeability by solution, notably in limestones; non-diffuse conduit flow is erratic through enlarged fissures and caves.

GROUNDWATER DEVELOPMENT

Springs are natural groundwater overflows from aquifers; many are capped or ponded for supply; a large spring yields 0·1–1·0 m^3/s; smaller springs are used in rural areas; limestone caves may feed larger springs.
Qanats are ancient, horizontal adits hand-dug to a sloping water table and freely draining to the surface.
Wells are hand-dug or drilled to below the water table; hand-dug wells may have horizontal adits to intersect productive fracture zones; wells need pumping unless they are artesian; well yield depends on depth below water table, diameter and aquifer permeability; good well yields 0·1 m^3/s, or about 3 litres/sec/m of depth below water table; improve yield by blasting to raise fracture permeability near well, or acid injection in limestone.
Cone of depression in water table is formed where pumped flow converging on a well creates steepening hydraulic gradient; the depth of the cone is the well drawdown, related to permeability and flow.
Reservoir impoundment raises the local water table; groundwater leaks through a ridge if water table slope is reversed in an aquifer that reaches a nearby valley.

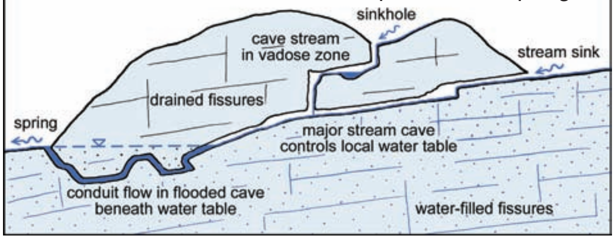
Pump testing of a well determines its potential yield, and also the regional permeability of the aquifer.

$$K = Q.\ln(B/A)/\pi(b^2 - a^2)$$



KARST GROUNDWATER

Cavernous limestones do not conform to normal groundwater rules, because their caves carry water along erratic routes in unpredictable patterns.
Karst limestones have complex water tables that are unrelated to surface topography.
Groundwater is difficult to abstract or control in karst, as wells and boreholes can just miss major conduits.
Cave streams transmit undiluted pollution to springs.



PORE WATER PRESSURE

The groundwater head provides the pore water pressure (p.w.p.) in saturated rocks and soils.
Increased p.w.p. may cause slope failure (*section 33*).
Decreased p.w.p. may permit or cause subsidence in clays (*section 28*).
In fractured rocks, joint water pressure is equivalent to p.w.p. and is critical to slope stability (*section 32*).

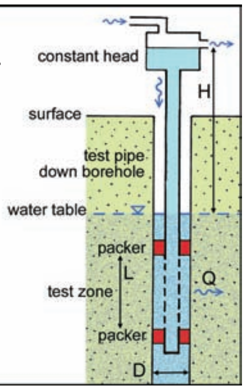
GROUNDWATER CONTROL

Dry excavation below the water table is possible within coalesced cones of depression created by pumping from well points round a site perimeter.
Groundwater barriers permit dry excavation without lowering the surrounding water table; barriers may be steel sheet piles, concrete diaphragm walls, grouted zones or ground freezing (in order of rising costs); grouting or freezing can also control groundwater rising from below in thick aquifers.
Slopes may be drained by ditches, adits or wells.
Capillary rise in embankments is commonly prevented by a basal gravel layer.

Packer test measures local permeability of rock and aquifer properties between two inflatable packer seals in a borehole.

$$K = Q.\ln(2L/D)/2\pi LH$$

H is measured to water table or to midpoint of test zone if this is above water table.
Falling head test is better for ground with low permeability.



GROUNDWATER RESOURCES

Aquifer stability only ensured if abstraction $<$ recharge.
Abstraction $>$ recharge is groundwater mining – aquifer is depleted; water table falls, springs and wells may dry up, pumping costs increase, artesian wells may cease to flow, resource will ultimately be lost.
Aquifer recharge is possible through intake wells or the floors of leaky reservoirs.
Artesian water emerges without pumping from a flowing artesian well. Large resources may lie in synclines.
Groundwater quality is ensured by both aquifer filtration and the underground residence time in contact with absorptive clays and cleansing bacteria within soils.
Pollution is most likely in shallow alluvial gravels and cavernous limestones; major pollutants are tank leaks, and hydrocarbons from road drains in recharge zones.
Water hardness is carbonate (limestone) and sulphate.

Villa Farm disposal site, near Coventry, separated liquids in lagoons in old sand quarry 50 m across. Fluid loss of 7000 m^3/year was infiltration to sand aquifer. Pollution had little radial spread, but formed a plume 600 m long in direction of hydraulic gradient.

Saltwater intrusion near a coastline is caused by over-pumping, which disturbs the saltwater interface beneath the freshwater lens fed by land infiltration. As saltwater has a density of 1·025, the freshwater lens floats on it like an iceberg and the inverted cone in the interface is 40 times higher than the matching cone of depression is deep (the Ghyben-Herzberg effect).