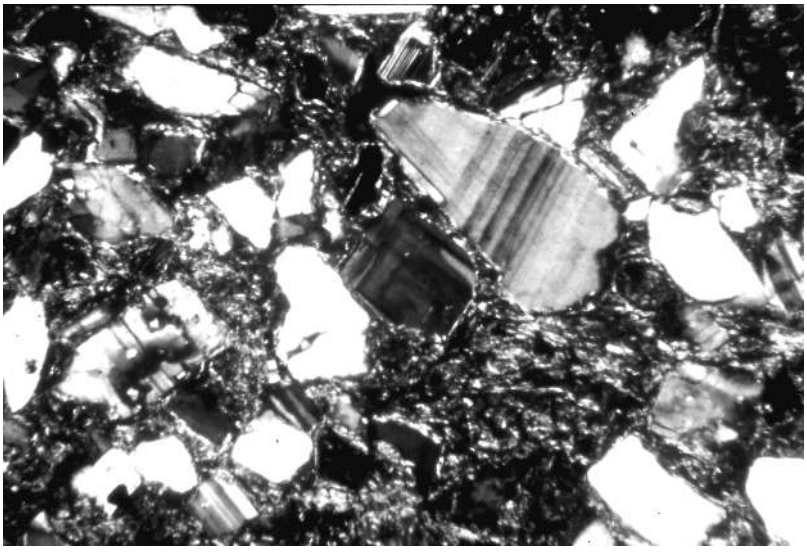
Part I

Principles



Photomicrograph of a poorly sorted, Pleistocene volcaniclastic sandstone, Japan Sea

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Origin, classification, and occurrence of sedimentary rocks

1.1 Introduction

Sedimentary rocks form at low temperatures and pressures at the surface of Earth owing to deposition by water, wind, or ice. By contrast, igneous and metamorphic rocks form mainly below Earth's surface where temperatures and pressures may be orders of magnitude higher than those at the surface, although volcanic rocks eventually cool at the surface. These fundamental differences in the origin of rocks lead to differences in physical and chemical characteristics that distinguish one kind of rock from another. Sedimentary rocks are characterized particularly by the presence of layers, although layers are also present in some volcanic and metamorphic rocks, and by distinctive textures and structures. Many sedimentary rocks are also distinguished from igneous and metamorphic rocks by their mineral and chemical compositions and fossil content.

Sedimentary rocks cover roughly three-fourths of Earth's surface. They have special genetic significance because their textures, structures, composition, and fossil content reveal the nature of past surface environments and life forms on Earth. Thus, they provide our only available clues to evolution of Earth's landscapes and life forms through time. These characteristics of sedimentary rocks are in themselves reason enough to study sedimentary rocks. In addition, many sedimentary rocks contain minerals and fossil fuels that have economic significance. Petroleum, natural gas, coal, salt, phosphorus, sulfur, iron and other metallic ores, and uranium are examples of some of the extremely important economic products that occur in sedimentary rocks.

Many different terms are used to describe the study of sedimentary rocks, including stratigraphy, sedimentation, sedimentology, and paleontology. This book deals with **sedimentary petrology**, which is that particular branch of study concerned especially with the composition, characteristics, and origins of sediments and sedimentary rocks. The book focuses on the physical, chemical, and biological characteristics of the principal kinds of sedimentary rocks; however, it is concerned also with the relationship of these properties to depositional conditions and provenance (sediment sources). I have attempted, where appropriate, to identify major problems and concerns regarding the origin of particular kinds of sedimentary rocks or particular properties of these rocks. Where controversy surrounds the origin, as with the origin of dolomites and iron-formations, different points of view are examined.

In this opening chapter of the book, I give a brief, generalized discussion of the origin, classification, occurrence, and study of sedimentary rocks. I also examine the tectonic setting of sediment accumulation. The composition of siliciclastic sedimentary rocks, in particular, is strongly influenced by tectonic provenance and the kinds of depositional basins and depositional conditions present in the tectonic setting. Therefore, it seems appropriate in this opening chapter to consider tectonic setting and basin architecture as a framework for discussion in succeeding chapters.

Chapters 2 and 3 examine the sedimentary textures and structures that are common to many kinds of sedimentary rocks. Chapter 4 describes the characteristics of sandstones, Chapter 5 discusses conglomerates, and Chapter 6 describes the characteristic features of shales and mudrocks. The extremely important topic of sediment provenance is discussed in Chapter 7, followed in Chapter 8 by discussion of diagenesis of siliciclastic sedimentary rocks. Chapters 9–13 deal with the chemical/biochemical sedimentary rocks. Chapter 9 describes limestones, Chapter 10 discusses dolomites, and Chapter 11 examines the diagenesis of these carbonate rocks. Chapter 12 describes the characteristics of evaporites, cherts, phosphorites, and iron-rich sedimentary rocks and discusses some of the controversial aspects of their origin. The final chapter of the book, Chapter 13, discusses the organic-rich, carbonaceous sedimentary rocks such as oil shales and coals.

1.2 Origin and classification of sedimentary rocks

As mentioned, all sedimentary rocks originate in some manner by deposition of sediment through the agencies of water, wind, or ice. They are the product of a complex, sequential succession of geologic processes that begin with **formation of source rocks** through intrusion, metamorphism, volcanism, and tectonic uplift. Physical, chemical, and biologic processes subsequently play important roles in determining the final sedimentary product. **Weathering** causes the physical and chemical breakdown of source rocks, leading to concentration of resistant particulate residues (mainly silicate mineral and rock fragments) and formation of secondary minerals such as clay minerals and iron oxides. At the same time, soluble constituents such as calcium, potassium, sodium, magnesium, and silica are released in solution. Soluble constituents are constantly carried from weathering sites in surface (and ground) waters that discharge ultimately into the ocean. **Explosive volcanism** may also contribute substantial quantities of particulate (pyroclastic) debris, including feldspars, volcanic rock fragments, and glass.

In time, particulates are removed from the land by erosion, and undergo **transportation** by water, wind, or ice to depositional basins at lower elevations. Within depositional basins, transport of particulates eventually stops when the particles are **deposited** below wave base. Soluble constituents delivered to basins by surface waters, or added to ocean water by water–rock interactions along mid-ocean spreading ridges, may eventually accumulate in basin waters in concentrations sufficiently high to cause their removal by inorganic processes. In many cases, however, precipitation of dissolved constituents is aided in some way by biologic processes. Also, plant or animal organic residues, which wash in from land or originate within the depositional basins, may be deposited along with land-derived detritus or chemical/biochemical precipitates.

After deposition of particulate sediment or chemical/biochemical precipitates, burial takes place as this sediment is covered by successive layers of younger sediment. The increased temperatures and pressures encountered during burial bring about **diagenesis** of the sediment, leading to solution and destruction of some constituents, generation of some new minerals in the sediment, and eventually consolidation and lithification of the sediment into sedimentary rock.

This highly generalized succession of sedimentary processes leads to generation of four fundamental kinds of constituents – terrigenous siliciclastic particles, chemical/biochemical constituents, carbonaceous constituents, and authigenic constituents – which, in various proportions, make up all sedimentary rock.

1. Terrigenous siliciclastic particles

The processes of terrestrial explosive volcanism and rock decomposition owing to weathering generate gravel- to mud-size particles that are either individual mineral grains or aggregates of minerals (rock fragments or clasts). The minerals are mainly silicates such as quartz, feldspars, and micas. The rock fragments are clasts of igneous, metamorphic, or older sedimentary rock that are also composed dominantly of silicate minerals. Further, fine-grained secondary minerals, particularly iron oxides and clay minerals, are generated at weathering sites by recombination and crystallization of chemical elements released from parent rocks during weathering. These land-derived minerals and rock fragments are subsequently transported as solids to depositional basins. Because of their largely extrabasinal origin and the fact that most of the particles are silicates, we commonly refer to them as terrigenous siliciclastic grains, although some pyroclastic particles may originate within depositional basins. These siliciclastic grains are the constituents that make up common sandstones, conglomerates, and shales.

2. Chemical/biochemical constituents

Chemical and biochemical processes operating within depositional basins may lead to extraction from basin water of soluble constituents to form minerals such as calcite, gypsum, and apatite, as well as formation of calcareous and siliceous tests or shells of organisms. Some precipitated minerals may become aggregated into silt- or sand-size grains that are moved about by currents and waves within the depositional basin. Carbonate ooids and pellets are familiar examples of such aggregate grains. There is no commonly accepted group name for precipitated minerals and mineral aggregates, analogous to the term siliciclastic; they are referred to here simply as chemical/biochemical constituents. These constituents are the materials that make up intrabasinal sedimentary rocks such as limestones, cherts, evaporites, and phosphorites.

3. Carbonaceous constituents

The preserved, carbonized residues of terrestrial plants and marine plants and animals, together with the petroleum bitumens, make up a third category of sedimentary constituents.

Humic carbonaceous materials are the woody residues of plant tissue and are the chief components of most coals. **Sapropelic** residues are the remains of spores, pollen, phyto- and zooplankton, and macerated plant debris that accumulate in water. They are the chief constituents of cannel coals and oil shales. **Bitumens** are solid asphaltic residues that form from petroleum through loss of volatiles, oxidation, and polymerization.

4. Authigenic constituents

Minerals precipitated from pore waters within the sedimentary pile during burial diagenesis constitute a fourth category of constituents. These secondary, or authigenic, constituents may include silicate minerals such as quartz, feldspars, clay minerals, and glauconite and nonsilicate minerals such as calcite, gypsum, barite, and hematite. They may be added during burial to any type of sedimentary rock but are never the dominant constituents of sedimentary rocks.

Depending upon the relative abundance of siliciclastic, chemical/biochemical, and carbonaceous constituents, we recognize three fundamental types of sedimentary rocks (Fig. 1.1): siliciclastic (terrigenous) sedimentary rocks, chemical/biochemical sedimentary rocks, and carbonaceous sedimentary rocks. As shown in Fig. 1.1, each of these major groups of sedimentary rocks can be further subdivided on the basis of grain size and/or mineral composition. Thus, the siliciclastic sedimentary rocks are divided by grain size into conglomerates/breccias, sandstones, and mudrocks (shales), each of which can be classified on a still finer scale on the basis of composition. The chemical/biochemical sedimentary rocks are divided by composition into carbonates, evaporites, cherts, ironstones and iron-formations, and phosphorites. Carbonaceous sedimentary rocks may be separated by composition into oil shales, impure coals, coals, and bitumens.

Although we recognize many types of sedimentary rocks on the basis of composition and grain size, only three of these rock types are volumetrically important. As discussed in greater detail below, mudrocks (shales), sandstones, and limestones make up the bulk of all sedimentary rocks in the rock record. The compositions, textures, and structures of sandstones and limestones make them particularly important as indicators of past depositional conditions. Therefore, I have placed major emphasis in this book on these two important groups of rocks.

1.3 Distribution of sedimentary rocks in space and time

Sedimentary rocks and sediments range in age from Precambrian to modern. The ages of the oldest known sedimentary rocks (in Greenland and northern Quebec, Canada) have been determined by iron isotope analyses to be about 3.7–3.8 billion years (e.g. Dauphas *et al.*, 2007). The first rocks that formed on Earth were probably basic volcanic rocks. Sedimentary rocks began to form once Earth's atmosphere and oceans had developed owing to degassing of Earth's interior.

The area of Earth's surface covered by sedimentary rocks has increased progressively with time as the area of volcanic rocks has been successively reduced by erosion (Fig. 1.2).

Composition		Group name	Particle size	Principal constituents	Main rock types
<~15% Carbonaceous residues	<50% Terrigenous siliciclastic grains	or siliciclastic rocks	>2 mm	Rock fragments	Conglomerates and breccias
			1/16–2 mm	Silicate minerals and rock fragments	Sandstones
			<1/16 mm	Silicate minerals	Shales (mudrocks)
	>50% Chemical/biochemical constituents	Chemical/biochemical rocks	Variable	Carbonate minerals, grains; skeletal fragments	Carbonate rocks (limestones and dolomites)
				Evaporite minerals (sulfates, chlorides)	Evaporites (rock salt, gypsum, anhydrite)
				Chalcedony, opal, siliceous skeletal remains	Siliceous rocks (cherts and related rocks)
				Ferruginous minerals	Ironstones and iron-formations
				Phosphate minerals	Phosphorites
>~15% Carbonaceous residues		Carbonaceous rocks	Variable	Siliciclastic or chemical–biochemical constituents: carbonaceous residues	Oil shales Impure coals
				Carbonaceous residues	Humic coals Cannel coals Solid hydrocarbons (bitumens)

Figure 1.1 Classification of sedimentary rocks.

Sedimentary rocks now cover about 80 percent of the total land area of Earth (Ronov, 1983). They also cover most of the floor of the ocean, above a basement of volcanic rocks. According to Ronov, sedimentary rocks make up about 11 percent of the volume (9.5 percent of mass) of Earth's crust and 0.1 percent of the volume (0.05 percent of mass) of the total Earth. Average thickness of Earth's sedimentary shell is 2.2 km, but thickness varies widely in different parts of the continents and ocean basins.

Most of the volume of sedimentary rocks of Earth's crust (about 70 percent) is concentrated on the continents, which make up about 29 percent of Earth's surface (Ronov, 1983). About 13 percent of sedimentary rocks occur on the continental shelf and continental slope, which together make up about 14 percent of Earth's surface. Approximately 17 percent of the total volume of sedimentary rocks occurs on the floors of the oceans, which constitute about 58 percent of Earth's surface.

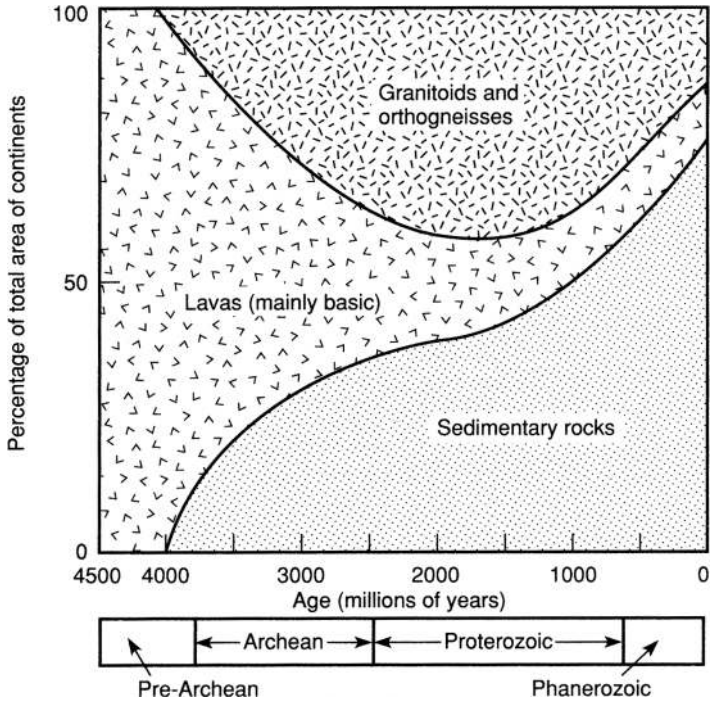

Figure 1.2 Percent of continents covered by most important groups of rocks as a function of age. (After Ronov, A. B., 1983, *The Earth's Sedimentary Shell*: American Geological Institute Reprint Series 5, Fig. 17, p. 31. Reproduced by permission.)

As mentioned, the rocks that make up Earth's sedimentary shell are mainly shales, sandstones, and carbonate rocks. Past estimates, by different workers, of the relative proportion of these rock types in the total sedimentary pile have varied significantly. Estimates by Ronov (1983), on the basis of data obtained by direct measurement of the distribution of the most important rock types, suggest that shales make up about 50 percent of the sedimentary rocks on the continents, sandstones 24 percent, carbonate rocks 24 percent, evaporites about 1 percent, and siliceous rocks (cherts) about 1 percent. In this tabulation, Ronov has apparently lumped iron-rich sedimentary rocks with carbonate rocks, possibly under the assumption that the iron-rich rocks formed by alteration of siderites (iron carbonates). Phosphorites and carbonaceous sedimentary rocks are omitted from the tabulation because their overall volume is quite small compared to that of the other sedimentary rocks. Conglomerates are probably included with sandstones.

The distribution of sedimentary rock types by age is shown in Fig. 1.3. Note that the relative volume of preserved shale per unit age has not changed significantly since early/middle (Archean) Precambrian time. Also, the volume of sandstone of various ages is fairly constant, although the proportion of different sandstone types (graywackes, arkoses, quartzitic sands) has changed somewhat through time. The most notable changes in volume of

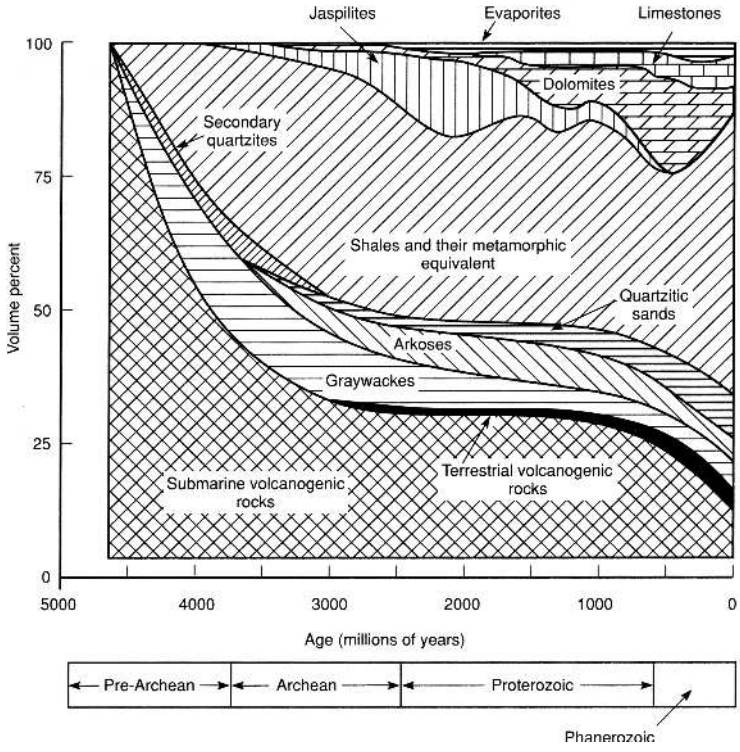

Figure 1.3 Volume percent of sedimentary rocks as a function of age. (After Ronov, A. B., 1983, *The Earth's Sedimentary Shell*: American Geological Institute Reprint Series 5, Fig. 19, p. 33. Reproduced by permission.)

preserved sediment per unit age are the marked decrease in iron-rich sedimentary rocks (jaspilites) after late Precambrian time and the significant increase in carbonate rocks and evaporites after the Precambrian.

1.4 Recycling of sedimentary rocks

Figure 1.4 depicts the mass of total sedimentary rocks graphed as a function of age of the rocks. This graph shows a very strong trend of increasing mass of sedimentary rock per unit time from the Precambrian into the Cenozoic. This trend reflects both rates of sedimentation and rates of erosion. Keep in mind that the volume of older sedimentary rocks has been progressively reduced through time by erosion. Thus, the volume of sediments shown for a given age in Fig. 1.4 does not represent the total volume of sediment deposited during that period of time. Rather, it is the preserved remnant of that original volume.

The particles that made up the first sedimentary rocks that formed on Earth were derived by erosion of basic volcanic rocks. Through time, the area of Earth's surface covered by sedimentary rocks increased as the area covered by basic volcanic rocks decreased

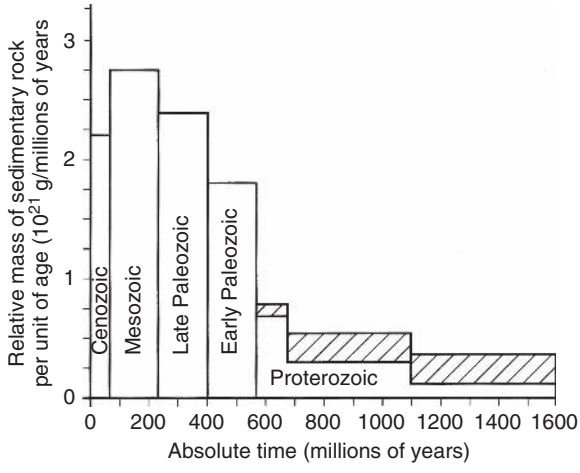

Figure 1.4 Relative volume of sedimentary rocks on the continents per unit of age. Crosshatched areas denote metamorphosed equivalents of the sedimentaray rocks of late Proterozoic age. (After Ronov, A. B., 1983, *The Earth's Sedimentary Shell*: American Geological Institute Reprint Series 5, Fig. 8, p. 14. Reproduced by permission.)

(Fig. 1.2). Some of these early formed sedimentary rocks were ultimately uplifted after burial and lithification to become the source rocks for a new generation of sedimentary rocks. These sedimentary rocks, in turn, were subsequently uplifted and exposed to become the source rocks for a still younger generation of sedimentary rocks, and so on. The constituents that make up younger sedimentary rocks have thus been recycled through the processes of uplift, weathering, and erosion. The number of times that sedimentary rock of a particular type has been recycled is a function of both the tectonic setting of the rocks within a continental mass and the relative susceptibility of the rocks to destruction by weathering and erosion. Tectonic setting (and climate) governs the intensity of the weathering/erosion process; rock type determines the relative ease of destruction. In general, evaporites are the most soluble and most easily destroyed sedimentary rocks. Limestones are next, dolomites are third, and shales, sandstones, and volcanogenic sediments are fourth (Garrels and McKenzie, 1971). Owing to the greater susceptibility of evaporite rocks to destruction, Garrels and McKenzie suggest that such rocks may have been recycled up to 15 times in the last three billion years. Carbonate rocks have been recycled about 10 times and shales and sandstones 5 times.

Garrels and McKenzie suggest two possible models to account for recycling of sedimentary rocks through time. The **constant mass model** assumes an early degassing of the Earth. All the water of the hydrosphere and atmosphere was presumably released at this time, along with all the CO_2, HCl, and other acid gases that could react with primary igneous rock to form sedimentary rock. The total volume of sedimentary rock was thus created very early in Earth's history. Since that time, no completely new sediment has been created because no new acid gases have been released to create them. Through time, these early formed

sediments have been recycled owing to erosion and destruction by metamorphism, with concomitant recycling of CO_2 and HCl. The **linear accumulation model** assumes that water, CO_2, and HCl are being continuously degassed from Earth's interior at a linear rate. New sedimentary rocks have thus continued to form through time by breakdown of primary igneous rock. Therefore, the mass of sediments has grown linearly through time from zero to the currently existing mass. This model represents the extreme opposite conditions to those assumed in the constant mass model. It is possible, of course, that the real recycling process may have combined elements of the two models. That is, an early high rate of degassing may have been followed by a continuously decreasing, possibly irregular, rate of degassing.

In any case, either model could account for the volume of preserved sediment that now exists. What is important in studying the petrology of sedimentary rocks is to keep in mind that the recycling process has brought about some important changes in sedimentary rocks through time. For example, the mineralogy of siliciclastic sedimentary rocks must have been affected through time as chemically and mechanically less-stable minerals and rock fragments were selectively destroyed as they moved through several cycles of uplift, weathering, erosion, transportation, deposition, and diagenesis – moving sediments toward a state of greater compositional maturity (more quartz rich). Textural properties such as shape, roundness, and grain size must also have been affected by multiple cycling, resulting, for example, in enhanced rounding of detrital grains. Recycling of sediments has also produced changes through time in the bulk chemical composition of sedimentary rocks, particularly in the amounts of major elements such as Fe, Mn, Ca, Mg, K, Na, and Si. The patterns of chemical change as a function of time are complex and not easily generalized.

1.5 Tectonic setting of sediment accumulation

1.5.1 Introduction

The physical, chemical, and biological properties of sedimentary rocks are strongly influenced by the nature of sediment source areas (provenance) and the conditions of the depositional environment. The characteristics of source areas and depositional environments, in turn, are the result of the tectonic and geologic history of the region in which the sediments accumulate. For example, source rock types are intimately related to the regional tectonic setting; e.g. volcanic source rocks originate mainly within magmatic arc settings, plutonic igneous rocks are more characteristic of continental block provenances, and metamorphic and sedimentary source rocks typically occur in orogenic belts characterized by collision tectonics. Furthermore, the topographic expression and relief of source areas are controlled by uplift and deformation. Similarly, such aspects of the depositional environment as basin size and geometry, water depth, proximity to source areas, and rate of basin subsidence are influenced by the position of the depositional environment within the regional tectonic framework.

Tectonism, through its influence on provenance and depositional environments, thus exerts an important, indirect control on sedimentation patterns and sedimentary rock characteristics. We will examine more closely the nature of this relationship in appropriate sections of the book.