Essential Soil Science

A clear and concise introduction to soil science

M. R. Ashman and G. Puri

Blackwell
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For May and Bob

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Contents

Preface vii
List of Abbreviations viii

1 Rocks to Soil 1
1 Soil formation – what are the initial inputs? 2
2 How are these inputs transformed into new compounds? 11
3 How is material moved and then finally lost from the soil? 14
4 How can we explain soil formation? 19

2 Particles, Structures and Water 26
1 What are the main soil particles? 27
2 What is meant by the term 'soil structure'? 31
3 How does water act in the soil? 38
4 Why are the physical characteristics of the soil so important? 41

3 Soil Surfaces, Acidity and Nutrients 46
1 How are chemicals stored and released from soil? 47
2 What determines the availability of acids and nutrients? 57

4 Soil Microbes and Nutrient Cycling 67
1 What types of organism are found in the soil? 68
2 How do soil microbes recycle nutrients? 77

5 Soil Survey, Classification and Evaluation 90
1 How do we carry out a soil survey? 91
2 How do we conduct a soil survey that measures change? 95
3 How do we conduct a soil survey that describes the soil in general terms? 98
4 How do we produce a map from soil descriptions made in the field? 106

6 Soils and Agriculture 114
1 How can we optimize the physical condition of the soil for plant growth? 115

2 How can we optimize the chemical condition of the soil for plant growth? 133
3 How can we optimize the biological condition of the soil for plant growth? 146

7 Soil Contamination and Erosion 151
1 What do we mean when we say a soil is either contaminated or polluted? 152
2 What is soil erosion? 177
3 How can we measure the 'quality' of the soil? 182

Further Reading 186
Index 191

Preface

This book has been written for students who need to understand quickly the basic principles of soil science. Studying a new subject can be a hard and tedious business. Things are not made any easier by the fact that these days very few students have the luxury of studying a single subject, such as 'soil science', full-time. The growth of modular degree schemes has meant that successful study has become something of a balancing act, often between completely different subject areas. This is especially true of soil science, which is taught over a range of courses, including engineering and ecology. This book was written with this problem in mind. Every attempt has been made to assume no previous scientific knowledge, to ensure new concepts are explained simply, often using examples of everyday items, and anything considered too detailed for the average undergraduate course has been ruthlessly cut from the text.

This book has not been written in isolation. Its style and content developed slowly as it was moulded into shape with the help and advice from colleagues and friends, all of whom gave their time freely. It gives me great pleasure finally to be in a position to thank them. I start with Ian Sherman, Blackwell Science Ltd (now at Oxford University Press), without whose enthusiasm and advice this book would never have happened; Nancy Dise, David Myrold, Peter Harris and Chris van Kessel for reviewing an early draft of the book. I also thank my colleagues at IACR-Rothamsted and Silsoe Research Institute, including Prof. David Powlson, Prof. David Jenkinson, Dr Keith Goulding, Paul Hargreaves, Dr Toby Willison, Dr Laurence Blake, Maureen Birdsey, Dr Phil Brookes, Dr Penny Hirsh, Dr Richard Webster, Jamie Allen, Dr Saran Sohi, Pete Falloon, Sharon Fortune, Pete Redfern, Tim Mauchline, Chris Watts, Dr Paul Hallett, Prof. Steve McGrath. A particular source of advice has been Prof. John Catt, who made numerous helpful suggestions. Other help, both practical and intellectual, was provided by Jason Ashman, Jo and Chris Rathbone, May and Bob Ashman, and Sarah Shannon at Blackwell Science Ltd.

A very special thank you must go to Dominique Niesten, who made a major contribution to this book. Her strong sense of chapter structure and clear writing style proved invaluable when revising the text. Without her advice and encouragement the manuscript would have never left my desk. Of course, all responsibility for errors of fact and interpretation remains with the authors.

M. R. Ashman, Rothamsted

List of Abbreviations

ANOVA	analysis of variance
CEC	cation exchange capacity
EC	electrical conductivity
FAO	(UN) Food and Agriculture Organization
FYM	farmyard manure
GIS	geographical information system
ICRCL	Interdepartmental Committee on the Redevelopment of Contaminated Land
ISSS	International Society of Soil Science
LR	leaching requirement
MAFF	Ministry of Agriculture, Fisheries and Food
MIT	mineralization and immobilization turnover
NV	neutralizing value
OC	organochlorine
PAH	polyaromatic hydrocarbon
PCB	polychlorinated biphenyl
rRNA	ribosomal ribonucleic acid
SMD	soil moisture deficit
SNS	soil nitrogen supply
SOM	soil organic matter
SOTER	Soils and Terrain Digital Data Base Project
Unesco	United Nations Educational, Scientific and Cultural Organization
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
WRB	World Reference Base

1 Rocks to Soil

Introduction

Let's start with a question – what is soil and how does it form? Immediately you will know that soils are brownish, turn muddy when wet, and have some importance to plant growth. However, this level of understanding is insufficient when we really want to understand and appreciate the formation and utilization of soils for agricultural purposes. We can start by saying that rocks are transformed into soil by physical and chemical changes that occur at the Earth's surface. Gradually, these mineral inputs are combined with organic matter. Over time both the mineral material and organic matter are transformed into new materials; these are then moved through the soil by percolating water, so that the more soluble compounds are finally lost completely. It is the nature of these inputs, transformations, movements and losses that determines what type of soil will form. This chapter will look at four main lines of enquiry:

1 **Soil formation – what are the initial inputs?**
   - What are soils made from?
   - What are the main mineral inputs?
   - Why do some rocks break up?
   - How do rocks break up?
   - What are the main organic inputs?
   - What are plants made from?
   - How does organic matter begin to accumulate in soil?
   - How does soil organic matter differ depending on environmental conditions?

2 **How are these inputs transformed into new compounds?**
   - What kinds of mineral material do soils contain?
   - What are clay minerals and how do they form?
   - How is organic matter transformed into new material?
   - What is humus and how does it form?

3 **How is material moved and then finally lost from the soil?**
   - How is soil material moved to new geographical locations?
   - How is material moved within the soil?

4 How can we explain soil formation?
Example one: podzol (spodosol)
Example two: gleysol (aquepts)
Example three: ferralsol (oxisol)
Example four: histosol (histosol)

1 Soil formation – what are the initial inputs?

What are soils made from?

The first step in soil formation happens when mineral material from rocks and organic matter from plants and animals are combined together. Rock fragments without organic matter are unable to support plant growth. For example, think about sowing wheat seeds in gravel – what do you think your chances of a successful crop would be? Although organic matter without mineral inputs can support plant growth, composted organic matter lacks many of the physical characteristics that are commonly associated with soil. It is the combination of mineral and organic matter that gives soil its unique properties. Together they make up approximately 50% of the soil volume: the remaining 50% is pore space, filled with either air or water depending on how wet the soil is. We will start by looking at the main mineral inputs.

What are the main mineral inputs?

Rocks are composed of one or a number of different minerals. Geologists have traditionally divided rocks into three broad classes: igneous (formed from molten magma); metamorphic (rocks that have been altered by heat and pressure); and sedimentary rocks (formed from sediment deposits). Rocks differ from each other because they contain either different types of minerals or the same minerals but in varying quantities. This concept is not difficult to understand if you compare, let's say, natural rock and artificial building materials. We can produce a wide range of bricks, blocks and slabs, all with differing properties, by simply varying the proportions of sand, gravel and cement from which they are made: rocks are no different. Rocks with differing mineral compositions vary in their ability to withstand the natural forces that slowly disintegrate them. However, before looking at *how* rocks disintegrate, we should ask *why* they break up in the first place.

Why do some rocks break up?

The Earth's surface is made up of many different types of rock. Some, such as carbonate rocks like limestone and chalk, are composed of prehistoric marine creatures, whereas others like coal are derived from prehistoric plants. However, in most cases rocks are mainly composed of the element silicon. In rocks, silicon is usually combined with oxygen to form silica and silicates. One important difference between rocks is the amount of silica they contain. The proportion of silica to other minerals affects rock susceptibility to disintegration when exposed at the Earth's surface. Generally, for a given set of climatic conditions, the rocks with the lowest concentration of silica break up more quickly than those with higher concentrations. These differences in silica content occur as the molten magma solidifies to form rock. As the magma starts to cool, minerals with the lowest concentrations of silica form first. They are followed by minerals with increasing silica contents. We can use the amount of silica igneous rock contains as a useful method of classification:

- ultrabasic: rocks with less than 45% silica, such as serpentinite and peridotite;
- basic: rocks with 45–55% silica, such as basalt, gabbro and dolerite;
- intermediate: rocks with 55–65% silica, such as amphibolite and andesite;
- acidic: rocks with over 65–85% silica, such as granite and pegmatite.

How do rocks break up?

A more scientific term for the break-up of rocks is 'weathering'. We use this term because climate, and the prevailing weather, is the main factor that eventually transforms rock to soil. Weathering can be either physical or chemical. Figure 1.1 shows how we can divide physical weathering into a number of separate processes.

Physical weathering

Thermal weathering Different minerals have different rates of expansion when heated. When rocks composed of several different minerals are exposed to heat they experience different rates of expansion. This causes stress within the rock, which can result in fracturing in areas of weakness. Thermal stress can also be caused by temperature differences between the outer and inner parts of the rock. This form of thermal stress is called exfoliation or 'onion skin' weathering, because as outer layers of the rock are fractured, they are gradually peeled away.

Mechanical weathering Water can penetrate rocks along small cracks. When water freezes, its volume expands by 10% (think about how uninsulated water pipes can burst in the winter). The force exerted by expanding ice is enough to break open cracks. This form of weathering is called 'frost shattering'. In addition, when exposed to water, different minerals often have different rates of swelling and shrinkage; this can initiate stresses within the rock that eventually cause it to fracture.

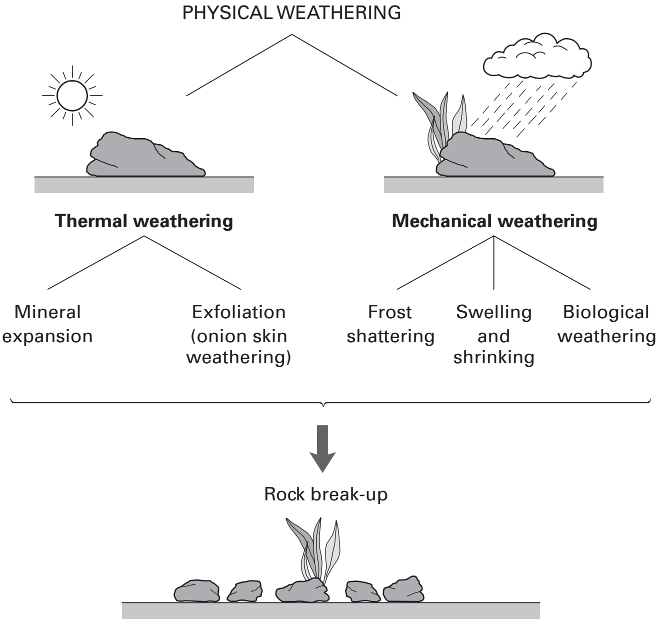

Fig. 1.1 The physical break-up of rocks by thermal and mechanical means.

Fig. 1.2 Plants can speed up physical and chemical weathering by expanding into rock fissures and excreting substances called exudates. These are then metabolized by microorganisms, thereby increasing the rate of chemical weathering.

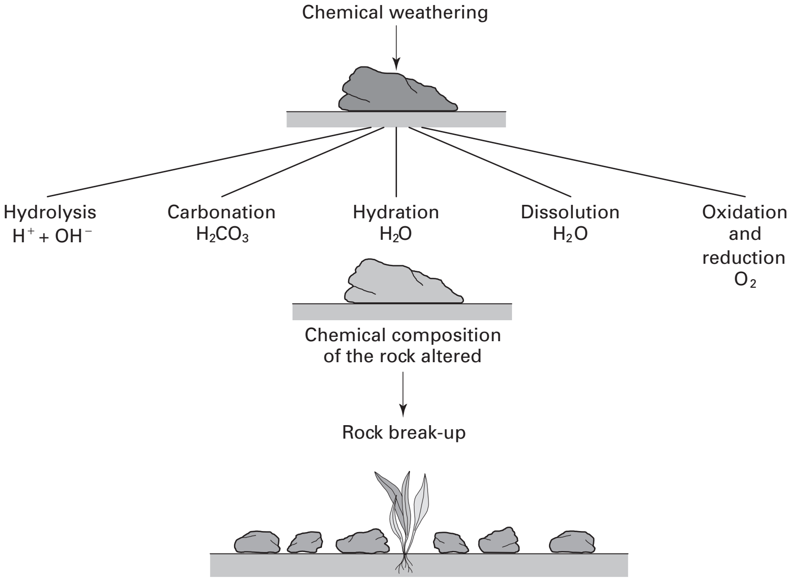

Fig. 1.3 The chemical break-up of rocks by hydrolysis, carbonation, hydration, dissolution, oxidation and reduction. Unlike physical weathering, which simply breaks the rock into smaller and smaller fragments, chemical weathering can also change the physical and chemical properties of the rock.

Another form of mechanical weathering comes from the pressure plant roots exert as they expand into crevices and small cracks in the rock. By widening existing cracks, more of the rock surface is exposed to the elements. This accelerates the weathering process and hastens the disintegration of the rock. Figure 1.2 is a good example of this process (it shows a small tree growing out of a crack in a rock).

Chemical weathering

In addition to being exposed to mechanical disruption rocks are also attacked chemically. Chemical weathering can be divided into the following set of processes (see Fig. 1.3).

Hydrolysis This is the most common form of chemical weathering. It occurs when water molecules (H_2O) separate (dissociate) into two charged particles, H^+ (a hydrogen ion) and OH^- (a hydroxyl ion). The term 'ion' refers to the fact that the particle carries a charge. Hydrogen and hydroxyl ions attack the bonds that hold minerals together. Hydrolysis not only causes rock disintegration but it also changes the chemical nature of the minerals. Hydrolysis is a very important process in soils and it is essential you understand the mechanism: it is shown in Fig. 1.4.

For **cations** (positively charged ions)

$$M^+ + H_2O \rightarrow MOH + H^+$$

For **anions** (negatively charged ions)

$$X^- + H_2O \rightarrow HX + OH^-$$

Fig. 1.4 Hydrolysis is the chemical reaction of a compound with water. The chemical reactions for cations and anions are shown.

$$\underset{\text{respiration}}{\underset{\text{Soil}}{CO_2}} + \underset{\text{water}}{\underset{\text{Soil}}{H_2O}} \rightarrow \underset{\text{of acid}}{\underset{\text{Formation}}{H_2CO_3}} \rightarrow \underset{\text{Dissociation}}{H^+ + HCO_3^-} \rightarrow \underset{\text{dissociation}}{\underset{\text{Further}}{2H^+ + CO_3^{2-}}}$$

Fig. 1.5 Biological activity in the soil leads to carbon dioxide being respired. This dissolves in soil water to produce a weak acid that can then attack minerals.

Carbonation This is an accelerated form of hydrolysis, which is caused by biological activity within the soil. The majority of soil organisms respire carbon dioxide (CO_2). When CO_2 comes into contact with water, a proportion of it dissolves to form carbonic acid (rain is naturally acidic for this reason). Plant roots are particularly destructive in this respect because, in addition to carbonic acid produced by respiration, they also excrete sugars that are then used and converted to acids by micro-organisms in a process not unlike tooth decay following a prolonged sugary diet. All acids are rich sources of hydrogen ions; carbonation therefore enhances hydrolysis. The process is shown in Fig. 1.5.

Hydration During hydration minerals absorb water, but unlike hydrolysis there is no ion formation: during hydration the water molecule remains intact. When a mineral undergoes hydration its physical and chemical properties can be altered. A similar process occurs when pasta is immersed in water: think about how physical characteristics are altered as it absorbs water. When some minerals become hydrated they can also become weakened physically.

Dissolution In this process minerals simply dissolve in water. A few minerals such as sodium chloride (table salt) and potassium chloride are completely soluble in water. Minerals such as these dissolve, and are then washed away in solution.

Oxidation and reduction When exposed to the atmosphere some minerals undergo chemical changes; some are 'oxidized' and others are 'reduced'. In its simplest form oxidation can be regarded as a mineral's tendency to take up oxygen, while reduction is its ability to lose oxygen. However,

Table 1.1 Broad soil carbon and nitrogen ratings.

Rating	Carbon (%)	Nitrogen (%)
Very high	>20	>1.0
High	10–20	0.5–1.0
Medium	4–10	0.2–0.5
Low	2–4	0.1–0.2
Very low	<2	<0.1

Source: J. R. Landon (1984) *Booker Tropical Soil Manual*, Longman Scientific and Technical, Harlow.

this narrow definition has been expanded so that it also refers to the loss (oxidation) or gain (reduction) of electrons. Although chemically the process can become quite complicated, the main point is that changes in a mineral's oxidation state can weaken it.

Although it has been convenient to subdivide weathering into chemical and physical processes, you must appreciate that they are not mutually exclusive. For example, the break-up of a large rock into smaller fragments by physical weathering also increases its rate of chemical weathering by exposing a greater proportion of its surface to the prevailing weather conditions. Put simply, in most situations smaller fragments of rock have higher rates of chemical weathering.

What are the main organic inputs?

Weathered rock finally becomes soil when organic matter is incorporated with mineral fragments. The term 'soil organic matter', in its widest sense, covers all the living and dead organisms contained within the soil. However, when soil scientists use the term they are usually referring to the remains of plants and animals. In some cases these residues are recent additions to the soil, while others may be many years old. When measuring soil organic matter soil scientists often refer to the concentration of soil carbon, because carbon is the main constituent of organic matter, typically accounting for around 58% of the total weight. Table 1.1 shows some typical soil carbon and nitrogen concentrations.

Soil organic matter not only supplies nutrients to plants but it also alters the physical nature of the soil by binding soil particles together into discrete units called aggregates (see Chapter 2). Before looking at soil organic matter in more detail, we will consider briefly what plant material is made from, because in most soils plant material is the commonest type of organic input.

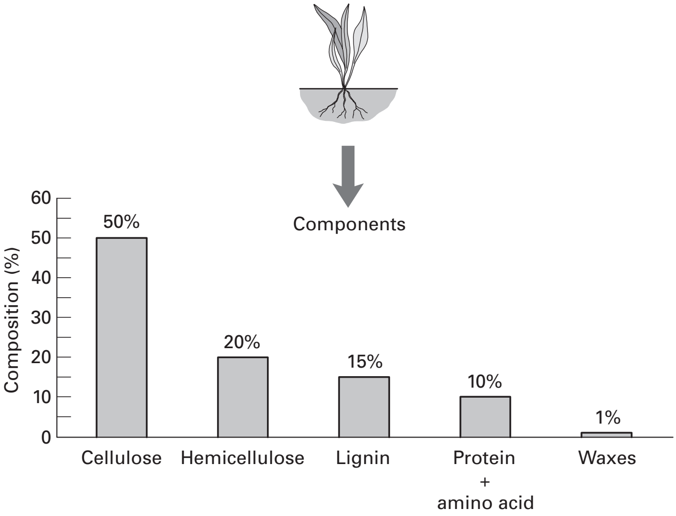

Fig. 1.6 Plant material can be broken down into the components shown.

What are plants made from?

In many respects the breakdown of soil organic matter is similar to rock weathering. As with rocks, the relative proportion of resistant to degradable compounds will largely determine how quickly plant residues are broken down by soil micro-organisms. When we considered rock break-up we used the term 'weathering'; when plant and animal residues are reduced to simple chemicals we use the term 'mineralization'. The main compounds present in plant material are shown in Fig. 1.6.

The main compounds

Cellulose and hemicellulose Plant tissue consists mostly of cellulose (15–50%) and hemicellulose (10–30%). Plant walls are made from a combination of cellulose fibres that are encrusted with hemicelluloses. Both compounds are made up of sugar molecules joined together to form long chains.

Proteins and amino acids Proteins and amino acids also consist of carbon compounds, but unlike cellulose they also contain considerable quantities of nitrogen. Typically, plant material consists of approximately 5% protein and 5% amino acids. Nitrogen is a very important nutrient and is essential to all living organisms. Plant material that is rich in protein therefore offers a valuable food source for soil micro-organisms.

Lignin Whereas proteins are attacked quickly, lignin is only mineralized slowly. It is the most resistant compound found in plant material. Plant material consists of approximately 15% lignin, whereas woody plant tissues contain higher concentrations, approximately 25–30%. The mineralization of woody tissue is undertaken by specialist organisms, mainly fungi, which slowly mineralize lignified material. Just as resistant mineral material can accumulate in the soil, so can resistant organic compounds such as lignin.

Fats and waxes Although these compounds make up only a small fraction of the dry-matter weight of deciduous plant material (1–5%), their concentration in coniferous plant litter may be as high as 20–25%.

How does organic matter begin to accumulate in soil?

Before soil organic matter can begin to accumulate in the soil, mineral particles need to be colonized by plants: this presents a problem. Rock fragments alone do not offer the most attractive conditions for a colonizing plant because they lack the ability to supply adequate quantities of water and nutrients. However, certain bacteria, fungi and plant species have evolved to live in water- and nutrient-limited environments. These organisms are called ‘primary colonizers’.

In many cases primary colonizers are able to obtain nutrition from sources other than the soil. This allows them to live in areas that other organisms would find too hostile. One important adaptation is the ability to obtain nitrogen (one of the most important plant nutrients) from atmospheric rather than soil sources. Organisms that have the ability to do this are called ‘nitrogen fixers’. One example of a primary colonizer that can fix atmospheric N is lichen.

Lichens are a mutually beneficial association between algae and fungi. The algae obtain carbon and in some cases nitrogen from the atmosphere using a combination of photosynthesis and N-fixation. Once their own carbon and nitrogen requirements have been met, surplus nutrients are then passed to the fungi. For their part, the fungi attack the rock with organic acids. This releases minerals for the algae. This type of biological process, whereby both organisms benefit by forming a close association with each other, is referred to as ‘symbiosis’. When these specialized organisms die, their tissues become combined with the mineral material, so forming the first organic-matter additions to the soil. However, it is important to note that not all N-fixers are primary colonists and not every primary colonizer can fix nitrogen. Other adaptations, such as the ability to obtain mineral nutrition from rock surfaces, also play an important part in the success of many primary colonizers.

As the amount of soil organic matter increases it becomes possible for other plants (which extract their N from soil, rather than atmospheric sources) to colonize the site. When these plants die, their residues are then

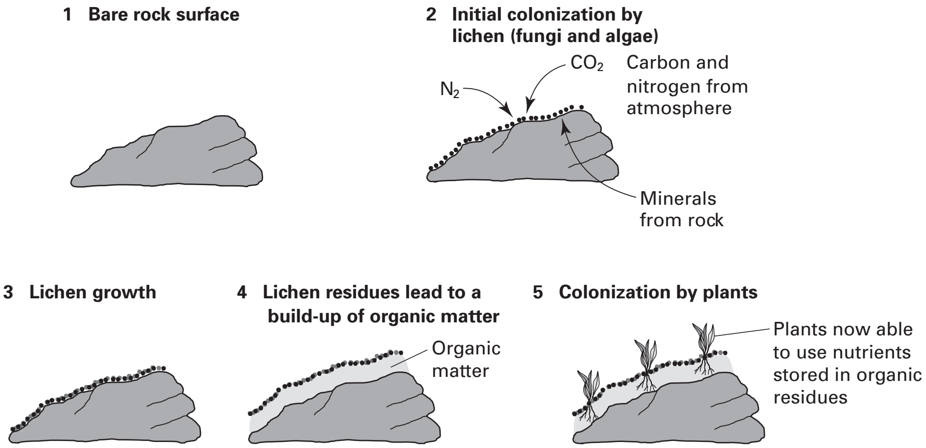

Fig. 1.7 One example of primary colonization is the role lichen plays in the initial stages of soil formation.

incorporated into the store of soil organic matter. The processes involved in primary colonization and soil formation are shown in Fig. 1.7.

How does soil organic matter differ depending on environmental conditions?

As ecosystems mature they develop their own characteristic vegetation in response to local environmental conditions. This means that soils supporting different types of vegetation will also contain different types of organic matter. For example, in some upland areas of the UK the soils are acidic and so support vegetation characteristic of acidic environments. Inputs of organic residues from acid-tolerant vegetation such as Ericaceae are relatively resistant to microbial attack because of their high concentrations of lignin. Lower levels of microbial activity, coupled with organic matter that is difficult to decompose, can lead to the accumulation of plant residues in a black-coloured layer in the top few centimetres of the soil. In neutral to alkaline soils, organic matter tends not to accumulate because high levels of biological activity and mixing by soil animals, such as earthworms, lead to a more uniform distribution of the organic matter throughout the whole soil. These two contrasting soil processes are normally visible in the field and are often associated with certain soil types. We will look at these processes in more detail later in this chapter.

So far we have looked at the main mineral and organic matter inputs, but before going further let's imagine mixing rock fragments with chopped-up plant residues – would the mixture resemble a soil? Probably not, and the reason why it doesn't is that the mixture still lacks some very important material. Although we have described the initial mineral and organic inputs, we now need to consider how they are transformed into new compounds. This is because weathering and mineralization do not simply break down mineral and organic material into smaller units, but transforms them, both chemically and physically. It is these transformed compounds that give soil many of its unique properties.

Essential points

♦ Rocks break up as they adjust to new conditions at the Earth's surface.

♦ Weathering is an umbrella term that covers a whole range of processes, all of which result in rock disintegration. It can broadly be divided into physical and chemical processes.

♦ Soils differ from weathered rock fragments because they contain an organic component, made up of living and dead organisms.

♦ Plant material is made up of five fractions: cellulose and hemicellulose, proteins, lignin, fats and waxes. These fractions differ in the ease with which they are mineralized by soil micro-organisms.

2 How are these inputs transformed into new compounds?

What kinds of mineral material do soils contain?

We can fractionate the mineral component of a soil into three particle-size classes: these are sand, silt and clay and their sizes are shown in Fig. 1.8.

The sand fraction (largely composed of resistant quartz grains) has the largest particles, 0.06–2 mm (or 0.05–2 mm in the US system and 0.02–2 mm in the International System) and the clay fraction the smallest. In fact, clay particles are so small (2 μm) that we use a special symbol 'μ' to describe their size. One μ is simply one millionth (1/1 000 000) of a metre. Apart from their size, sand and silt particles are largely unaltered by chemical weathering. Chemically they are the same as the mineral material in the parent rock, mainly composed of resistant minerals such as quartz. Clay-sized particles, on the other hand, are referred to as 'secondary minerals' because, unlike primary minerals, they have already undergone one phase of chemical weathering, which has altered their physical and chemical composition. Within the clay size range there are several different minerals; we will concentrate on the aluminosilicate clay minerals.

What are clay minerals and how do they form?

The combined effect of hydrolysis, hydration and dissolution causes rocks to disintegrate into their chemical constituents, mainly silicon, iron, aluminium, magnesium, potassium and calcium. Once these elements are released from the old skeletal framework of the primary mineral they are able to