How Soil Is Formed

The flakes of inky thunderclouds
Above the convex whiteness of the glacier.
A lifeless river dressed in yellow till
And sun rays, glistering like spears at daybreak,
Pierce through the silent, silver sky
"Awake, oh Earth, awake!"—I cry
"Break free from this eternal coldness!

Transform your till and gravel into soil
And let the frigid puddles of the tundra
Be overgrown by reeds, green and unspoiled!"
The Earth is silent, and the pearly slabs of glaciers
Lie far beneath the icy sun, as in a trance.
Indeed, no human measure ever
Can wrap around this ancient, vast expanse.

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Abstract Plants play a crucial role in the formation of soil; soil formation accelerated when the first plants wandered onland 400 million years ago. One of the conditions enabling plants to develop was that algae joined forces with fungi, which were better at absorbing phosphorus from the ground. However the first soils were formed by microorganisms. Their complex miniature worlds, so-called biofilms, are described and compared with human cities. Acids secreted by microbes and plant roots accelerate the weathering of minerals, and dead plant material helps to build up humus in the soil. But soil formation is a slow process, and one has to be ingenious to follow the phenomenon over long periods of time. You can take soil samples where glaciers are receding, and along the gradients from the coast towards the highest shoreline, in regions which are in a process of post-glacial rebound still rising after being depressed under the weight of the ice during the last ice age. This makes it possible to follow the soil formation process over thousands of years.

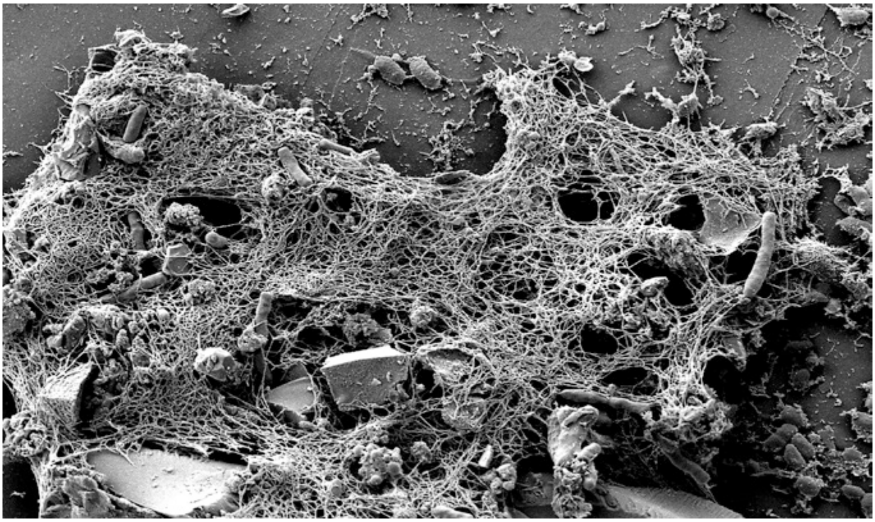
H. Wallander, *Soil*, DOI 10.1007/978-3-319-08458-9_2

The Very First Soils

How the first soil formed on our planet remains a matter of speculation, but we do have a few clues. Paracelsus, a sixteenth-century Swiss scientist and alchemist, made interesting observations of paper-like fragments that he found while hiking in the Alps. When he put them in water they swelled into a slimy, jelly-like mass containing a complex microbiological world later compared to the structure of human cities. In water, this gelatinous material helps prevent the organisms from being washed away by currents. One could liken it to taking shelter indoors from a storm. The material also provides insulation, safeguarding the organisms from excessive temperature swings. Waste products are transported in channels akin to urban sewers. Remarkably, the organisms in these societies can communicate with each other. Each bacterium emits signalling molecules whose concentration determines when the bacteria start producing jelly.

Blue-green bacteria play a critical role in these gelatinous worlds—or biofilms as we call them today. Paracelsus named them *Nostoc* because their mucus reminded him of the symptoms he experienced when he caught a cold. Nostoc has the same ability as the bacteria in bean and alder roots to bind nitrogen in the air to proteins.

The first soils. Even if we brush our teeth morning and night, bacteria are continually forming new colonies inside our mouths. The oral cavity is a favourable environment, with regular provision of nutrition and just the right temperature, and teeth are a suitable material to adhere to. Once the bacteria have attached, they form a protective material in which they embed themselves—known as biofilm. A similar process occurs on the roots of plants and on soil particles where there is good access to nutrients. The very first soils, predating plants and lichens, were formed by biofilm material gradually gathering in the ground and becoming organic matter



Supermuck. Bacteria in a biofilm form a gelatinous material that protects the colony from external disruption. In human lungs, for example, antibiotics can have a hard time reaching the bacteria in a biofilm, which can make some infections hard to combat. Observing the true nature of a biofilm is difficult. In an electron microscope, the gelatinous material dries into a spaghetti-like network. The image shows rod-shaped bacteria embedded in the material

Like these plants, Nostoc can photosynthesise and form carbohydrates from sunlight and carbon dioxide. In South Africa and Australia, scientists have found biofilm traces more than three million years old—the oldest known life forms on the planet.

Biofilms often form on underwater rocks. We have all trodden on submerged rocks at the seaside and can doubtless imagine how fragments of biofilm might dry out at low tide and be blown by the wind onto the shore. But some biofilm organisms were able to survive on land. Many fungi have special pigmentation to protect them against ultraviolet light, and their ability to withstand drought by secreting a tissue-protecting barrier with high drought tolerance is likely to have played a critical role in the formation of the first soil. Today we know that most areas of land exposed to the atmosphere are covered in biofilms, some invisible to the human eye and others forming delicate patterns on old stone buildings.

Inspiration from Crete

I took the opportunity to study fungi and their unique properties on a walking holiday one summer in Crete. The terrain on the southern side of the island is so rugged that there are no coastal roads: getting there means walking or taking a boat. The trail that runs west from the village of Sougia, south of Chania, passes a harbour and then enters a leafy ravine where pink oleander bushes bloom and olive trees offer welcome shade. Pigeons and tree sparrows nest in the steep sides of the gully—an environment

not dissimilar to the urban environments that these species frequent today. After about half a mile you can turn left into a pine forest which leads to a ridge with a view of the sea. The scent of thyme floats over the thorny scrubland and wheatears flash their white rumps as they fly from stone to stone. A little farther on you reach a spectacular view

◀ *Splendid life artists.* Growing on rock is an arduous business. Temperature varies greatly between day and night, periods of drought may be prolonged and the sun's ultraviolet rays can damage cells. But if an organism can adapt to such an environment, it is often left in peace and not out-competed by other species. Some fungi form water-repellent substances that minimise water loss. They also secrete acids that corrode rock so they can penetrate it with their hyphae, gaining protection. Black yeast fungi have lived in this way since prehistoric times. Four hundred million years ago, some of them combined with algae to form lichens—one of nature's most successful organisms. Lichens have spread to most environments on Earth and display an array of colour and form. Here the elegant sunburst lichen forms distinct and well-delimited patches on a gravestone near a medieval church in Vågå, Norway

over a bay immersed in green in the valley below. This is Lissos, once a Roman commercial centre and now an archaeological attraction with an ancient temple and ruins of Roman houses and storerooms. The finest relics are on view in Chania Museum but the ground is still peppered with marble fragments, perhaps the remains of an ancient column. It is hard to believe the area has not been cordoned off to the public but it makes the excursion all the more exciting—a bit like being on a treasure hunt.

The marble shards I found were peppered with tiny black dots made by a yeast-like and highly durable fungus. Even if washed from the surface, the fungus soon grows out again from the inside. Black yeasts are among nature's great survivors and can adapt to severe drought and temperature fluctuations. They are found from the most inhospitable deserts to the coldest places on Earth, their black pigment protecting them from ultraviolet radiation. They are extremely adept at penetrating between the mineral granules inside a stone, where they create cavities that protect them from drought and the rays of the sun. Their only source of nutrition is wind-borne particles that adhere to the surface of the stone. Black yeasts are regarded as predecessors of lichens, organisms that have successfully colonised most environments on the planet. Lichens are a symbiosis between a fungus and an alga. The fungus provides a protective layer that enables the alga to photosynthesise even in the dry conditions found on rocks and other exposed places. Scientists believe that when the Earth was in its infancy, the action of fungi caused rocks to crumble and mingle with dead fungi and algal tissue to form the first soil. Some soils are formed in this way even today—that is, without any intervention from plants. In Antarctic deserts, which are too cold to sustain plant life, soil formation is based on blue-green bacteria, fungi, algae and lichens that penetrate a millimetre or two into rock surfaces, thereby causing the stone to slowly fracture and join dead microorganisms in forming a primitive soil. There are other places where one can study soil formation. Come with me on a journey to some of them.

Soil Formation on a Glacier's Edge

A flight over northwest America en route to Seattle gives a spectacular view of Mount Hood, which stands in the middle of the Cascade Volcanic Arc, a mountain range that saw a major eruption less than thirty years ago when the top of Mount Saint Helens exploded with such force that it deposited ash residues as far away as Costa Rica. We know this due to scientific studies of soil formation in the Costa Rican rainforest, where leaves and other matter that collects in tree forks gradually forms a soil base in which seeds can germinate. It was several centimetres down inside the soil of one such fork that researchers found ash originating from the Mount Saint Helens eruption.

On arrival at Seattle airport, I am greeted by American colleagues who are to take me to Lyman Lake, which lies at an altitude of eighteen hundred metres near Glacier Peak Wilderness National Park—a journey of many hours by car and then boat. This pristine area was formed by meltwater from a glacier that has retreated at a rate of eight to twelve metres per year during the last century and now lies some distance from the water's edge. We are here to study pristine soil never previously exposed to the elements and answer a host of questions, such as the impact of rainwater when it seeps through the soil, what species of plants colonise the area and what happens to the soil when vegetation takes hold. Thanks to photographs, we know the exact position of the glacier's edge and how it has shifted over the last hundred years.

On our way to the lake, we hike through dense deciduous forest that gradually turns into sparse fir woodland. Yellow wolf lichen grows on the boughs of the

Tentative steps towards new soils. When a glacier melts and recedes, it leaves behind an assortment of fine and coarse soil particles—everything from clay to rocks. Known as moraine, this mixture slowly becomes soil due to the action of the elements and as plants take root. The stony moraine contains plenty of phosphorus and potassium but lacks nitrogen. Plants must therefore find another way to access this critical element. The yellow plant in the foreground—alpine birdsfoot-trefoil—lives in symbiosis with bacteria that capture nitrogen from the air. The nitrogen content in the ground accumulates when these plants decay, facilitating the establishment of other plant species trees, whose elongated crowns necks remind me of Donald Duck's national park visit with his nephews. As we approach the glacier, the forest thins further and the blueberry scrub grows higher.

A cold draught from the glacier hits us as we approach. Countless rivulets of murky meltwater run from the ice, forming a stream that continues down into the lake.

As it moves down the slope, the glacier slowly grinds underlying gravel and stones into smaller pieces. The ice is in constant forward motion but will retreat at the edges during persistent or accelerated periods of melting, as during summer. The edge of the ice will recede if this crimping exceeds the distance the glacier travels during the year. If the ice sheet ceases to move the glacier becomes dead-ice and after it melts, it leaves behind an expanse of pulverised rock that eventually forms the basis for soil. Soil is the top layer of earth that is exposed to the elements and supports life forms. It begins to form as soon as vegetation takes hold. It can be partially unsorted, as with moraine deposited in front of a glacier, or more finely sorted into fractions that are carried away in meltwater as silt. The silt settles as mud or sand at the bottom of the lake and forms muddy or sandy soil when the lake eventually dries out.

Close to the glacier, the loosely piled rocks are treacherous to walk on. In winter the water freezes, dislodging particles of gravel and sand that in spring are carried by rainwater into the crevices, where they stabilise the more outlying rocks. This is the start of soil formation—a process that begins when clumps of grass and sedge take root thirty metres or so from the edge of the ice. They do not look like much, but when they die they provide the organic matter needed for willow bushes to grow.

Return of the trees. The glacier in the photo has retreated by an average of ten metres per year over the past century. Various plants have gradually gained a foothold: lichens, mosses, sedges, small willow shrubs. After eighty years, soil formation has reached a point enabling the fir trees in the foreground to take root. It is fascinating to think that the entire Nordic region has undergone this process

It takes around eighty years and the arrival of the first blueberry and other low shrubs and conifers for soil formation to gather genuine pace. The low air temperature slows the decomposition process. Blueberry leaves and conifer needles also contain components that degrade slowly, resulting in an accumulation of organic matter at the surface. Dissolved organic compounds seep into the soil with rainwater and dissolve the ions from mineral particles. The vegetation absorbs some ions, while others collect further down in the soil or leach into the groundwater. As time passes, the soil separates into an upper leached layer and a lower enriched layer, though this process can be affected by the presence of earthworms, whose burrowing mixes the soil profile. At Lyman Lake, one can study the soil formation process during the hundred years immediately following the deposition of moraine by the glacier. There are plenty of other places to visit for those who wish to study the process over a longer time frame.

Podzolisation and Soil Formation in Sweden

In Sweden, the ice sheets melted around ten thousand years ago in a process mirroring that at Lyman Lake. In their wake, they left an unconsolidated moraine that is the dominant soil type in Sweden. During the Ice Age, the weight of the ice depressed the surface of the Earth's crust, which is now in a process of post-glacial rebound as the land regains its former form. In northern Sweden, the land is rising at a rate of one centimetre per year and here, as at Lyman Lake, we can use a natural time experiment to study the progression of the soil formation process, this time under Scandinavian conditions.

I travelled to Åkerbäck, some twenty-five kilometres inland from the Baltic coast in northern Sweden, to take some soil samples. A nearby patch of shingle beach reveals the line the coast took around eight thousand years ago. Lush spruce forest has dominated the landscape for the last three thousand years or so, having colonised the area from the north. So stony was the ground that it was impossible to use my soil sampler, though after much effort I managed with my colleague's help to dig a deep enough hole to examine the soil structure. Above the mineral soil, which was primarily moraine, lay a ten-centimetre layer of organic matter topped by newly shed spruce needles and leaves embedded in blueberry twigs and moss. The matter adjacent to the mineral soil had degraded into a black paste-like substrate showing no direct evidence of needles or leaves. The upper section of the mineral soil was greyish-white in colour, becoming reddish lower down.

Carbon dioxide emitted by plant roots and microorganisms dissolves in the soil to form carbonic acid, which accelerates the disintegration of soil minerals. The acidification effect is augmented by the positively charged hydrogen ions that these life forms release in exchange for the potassium, magnesium and other positively charged ions that they need in order to grow. As the most easily weathered minerals disintegrate and leach, the soil looks bleached because only grey quartz remains and is resistant to disintegration. The bleached soil is called the eluviated

A postglacial profile. Podzol is the most common soil type in Sweden, formed when conifers grow on acidic bedrock, such as granite, in places with abundant rainfall. The bedrock and acidic conifer leaf litter result in slow decomposition, leaving organic material to accumulate on the ground. Acids from the organic layer are carried in rainwater and dissolve the easily weathered minerals in the top layer of soil. A bleached soil is thus formed in which only grey-white quartz is left. Iron and aluminium from the bleached eluviated soil layer trickle down and form rust-red oxides in the layer below, which becomes the reddish illuviated horizon. Below this, the original moraine has not yet been affected

horizon and at Åkerbäck it reached a depth of twenty centimetres. Below it was a reddish layer known as the illuviated horizon. The reddish colour comes from iron and aluminium dissolved from the upper soil layers, a process aided by the seepage of dissolved acids from organic material lying at the surface.

Podzol is commonly found in Swedish coniferous forests and forms on acidic bedrock where the decomposition process is slow and in areas of plentiful rainfall that accelerates the leaching of minerals to the lower layer of soil.

◀ *Earthy hues.* Soil gets its reddish tint from iron and aluminium oxides. Known as ochre, these compounds have been used as pigments since ancient times. Aboriginal Australians still use ochre to colour their faces and for their traditional bark paintings. During the 1800s it was popular to extract ochre for textile dyeing. The southern French village of Roussillon was an ochre centre and the warm colours of the buildings there still bear witness to that period. Nowadays, the village is a tourist destination where visitors can wander round the old open quarry and enjoy the sunlight playing on the colours in the soil and vegetation

Coniferous forest litter promotes podzolisation and the phenomenon is most strongly observed in New Zealand in areas with high precipitation, where the kauri tree grows on acidic ground. The tree sheds large fragments of bark, which intensifies podzolisation in the area of soil directly beneath the tree, resulting in egg-cup-shaped deposits of bleached soil in podzolised areas.

Time is a key factor in soil formation. At Åkerbäck we observed how both bleached and rusty soil layers grew thinner the nearer to the coast we did our sampling. A few hundred metres from the shore, it was hard to identify any bleached layer at all. On the shoreline itself we found a cordon of alder trees, whose nitrogen-fixing root bacteria had helped bind nitrogen in the soil—a critical factor enabling spruce to colonise.

Plants Accelerate Soil Formation

How, one might well ask, would the soil formation process work if plants were absent? Rainwater washes away soil on an unvegetated hillside but penetrates flatter ground, possibly allowing eluviated soil layers to form because atmospheric carbon dioxide dissolves in rainwater and makes it acidic. But it would doubtless take time.

In summer I often stop at a place called Kastad, near Gjövik in Norway, on my way to my cabin in the Norwegian fells. There is a clearing in the spruce forest where the ground is completely bare. Clumps of grass grow around the edges amid a string of low, stressed spruces. The soil here is highly polluted by lead—not from human activity but from an underground source of galena, the natural mineral source of lead sulphide. On top of the galena lies a metre-thick layer of moraine. The area is interesting because the barren space allows one to study the significance of plants for soil formation. Eluviated soil layers always occur in soil where spruces have grown—soil where apatite has leached from the topsoil. Apatite is a phosphate mineral and important source of nutrition for the spruce, and the fungi that live in symbiosis with the tree's roots are effective at utilising it. Apatite dissolves from the topsoil due to the action of rainwater on the bare ground, though our models indicate that the rate of weathering is one hundred times faster when spruce grows there. Clearly, ground vegetation plays a key role in soil formation, which helps explain why soil in the Antarctic, where vegetation cannot grow, is so thin and underdeveloped.

A pocket in time. Take a walk through the spruce forest near Gjøvik in Norway and you may come across this clearing, devoid of vegetation due to the high lead content in the ground. The area was discovered by Norwegian geologists who ascertained the presence of mineral deposits by noting changes in the vegetation. Below the surface is a seam of galena which may be mined in the future. Scientists use the area to study how vegetation affects soil formation, comparing soil in the forest to that in the clearing

Nature's Own Soil Archive

If you want to study soil formation over a long period of time, the place to go is the Franz Josef glacier in Westland National Park on New Zealand's South Island. The area receives high annual snowfall of three to five metres in liquid equivalent, which has resulted in one part of the glacier almost reaching the coast and a milder climate zone. The temperate rainforest just below the glacier edge stands in sharp contrast to the wall of ice. Franz Josef has left deposits along the narrow valley that leads to the sea and has retreated many kilometres since the Ice Age. Uniquely, the glacial deposits here date back to the last interglacial period, around one hundred and twenty thousand years ago, allowing scientists to study soil formation over a much longer time frame than in areas where glaciers are shrinking.

Soil composition is ever-changing, with no end point at which one can say the soil is "finished". In fact, it is preferable to view soil formation as a two-step process consisting of an accumulation phase and a depletion phase—a process that begins all over again when a new ice age arrives. This is because the ice scrapes away the old weathered soil, paving the way for soil formation in the moraine left behind when the glacier melts. Nitrogen-fixing plants tend to

Between the ice. It snows copiously on the Franz Josef glacier in New Zealand—three to five metres per year in melted form. The high precipitation affects the moraine left behind by the melting glacier, weathering it faster than on many other glaciers. The rainwater slowly dissolves the phosphorus in the soil and carries it away. Moss grows close to the glacier edge and a temperate rainforest covers the valley. However, soil phosphorus decreases with distance from the ice, eventually falling to such a low concentration that shrubs replace the rainforest establish a foothold during the accumulation phase, building up the earth's nitrogen content. Phosphorus content is high at this point but then enters a steady decline. This is because the presence of plant roots makes the soil acidic and results in phosphorus leaching from minerals. If not absorbed by plants, the phosphorus may be washed away by rain. It can also attach to aluminium and iron-rich surfaces, which also takes it out of the equation. As phosphorus content declines, plants start to economise on its use, retaining their leaves for longer and adapting to a lower level of nutrients. This adaptation comes at the expense of reduced growing power stemming from reduced efficiency in photosynthesis. At this point, the vegetation will thin and once-tall forest may revert to scrub. The rate of this process is determined by rainfall. At the Franz Josef glacier, it has taken around twelve thousand years for phosphorus leaching to affect plant growth. The result is an increase in coniferous trees and later on a dominance of species-poor but stress-resistant scrubland. Soil formation over even longer timeframes has been studied in some areas. Studies spanning several million years are possible at Hawaii's lava flows, where the transition from nitrogen to phosphorus deficiency can take several hundred thousand years due to lower rainfall than in New Zealand.

The First Plants Needed Fungi

Phosphorus deficiency also played a key role when plants evolved from exclusively aquatic to terrestrial organisms. The first plants grew on the sea line and had creeping rootstalks, or rhizomes, rather than roots. Aquatic plants easily absorb phosphorus dissolved in the water, but phosphorus on land is fixed and hard to access. The plants that successfully absorbed sufficient phosphorus in this inhospitable environment gained a competitive advantage in terms of stronger growth and a better survival rate. Here, they had fungi to thank. The fungi attached themselves to the plant to gain access to carbohydrates. When confronted with a phosphorus deficiency inside the plant they absorbed phosphorus from the soil, some of which became a food source for the plant. Fungi that did not kill their host plant gained continuous access to carbohydrates, giving them an advantage—and by transporting phosphorus to the plant, they ensured a stable supply of carbohydrate for themselves as photosynthesis requires phosphorus. This was how the mycorrhizal symbiosis, one of the natural world's most successful collaborations, evolved. Mycorrhizal fungi exist on between eighty and ninety percent of plants today. Terrestrial plants would probably have not evolved were it not for the presence of collaborative fungi.

Conditions for soil formation changed significantly when terrestrial plants developed around four hundred million years ago. The plants produced vast amounts of biomass that over time created the organic matter needed for soil to develop. As mineral soil weathered, so the soil formation accelerated.

Ancient recipe for success. During the dinosaur era, gymnosperms such as gingko, cone palms and, later, conifers dominated the flora. Cone palms succeeded by joining forces with cyanobacteria capable of capturing nitrogen from the air. Such symbiosis is today found in some lichens but is unusual among plants. One example is the *Gunnera* family (photo), which is among our oldest angiospermous (flowering) plants and which existed at the time of the dinosaurs. Other groups, including legumes and alders, went on to evolve collaborative strategies with different types of nitrogen-capturing bacteria

Today, it takes a long time for new soil to develop in areas where the topsoil has eroded—too long to restore the areas we have destroyed. The best way to speed up this process is to plant nitrogen-fixing plants that bind carbon and nitrogen in the soil as this creates conditions for other plants to establish themselves and for organic matter to accumulate, in turn creating stable soil that is less prone to erosion. In the next chapter we will explore how the soil's properties determine what grows in it—and how the way we manage the land plays a part in determining what plants will grow there.

Further Readings

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Springer
http://www.springer.com/978-3-319-08457-2

Soil
Reflections on the Basis of our Existence
Wallander, H.
2014, VIII, 141 p. 101 illus., 90 illus. in color., Hardcover
ISBN: 978-3-319-08457-2