1

Introduction: Basic Concepts and Approach

1.1 Introduction

Some 75% of the rocks at the Earth's surface are sedimentary in origin, and these include the familiar sandstones, limestones and shales, and the less common but equally well-known salt deposits, ironstones, coal and chert.

Sedimentary rocks of the geological record were deposited in the whole range of natural environments that exist today. The study of these modern environments and their sediments and processes contributes much to the understanding of their ancient equivalents. There are some sedimentary rock types; however, for which there are no known modern analogues, or their inferred depositional environments are only poorly represented at the present time.

Once deposited, sediments are subjected to the processes of diagenesis, that is physical, chemical and biological processes which bring about compaction, cementation, recrystallisation and other modifications to the original sediment, to form rocks.

There are many reasons for studying sedimentary rocks, not least because of their importance as aquifers for groundwater and the wealth of economic minerals and materials contained within them. The fossil fuels oil and gas are derived from the maturation of organic matter in sediments and these then migrate to suitable reservoirs, mostly porous sedimentary rocks. The other fossil fuel, coal, is also contained within sedimentary sequences of course. Sedimentary rocks supply much of the world's iron, potash, salt, building materials and many, many other essential raw materials. Sedimentological and petrological techniques are increasingly used in the search for new reserves of these fuels and other natural resources.

As the transition to a low-carbon economy gains pace, the importance of sedimentary petrology is being realised for the storage of CO_2 in sandstone reservoirs where injecting CO_2 often promotes geochemical reactions and diagenesis. Exploring deep aquifers to act as potential sources of geothermal energy requires sedimentary rocks with appropriate porosity and permeability distributions at depth, such that the natural heat flow in the Earth's subsurface allows water present in pore spaces within the rock to be heated to temperatures suitable for the production of hot water back to the surface via wells.

Non-biodegradable plastics and microplastics are accumulating in sediments across all depositional environments globally and process-based sedimentology is important to assess their distribution and burial. The growing awareness of the environmental pollution caused by plastics from rivers to deep-marine environments needs quantitative detailed approaches using sedimentology and petrology to fully constrain their impact and better understand how that can be mitigated.

Environments and processes of deposition, palaeogeography and palaeoclimatology, can all be deduced from studies of sedimentary rocks. Such studies contribute much towards a knowledge and understanding of the Earth's geological history. Sedimentary rocks contain the record of life on Earth (and extraterrestrial), in the form of fossils, and these are the principal means of stratigraphic correlation in the Phanerozoic.

1.2 Basic Concepts

1.2.1 Classification of Sedimentary Rocks

Sedimentary rocks are formed through physical, chemical and biological processes. On the basis of the dominant process(es) operating, the common sediment lithologies can be grouped into four broad categories (Table 1.1). The siliciclastic sediments (also referred to as terrigenous or epiclastic deposits) are those consisting of fragments or broken pieces (clasts) of pre-existing rocks, which have been transported and deposited by physical processes. The conglomerates and breccias, sandstones and mudrocks,

Sedimentary Petrology, Fourth Edition. Maurice E. Tucker and Stuart J. Jones.

Table 1.1 Principal groups of sedimentary rock (volcaniclastic sediments are not covered in this book).

Siliciclastic sediments	Biogenic, biochemical, organic sediments	Chemical sediments	Volcaniclastics
Conglomerates and breccias, sandstones, mudrocks	limestones (and dolomites), cherts, phosphates, coal and oil shale	Evaporites, ironstones	e.g. ignimbrites, tuffs, hyaloclastites

discussed in Chapters 2 and 3 belong to this group. Sediments largely of biogenic, biochemical and organic origin are the limestones, which may be altered to dolomite (Chapter 4), phosphate deposits (Chapter 7), coal and oil shale (Chapter 8) and cherts (Chapter 9). Sedimentary rocks largely of chemical origin are the evaporites (Chapter 5) and ironstones (Chapter 6), although biological processes are increasingly being recognised as involved in the formation of iron-rich deposits. Each of these various sedimentary rock types can be divided further, usually on the basis of texture and composition. In addition, many rock types grade laterally or vertically into others through intermediate lithologies. A scheme to help with the identification and description of sedimentary rock types is presented in Table 1.6.

1.2.2 Sedimentary Environments and Facies

Sedimentary environments vary from those where erosion and transportation dominate, to those where deposition prevails. Most weathering and erosion, liberating sediment grains and ions in solution, takes place in continental areas, and climate, local geology and topography control the type and amount of material released. The main continental depositional environments are fluvial and glacial systems, lakes and the aeolian sand seas of deserts. Most shoreline environments, deltas, lagoons, tidal flats, sabkhas, beaches and barriers, and open-marine environments, shallow shelves and epeiric seas, and bathyal–abyssal sites of pelagic, hemipelagic and turbidite sedimentation are areas of net deposition, involving the whole range of sediment lithologies. Changes in sea level however can have a drastic effect on these marine systems. Many modern marine sediments possess distinctive characteristics which can be used to recognise their equivalents in the geological record.

Sediments can be transported and deposited by a wide range of processes including wind, flowing water as in streams, tidal currents and storm currents, waves, sediment + water flows such as turbidity currents and debris flows. Sediments may also form *in situ*, the formation of reefs and microbialites, and the precipitation of minerals, as in evaporites. Depositional processes leave their record in the sediment in the form of sedimentary structures and textures. Some depositional processes are typical of a particular environment, whereas others operate in several or many environments. Water depth, degree of agitation and salinity are important physical attributes of subaqueous environments and these affect and control the organisms living on or in the sediment or forming the sediment. Chemical factors such as Eh (redox potential) and pH (acidity–alkalinity) of surface waters and pore waters affect organisms and control mineral precipitation.

1.2.2.1 Facies

With sedimentary rocks, once they have been described and identified (the theme of this book), and their stratigraphic relationships elucidated, then the concept of facies can be applied. *A facies is a unit of sedimentary rock with features that distinguish it from other facies.* A facies is the product of deposition, and it may be characteristic of a particular depositional environment, or a particular depositional process. Features used to separate facies are sediment composition (lithology), grain size, texture, sedimentary structures, fossil content and colour. The diagenetic textures may also be a distinguishing feature. *Lithofacies* are defined on the basis of sedimentary characteristics, whereas *biofacies* rely on palaeontological or palaeoecological differences. With detailed work, *subfacies* can be recognised and *microfacies* if microscope studies are used to distinguish between rocks which in the field appear similar (often the case with limestones). Facies can be described in terms of (i) the sediment itself (e.g. cross-bedded sandstone facies), (ii) the depositional process (e.g. stream-flood facies) and (iii) the depositional environment (e.g. tidal-flat facies). Only (i) is objective and, hopefully, unequivocal; (ii) and (iii) are both interpretative. Different facies commonly occur together and so form *facies associations* or *facies assemblages*. Repetitions of facies sequences are common and give rise to small-scale cycles a few metres thick. Some cycles develop naturally within a sedimentary environment (autocyclicity); others are controlled by external factors, such as sea level or climate change (allocyclicity).

1.2.2.2 Facies Models

Many attributes of a facies are reflections of the depositional processes and environment. There are a finite number of environments so that similar facies and facies associations are produced wherever and whenever a particular environment existed in the geological past. Differences do arise of course, from variations in provenance (the source of the sediment), the nature of the fossil record at the time and climatic and tectonic considerations. From studies of modern and ancient sedimentary environments, processes and facies, generalised *facies models* have been proposed to show the lateral and vertical relationships between facies. These models facilitate interpretations of sedimentary formations and permit predictions of facies distributions and geometries. However, facies models are just snapshots of an environment; depositional systems are dynamic and a facies model may only relate to a particular state of relative sea-level change. The importance of the vertical succession of facies was first appreciated by Johannes Walther at the end of the nineteenth century in his 'Law of the Correlation of Facies': different facies in a vertical succession reflect environments which were originally adjacent to each other, providing there were no major breaks in sedimentation. Vertical changes in facies result from the effects of internal (*autogenic*) and external (*allogenic*) processes. Familiar examples of the former are the progradation (building out) of deltas and tidal flats into deeper water (generating a shallowing-upward package), and the combing of a river across its floodplain. External processes are again chiefly tectonic movements, acting on a regional or global scale, and climatic changes. Both of these affect the relative position of sea level, a major factor in facies development, and the supply of sediment, as noted above and explained further below. Facies and facies models for all environments are discussed in James and Dalrymple (2010) and for carbonates in Flügel and Munnecke (2010).

In the 1980s–1990s, the study of facies and facies models moved more into understanding the over-riding controls on deposition and roles of changing relative sea level and other factors. These approaches developed further within the concepts of *sequence stratigraphy*, emerging from the interpretation of seismic reflection data and discussed in Section 1.2.5, and in more detail in Sections 2.13 for siliciclastics and 4.14 for carbonates.

1.2.3 Controls on Deposition: Tectonics, Climate and Sea Level

Apart from the depositional environments and their processes themselves, two over-riding external (allocyclic) controls on deposition are tectonics and climate.

Tectonics is of paramount importance since it determines the overall larger scale depositional setting, whether it is, for example, a stable craton, a back-arc basin or a rift valley. Ultimately, tectonics generates the space where sediments can accumulate. It is subsidence over geologically significant intervals of time that continually provides the *accommodation space* for the accumulation and burial of sediment in sedimentary basins. The accommodation available in a basin at any one time will control the geometry and character of the sedimentary fill on a gross scale. Accommodation generally increases during bouts of tectonic activity and decreases as sediment starts to fill the available space. There have been many studies in recent years of modern and ancient *sedimentary basins* and the main categories are given in Table 1.2. Each basin type has a particular pattern of sedimentary fill, some with distinctive facies or even characteristic lithologies. The deposits of many ancient passive margins, back-arc/fore-arc basins and ocean floors, commonly much deformed, occur in mountain belts, produced by plate collisions. Rates of subsidence and uplift, the level of seismic activity and occurrence of volcanoes are all dependent on the tectonic context and are reflected in the sediments deposited. In siliciclastic

Table 1.2 Plate-tectonic classification of sedimentary basins and their typical rock types.

I Spreading-related or passive settings

- a) Intracratonic rifts (e.g. East Africa). Mostly filled by alluvial fan, fluvial and lacustrine facies.
- b) Failed rifts or aulacogens (e.g. Benue Trough). Thick successions from deep-sea fan to fluvial.
- c) Intercontinental rifts
  - 1) Early (e.g. Red Sea). Evaporites, carbonates, siliciclastics; fluvial to deep marine.
  - 2) Late (e.g. Atlantic margin). Fluvial–deltaic, clastic shelf, carbonate platform on passive margin, passing to turbidites, hemipelagites and pelagites on ocean floor.
- d) Intracratonic basins (e.g. Chad, Zechstein, Delaware, Michigan). Terrestrial to marine facies, clastics, carbonates, evaporites.

II Active settings

- a) Continental collision-related
  - 1) Remnant ocean basins (e.g. Bay of Bengal, Mediterranean). Sediments variable, turbidites, anoxic muds, evaporites.
  - 2) Foreland basins (e.g. sub-Himalayas, Alpine molasse basins, Western Canada). Terrestrial to shallow to deep-marine clastics and carbonates.
- b) Strike-slip/pull-apart basins (e.g. California). Thick successions, deep-sea fan to fluvial.
- c) Subduction-related settings
  - 1) Continental margin magmatic arcs (e.g. Andes).
    - a) Fore-arc basins. Thin to thick successions, fluvial to deep-sea fan and volcaniclastics.
    - b) Back-arc/retro-arc basins. Mostly terrestrial facies and volcaniclastics.
  - 2) Intra-oceanic arcs (e.g. Japan, Aleutians).
    - a) Fore-arc basins. Turbidites, hemipelagites, pelagites, volcaniclastics.
    - b) Back-arc basins. Marine and volcanic facies; terrigenous influences.

systems, dynamic tectonic settings are connected by the sediment flux of particulate sediment and dissolved loads from source areas to their depositional basins, i.e. *source to sink*; these are the *sediment routing systems* (see Section 2.11). In carbonate systems, biological–biochemical processes operate in different types of *carbonate factory* and sediments may be deposited there where formed or exported out of the factory, to near or distant sites, thus *sources and sinks* (see Section 4.4.1).

1.2.3.1 Climate

This is the major factor in subaerial weathering and erosion and strongly affects the composition of terrigenous clastic sediments. Climate is instrumental in the formation of some lithologies, evaporites and limestones, for example, and there is a strong palaeolatitudinal control on some rock types (Figure 1.1). Two other factors controlled by climate and tectonic context are sediment supply and organic productivity. Clastic sediment supply is important in the deposition of sandstones and mudrocks of course but also in the generation of limestones, evaporites, phosphates, and ironstones, typically where clastic supply rates are low or insignificant. High levels of organic productivity, controlled by nutrient availability and other factors, are important in the formation of certain limestones, phosphates, cherts, coal and oil shale. Apart from the many factors on Earth controlling climate (i.e. tectonic plate - ocean configuration, palaeogeography and atmosphere), climate may also be a response to astronomical patterns relating to the Earth's orbit and solar insolation variation. Differentiating between the effects of climate and tectonism is not easy, especially for relatively short timescale changes.

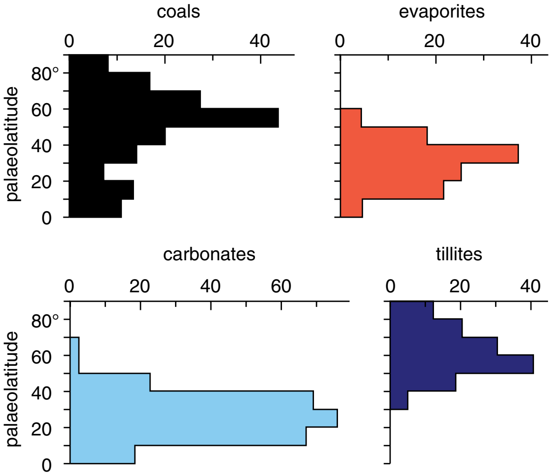


Figure 1.1 Palaeolatitude zonation of climate-sensitive deposits. Frequency (number of occurrences against palaeolatitude). Note that tillites did form at low latitudes during times of Snowball Earth in the Neoproterozoic (see Section 2.12.8).

1.2.3.2 Sea Level

Commonly operating together, climatic and tectonic factors determine the global position of sea level and the changes in *relative sea level*, both of which have a major influence on the depositional system. Changes in relative sea level may be regional (e.g. changes in rates of uplift/subsidence and sediment supply), or global, referred to as *eustatic*, e.g. variations in climate causing changes in the size of the polar ice caps, opening/closing of ocean basins and fluctuations in rates of seafloor spreading causing ocean-basin volume changes.

Eustatic sea level does change on different timescales and orders (Table 1.3), and these may be superimposed, to give *composite eustasy* (Figure 1.2). The long-term pattern of sea-level change, the first order, on the scale of 100s of Ma (10^8 years) relates to opening and closing oceans and rates of seafloor spreading. This is *tectonoeustasy*, acting through changes in ocean-basin volume; the long-term sea-level curve through the Phanerozoic is shown in Figure 4.19 and is basically the result of the opening and closing of the Iapetus Ocean in the Palaeozoic and the formation of Pangea, followed by the opening of the Atlantic and Tethys

Table 1.3 The orders of sea-level change and possible mechanisms. There is still much discussion over the mechanism(s) behind global eustasy as a cause of sea-level changes on the 1–10 million year scale (second to third order), and the significance of changes of the in-plane stress regime within plates in terms of relative sea-level change has still to be evaluated.

First-order, 10^8 yr	tectono-eustasy	
Second-order, 10^7 yr	rifting and thermal subsidence	eustasy
Third-order, 10^6 yr	in-plane stress	
Fourth-order, 10^5 yr	glacio-eustasy, tectonics, sedimentary processes	
Fifth-order, 10^4 yr		

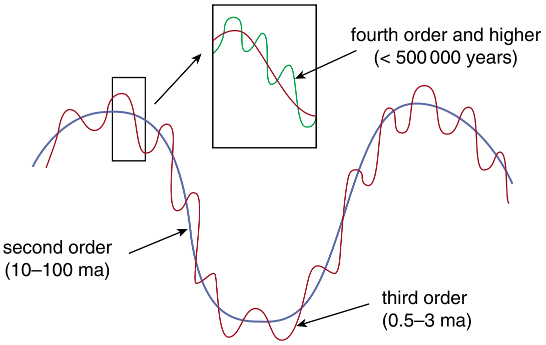


Figure 1.2 Sketch of the hierarchy of sea-level rhythms from superimposition of the various orders of sea-level change (often referred to as composite eustasy).

and closing of Tethys in the Mesozoic and Cenozoic. The occurrence of limestones (more abundant at times of relative sea-level highstand) and their primary mineralogy (see Figure 4.19), the development of hydrocarbon source rocks (Figure 8.12) and to a certain extent the abundance of dolomites, phosphorites and ironstones, all broadly correlate with this first order, dominantly plate-tectonically controlled sea-level curve. The opening and closing of small ocean basins, and the formation of mountain ranges and island arcs, operates more on a 10s of Ma (10^7) timeframe (a second order of sea-level change). A recent statistical analysis of sea-level changes through the Phanerozoic, however, has detected strong periodicities of 250 and 36 Ma, and lesser ones of 91 and 9.3 Ma; these were attributed to 'solar system motions' (see Boulila et al. 2018).

Higher frequency sea-level changes may be the result of astronomic orbital forcing: the Milankovitch rhythms of eccentricity (100 kyr, 400 kyr, 2 Ma), obliquity (40 kyr) and precession (20 kyr), operating on the 10^5–10^4 year scale. Such sea-level changes are most marked during icehouse times when ice-caps expand and contract, giving changes up to 100 m (glacioeustasy). They also occur during greenhouse times, but more on a metre-scale, as a result of temperature changes on ocean-water volume (the icehouse–greenhouse episodes are shown in Figure 4.19). Such orbitally-forced sea-level changes, on the 10^5–10^4 -year timescale, are a major control on metre-scale cycle development and stacking patterns, although processes within the depositional systems themselves (autocyclicity), such as tidal-flat/shoreline progradation, and migration of facies mosaics, are also involved.

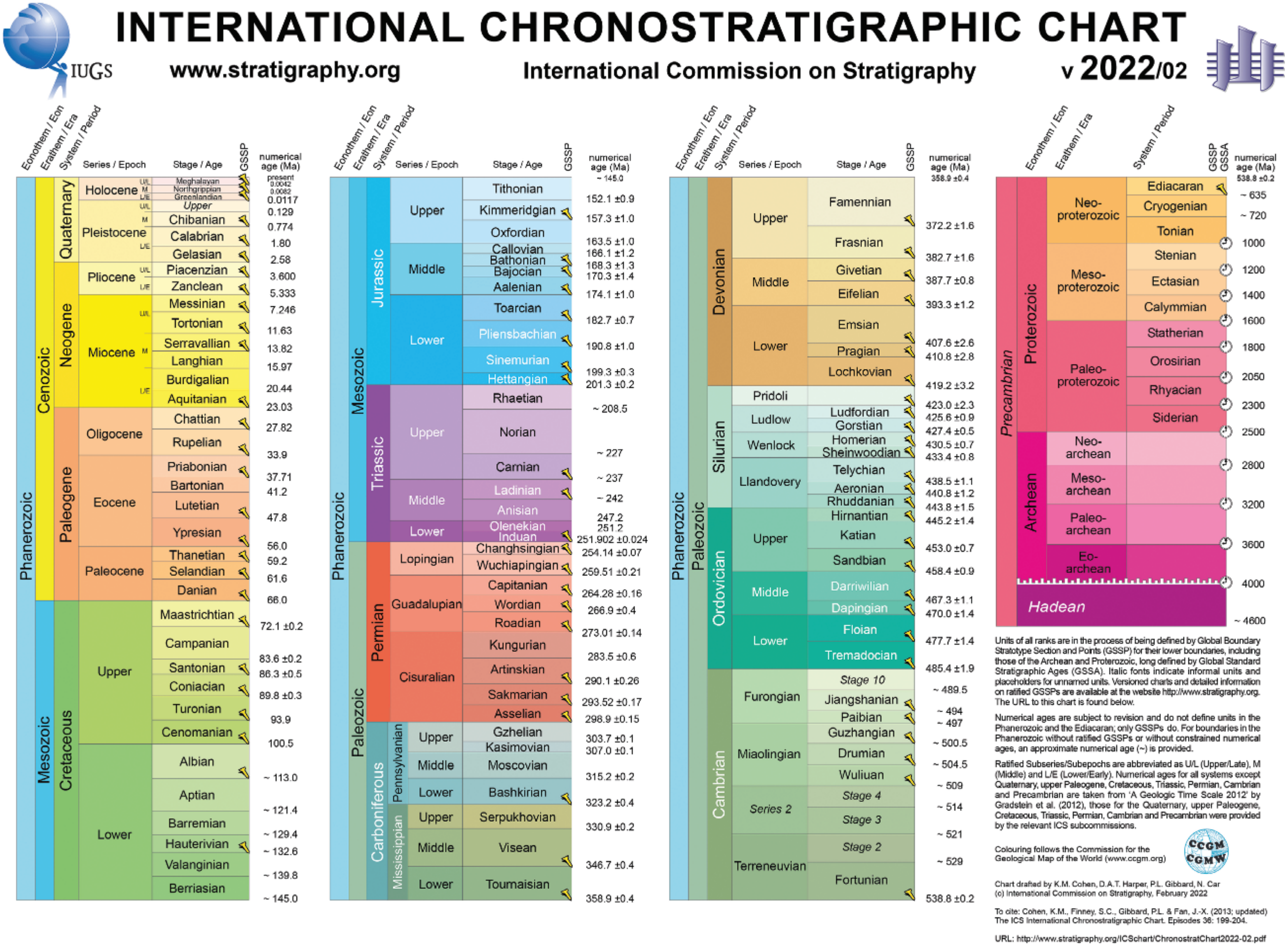
1.2.4 Stratigraphic Practice

Knowing the stratigraphic background and context of the sedimentary rocks being studied is useful background in unravelling their character, deposition and distribution in space and time. Lithostratigraphy, based on lithologies, and sequence stratigraphy, based on key surfaces, are two approaches which can be applied in the field, as well as to subsurface data (seismic, well logs). Having conducted such exercises, then chronostratigraphy can be applied to consider the strata in terms of time, as well as space. ***Lithostratigraphy*** divides the rock record on the basis of lithology; the fundamental unit is the formation, a unit of largely homogeneous lithology which forms a mappable unit. The divisions are supergroup, group, formation, member and bed. This stratigraphic approach is basically descriptive, concerned with separating lithological units and their lateral–vertical distribution. ***Sequence stratigraphy***, discussed in the next section, involves dividing a sedimentary succession into related facies units on the basis of their geometries and bounding surfaces, and then interpreting these in terms of changes in accommodation space and base level.

Chronostratigraphy considers the stratigraphic record in terms of time. Chronostratigraphic correlation uses *biostratigraphy* (zone fossils) in particular, to date strata relatively, as well as event stratigraphy, which may include storm beds, reefal biostromes, flooding events, exposure horizons, unconformities, sequence boundaries and tuff bands (tephrostratigraphy). There is also magnetostratigraphy, magnetic susceptibility, and chemostratigraphy, especially isotope stratigraphy for correlation and relative dating.

It can be useful to consider a succession in terms of its chronostratigraphy, especially when examining the succession on a basin-scale and there are breaks in sedimentation and periods of uplift. A chronostratigraphic diagram depicts the succession in space and time, and so does not indicate thickness. It will show where and when deposition and subaerial exposure took place and bring out the relationships between different units (Figure 1.6b shows the chronostratigraphy for the sequence stratigraphy in Figure 1.6a; explanation in next section). Chronostratigraphic divisions are time-rock units, i.e. they refer to the succession of rocks deposited during a particular interval of time, with the terms system, series and stage. The international chronostratigraphic chart for geological time is shown in Figure 1.3 which also gives the approximate age of each stage. From sequence and chronostratigraphy, 'global sea-level' charts have been constructed for the Phanerozoic which have proved useful in correlation between regions and basins.

Rates of deposition and stratigraphic completeness. Geological processes operate over a huge range of timescales, seconds to billions of years and this is also the case with those relating to the stratigraphic record. The rate of deposition of sediment varies significantly, from a storm or turbidity current depositing a huge amount of material in a matter of minutes or hours through to the low accumulation rate of fine mud on the deep seafloor, barely measurable, even less than a mm per year. And then in some environments, notably terrestrial ones, there is much time during which no sediment is being deposited (or produced) at all, but rather weathering and erosion are taking place, removing sediment (and rock), again at variable rates. Such phases of sediment removal can also happen on a very large scale but very quickly, geologically instantaneously, as during a hurricane for example when a beach may be removed or through a seismic event causing collapse of a shelf margin. Thus in looking at the stratigraphic record, one must be aware of gaps in the succession, usually



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v 2022/02

Eonothem / Eon	Erathem / Era	System / Period	Series / Epoch	Stage / Age	GSSP	numerical age (Ma)
						present
Phanerozoic	Cenozoic	Quaternary	Holocene U/L	Meghalayan	✓	0.0042
			M	Northgrippian	✓	0.0082
			L/E	Greenlandian	✓	0.0117
			Pleistocene U/L	*Upper*		0.129
			M	Chibanian	✓	0.774
			L/E	Calabrian	✓	1.80
				Gelasian	✓	2.58
		Neogene	Pliocene U/L	Piacenzian	✓	3.600
			L/E	Zanclean	✓	5.333
			Miocene U/L	Messinian	✓	7.246
				Tortonian	✓	11.63
			M	Serravallian	✓	13.82
				Langhian		15.97
			L/E	Burdigalian		20.44
				Aquitanian	✓	23.03
		Paleogene	Oligocene	Chattian	✓	27.82
				Rupelian	✓	33.9
			Eocene	Priabonian	✓	37.71
				Bartonian		41.2
				Lutetian	✓	47.8
				Ypresian	✓	56.0
			Paleocene	Thanetian	✓	59.2
				Selandian	✓	61.6
				Danian	✓	66.0
	Mesozoic	Cretaceous	Upper	Maastrichtian	✓	72.1 ±0.2
				Campanian		83.6 ±0.2
				Santonian	✓	86.3 ±0.5
				Coniacian	✓	89.8 ±0.3
				Turonian	✓	93.9
				Cenomanian	✓	100.5
			Lower	Albian	✓	~ 113.0
				Aptian		~ 121.4
				Barremian		~ 129.4
				Hauterivian	✓	~ 132.6
				Valanginian		~ 139.8
				Berriasian		~ 145.0

Eonothem / Eon	Erathem / Era	System / Period	Series / Epoch	Stage / Age	GSSP	numerical age (Ma)
						~ 145.0
Phanerozoic	Mesozoic	Jurassic	Upper	Tithonian		152.1 ±0.9
				Kimmeridgian	✓	157.3 ±1.0
				Oxfordian		163.5 ±1.0
			Middle	Callovian		166.1 ±1.2
				Bathonian	✓	168.3 ±1.3
				Bajocian	✓	170.3 ±1.4
				Aalenian	✓	174.1 ±1.0
			Lower	Toarcian	✓	182.7 ±0.7
				Pliensbachian	✓	190.8 ±1.0
				Sinemurian	✓	199.3 ±0.3
				Hettangian	✓	201.3 ±0.2
		Triassic	Upper	Rhaetian		~ 208.5
				Norian		~ 227
				Carnian	✓	~ 237
			Middle	Ladinian	✓	~ 242
				Anisian		247.2
			Lower	Olenekian		251.2
				Induan	✓	251.902 ±0.024
	Paleozoic	Permian	Lopingian	Changhsingian	✓	254.14 ±0.07
				Wuchiapingian	✓	259.51 ±0.21
			Guadalupian	Capitanian	✓	264.28 ±0.16
				Wordian	✓	266.9 ±0.4
				Roadian	✓	273.01 ±0.14
			Cisuralian	Kungurian		283.5 ±0.6
				Artinskian	✓	290.1 ±0.26
				Sakmarian	✓	293.52 ±0.17
				Asselian	✓	298.9 ±0.15
		Carboniferous	Pennsylvanian Upper	Gzhelian		303.7 ±0.1
				Kasimovian		307.0 ±0.1
			Pennsylvanian Middle	Moscovian		315.2 ±0.2
			Pennsylvanian Lower	Bashkirian	✓	323.2 ±0.4
			Mississippian Upper	Serpukhovian		330.9 ±0.2
			Mississippian Middle	Visean	✓	346.7 ±0.4
			Mississippian Lower	Tournaisian	✓	358.9 ±0.4

Eonothem / Eon	Erathem / Era	System / Period	Series / Epoch	Stage / Age	GSSP	numerical age (Ma)
						358.9 ±0.4
Phanerozoic	Paleozoic	Devonian	Upper	Famennian	✓	372.2 ±1.6
				Frasnian	✓	382.7 ±1.6
			Middle	Givetian	✓	387.7 ±0.8
				Eifelian	✓	393.3 ±1.2
			Lower	Emsian	✓	407.6 ±2.6
				Pragian	✓	410.8 ±2.8
				Lochkovian	✓	419.2 ±3.2
		Silurian	Pridoli		✓	423.0 ±2.3
			Ludlow	Ludfordian	✓	425.6 ±0.9
				Gorstian	✓	427.4 ±0.5
			Wenlock	Homerian	✓	430.5 ±0.7
				Sheinwoodian	✓	433.4 ±0.8
			Llandovery	Telychian	✓	438.5 ±1.1
				Aeronian	✓	440.8 ±1.2
				Rhuddanian	✓	443.8 ±1.5
		Ordovician	Upper	Hirnantian	✓	445.2 ±1.4
				Katian	✓	453.0 ±0.7
				Sandbian	✓	458.4 ±0.9
			Middle	Darriwilian	✓	467.3 ±1.1
				Dapingian	✓	470.0 ±1.4
			Lower	Floian	✓	477.7 ±1.4
				Tremadocian	✓	485.4 ±1.9
		Cambrian	Furongian	*Stage 10*		~ 489.5
				Jiangshanian	✓	~ 494
				Paibian	✓	~ 497
			Miaolingian	Guzhangian	✓	~ 500.5
				Drumian	✓	~ 504.5
				Wuliuan	✓	~ 509
			Series 2	*Stage 4*		~ 514
				Stage 3		~ 521
			Terreneuvian	*Stage 2*		~ 529
				Fortunian	✓	538.8 ±0.2

Eonothem / Eon	Erathem / Era	System / Period	GSSP GSSA	numerical age (Ma)
				538.8 ±0.2
Precambrian	Proterozoic	Neoproterozoic Ediacaran	✓	~ 635
		Cryogenian		~ 720
		Tonian	◷	1000
		Mesoproterozoic Stenian	◷	1200
		Ectasian	◷	1400
		Calymmian	◷	1600
		Paleoproterozoic Statherian	◷	1800
		Orosirian	◷	2050
		Rhyacian	◷	2300
		Siderian	◷	2500
	Archean	Neoarchean	◷	2800
		Mesoarchean	◷	3200
		Paleoarchean	◷	3600
		Eoarchean	◷	4000
	Hadean			~ 4600

Units of all ranks are in the process of being defined by Global Boundary Stratotype Section and Points (GSSP) for their lower boundaries, including those of the Archean and Proterozoic, long defined by Global Standard Stratigraphic Ages (GSSA). Italic fonts indicate informal units and placeholders for unnamed units. Versioned charts and detailed information on ratified GSSPs are available at the website http://www.stratigraphy.org. The URL to this chart is found below.

Numerical ages are subject to revision and do not define units in the Phanerozoic and the Ediacaran; only GSSPs do. For boundaries in the Phanerozoic without ratified GSSPs or without constrained numerical ages, an approximate numerical age (~) is provided.

Ratified Subseries/Subepochs are abbreviated as U/L (Upper/Late), M (Middle) and L/E (Lower/Early). Numerical ages for all systems except Quaternary, upper Paleogene, Cretaceous, Triassic, Permian, Cambrian and Precambrian are taken from 'A Geologic Time Scale 2012' by Gradstein et al. (2012), those for the Quaternary, upper Paleogene, Cretaceous, Triassic, Permian, Cambrian and Precambrian were provided by the relevant ICS subcommissions.

Colouring follows the Commission for the Geological Map of the World (www.ccgm.org)

CCGM CGMW

Chart drafted by K.M. Cohen, D.A.T. Harper, P.L. Gibbard, N. Car
(c) International Commission on Stratigraphy, February 2022

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URL: http://www.stratigraphy.org/ICSchart/ChronostratChart2022-02.pdf

Figure 1.3 International chronostratigraphic chart. *Source:* From the International Commission on Stratigraphy, www.stratigraphy.org, http://www.stratigraphy.org/ICSchart/ChronostratChart2022-02.pdf.

marked by disconformities or unconformities: they may represent long periods of non-deposition or erosion. Indeed, it has been estimated that in many successions, up to 90% of the time involved is not preserved. This topic has been reviewed by Miall (2016) with all other aspects of stratigraphy and Miall et al. (2021) introduced the concept of the 'Stratigraphy Machine' as a framework within which to explain the completeness of the stratigraphic record. All aspects of stratigraphy are covered in Coe (2022).

1.2.5 Sequence Stratigraphy

1.2.5.1 Introduction

Sequence stratigraphy is a methodology which provides a framework for understanding the evolution of depositional systems in space and time, as well as facilitating palaeogeographic reconstructions, providing a degree of prediction of facies away from known areas (useful in exploration for hydrocarbons and some mineral deposits) and enabling correlation on local, regional and even global scales. The approach derives from PR Vail and colleagues in the Exxon Oil Co. in the 1970s when it was realised that sedimentary packages could be distinguished on seismic sections, where reflectors show features including downlap, offlap, onlap, toplap and truncation, with bounding surfaces that could be correlated across large areas. Sequence stratigraphy has been described as 'the study of rock relationships within a chronostratigraphic framework of repetitive, genetically-related strata, bounded by surfaces of erosion or non-deposition, or their correlative conformities'. A more recent description is: 'A stratigraphic sequence corresponds to a cycle of change in stratal stacking patterns, defined by the recurrence of the same type of sequence stratigraphic surface in the rock record' (Catuneanu 2019, 2022). Also of note is that sequences, as well as their component systems tracts and depositional systems, can be observed at all stratigraphic scales. Sequence stratigraphy is not a replacement or an alternative to process sedimentology and facies interpretation, but it is a useful framework within which these aspects can be analysed.

The literature on sequence stratigraphy is vast and many models and concepts have been developed since the 1970s with much jargon introduced (see Table 1.4 for a list of common terms). The debates and criticisms still continue, notably with regard to carbonate sediments (Reijmer 2021). However, there has become a consensus in the last decade following a collective effort (Catuneanu et al. 2011) such that a standardised approach has been advanced for the application of the methodology, especially to siliciclastic facies. A workflow has been devised so that the application of sequence stratigraphy to a succession in an area can follow recommended guidelines enabling a consistent approach. This is basically the subdivision of the stratigraphic section into a succession of genetic units separated by *key sequence stratigraphic surfaces*. Once this has been achieved, then interpretations and correlations can be advanced (see Sections 2.13 and 4.14). These days, sequence stratigraphy is data-led rather than model-led, and the data can come from seismic, well-logs and fieldwork, supported by laboratory analysis.

1.2.5.2 Accommodation and Sedimentation Rates

In a broad sense, stratigraphic successions are controlled by two over-riding factors: accommodation and sedimentation. *Accommodation* is a useful concept: it refers to the space available for sediments, and it can increase (positive) and decrease (negative) in space and time. Accommodation space is created by movements on faults and regional subsidence, rises in sea level (or base level for lakes and rivers), and compaction of sediments. Accommodation space decreases through deposition filling space, tectonic uplift and falls in sea level. In many cases, changes in accommodation space are loosely referred to as changes in relative sea level. The interplay between accommodation and sedimentation results in the stratal stacking patterns and stratigraphic relationships that one can observe in the field and deduce from subsurface seismic and well data.

Rates of sediment supply and production determine how much accommodation space is filled; high rates may fill space leading to sediment bypass. Erosion takes place when the amount of accommodation is negative. Sediment units show different geometries and stacking patterns depending on the interplay of changes in accommodation (A) and sedimentation rate (S), sometimes expressed as the A/S ratio. Three basic sedimentary processes are: *aggradation* (building up), *progradation* (building out, offlap) and *retrogradation* (back-stepping, onlap) (Figure 1.4). These are responses to changes in relative sea level and sediment supply/production. With a relative rise, i.e. a transgression, possibilities are back-stepping/retrograding of environments, or drowning, or seafloor aggradation, depending on the rate of rise vs rate of clastic sediment input or carbonate production. With a stillstand, aggradation and progradation are likely. Thus, there are three basic types of sediment-facies arrangement: *normal regressive*, *forced regressive*, and *transgressive* (Figure 1.4). Each type is defined by specific stratal stacking and facies patterns, and bounded by particular surfaces, as explained below; each package consists of a tract of a correlatable depositional system (i.e. a systems tract).

Table 1.4 Definitions of common sequence stratigraphic terms.

Accommodation: the space available for sediments. It can increase (positive) and decrease (negative) in space and time and is created by movements on faults and regional subsidence, rises in sea level (or base level for lakes and rivers), and compaction of sediments.

Sequence: succession of strata deposited during a cycle of change in stratal stacking patterns, defined by the recurrence of the same type of sequence stratigraphic surface in the rock record. Three main types recognised: Depositional Sequence, T-R Sequence and Genetic Sequence.

Key surfaces: subaerial unconformity (su)–correlative conformity (cc), transgressive surface (ts), maximum flooding surface (mfs), basal surface of forced regression (bsfr), which divide sequences into **systems tracts.**

Subaerial unconformity (su)-correlative conformity (cc): The subaerial unconformity forms under subaerial conditions as a result of fluvial erosion or bypass, pedogenesis, wind degradation, dissolution and/or karstification. The submarine equivalent is the correlative conformity, a surface marking the change from highstand normal regression/forced regression to lowstand facies.

Transgressive surface (ts)(coincides with the **maximum regressive surface, mrs**): stratigraphic surface that marks a change in stratal stacking pattern from lowstand normal regression to transgression.

Maximum flooding surface (mfs): marks a change in stratal stacking pattern from transgression to highstand normal regression, usually the deepest-water facies; distal areas starved of sediment may form a **condensed section (CS)**, overlain by a shallowing-upward succession.

Basal surface of forced regression (bsfr): marks a change in stratal stacking pattern from highstand normal regression to forced regression.

Sequence boundary (sb): separates one sequence from another; which key surface is the sb depends on the sequence model. In the Dep Seq model (Figure 1.7a), the sb is the su-cc; in the T-R Seq, the sb is the mrs-ts, and in the Gen Seq, the sb is the mfs.

Systems Tract (ST): a linkage of contemporaneous depositional systems.

Five are commonly distinguished:

1) falling stage (FSST) (also called forced regressive, FRST): facies deposited during negative accommodation (falling relative sea level), i.e. forced regression (bsfr below, su-cc above).
2) lowstand (LST): facies deposited during relative sea-level low, i.e. normal regression (su-cc below, ts-mrs above).
3) transgressive (TST): facies deposited during positive accommodation (rising relative sea level), i.e. transgression (ts-mrs below, mfs above).
4) highstand (HST): facies deposited during relative sea-level high, i.e. normal regression (mfs below, bsfr above).
5) regressive systems tract (RST): HST+FSST+LST (mfs below, ts-mrs above).

Parasequence (psq): relatively conformable succession of genetically related beds or bedsets, typically metre-scale, which may be bounded by marine flooding surfaces. Also called metre-scale cycle, elementary sequence or high-frequency sequence.

Parasequence set: succession of genetically related parasequences that have a distinctive stacking pattern (e.g. thinning/thickening up); usually bounded by major marine flooding surfaces.

Marine flooding surface (fs): a surface that separates younger from older strata, across which there is evidence of an abrupt increase in water depth.

1.2.5.3 Scale and Order

Sequence stratigraphy is scale independent. It is based on dividing up the stratigraphic record into depositional packages, that is *stratigraphic cycles*. These occur on a variety of scales, referred to as orders (also ranks), from (i) first order, those on a basin scale, several km thick, formed over many 10s to 100s Ma, termed *megasequences*, (ii) second order, those on a continent-seismic scale, many 100s m thick, deposited over several 10s Ma, referred to as *supersequences*, (iii) third order, those on a seismic, large outcrop or mountain-side scale, many 10s to a few 100 m thick, deposited over 0.5–3 Ma, referred to as *sequences*, and (iii) those of a fourth, fifth or sixth order on a metre-scale, deposited over 10s to 100s of kyr, referred to as *parasequences* (also called *metre-scale cycles* or *high-frequency sequences*) (see Table 1.5). These may be grouped into *sets*. In this scheme, the basic building blocks of a sedimentary succession, the individual *beds*, would be sixth–seventh order, i.e. deposited in hours/days (as by a storm) up to a few 1000 years. Different factors, themselves operating on different scales, are involved in forming these sediment units, notably tectonics, sea-level change, climate, and depositional processes.

Sedimentary facies as observed in the field will mostly be contained within the framework of third-order sequences, in most cases with higher order stratal units. Documenting facies and bedding relationships, stacking patterns and geometries, and vertical and lateral changes in bed thickness, grain size, facies, fossil-trace fossil occurrence etc., enable a sequence stratigraphy to be devised. See Tucker (2011) for guidance on field documentation.

1.2.5.4 Stratigraphic Sequences, Key Surfaces, Systems Tracts

A stratigraphic sequence, then, corresponding to a cycle of change in stratal stacking patterns, is delimited on the basis of *key surfaces*, basically *unconformities* and *flooding surfaces*. These key surfaces separate particular packages of rock

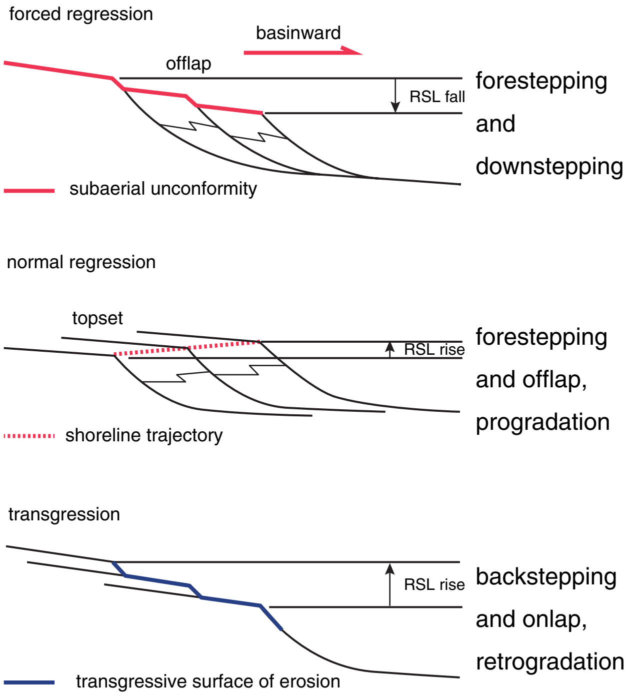

Figure 1.4 The three basic patterns of relative sea-level change: forced regression (RSL falling), normal (depositional) regression (stillstand to early rise) and transgression (RSL rising), which generate characteristic stratal stacking patterns. *Source:* After Catuneanu et al. (2011).

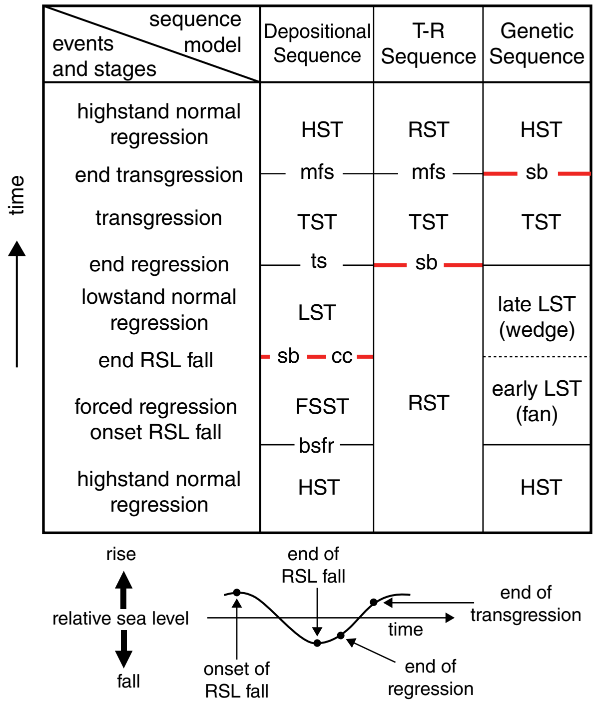

Figure 1.5 Systems tracts and key surfaces for 3 sequence models: the Depositional Sequence, Transgressive-Regressive Sequence and Genetic Sequence. Abbreviations in Figure 1.2, RSL – relative sea level. *Source:* Modified from Catuneanu et al. (2011).

Table 1.5 Sequence stratigraphic units, their rank (order) and typical duration. Ma = millions of years, kyr = thousands of years, yr = years.

Typical duration	Sequence rank	Stratigraphic unit
10^8 yr 100s Ma	**First-order** Basin-fill	**Megasequence**
10^7 yr 10s Ma	**Second-order** Continent scale	**Supersequence**
10^6 yr 0.5–3 Ma	**Third-order** Seismic-scale/ mountain-side scale	**Sequences:** Depositional Sequence or TR-Seq or Genetic Seq
10^4–10^5 yr 20–400 kyr	**Fourth-fifth order** Sub-seismic/ outcrop scale	Parasequence or Metre-scale cycle or High-frequency sequence and their sets
1–10^3 yr 1–1000 yr	**Sixth-seventh order** Outcrop scale	Laminae, beds, bed-sets

termed *systems tracts*, that is facies deposited in the same time interval in related contemporaneous environments. The key surfaces are used to define the time relationships between rock packages. Several sequence stratigraphic models have been proposed over the last few decades, with two currently widely used: the Depositional Sequence (*Dep Seq*) and the Transgressive-Regressive Sequence (*T-R Seq*), differing basically in their internal arrangement of systems tracts (Figures 1.5 and 1.6); there is a third model, the *Genetic Sequence*, which has been used notably for deeper-water clastics. The current wisdom, following a recommended workflow (Catuneanu et al. 2011; Catuneanu 2017, 2019, 2022), is to document the key surfaces, facies and geometries from the assembled data and then use the model that is most appropriate to the succession being studied. This can depend on the data available, the depositional setting and facies: e.g. marine versus non-marine, clastic vs carbonate, shallow vs deep, and your point of view.

An *unconformity* (taken as a *sequence boundary* (sb) in the *T-R Seq* and *Dep-Seq* models is a surface separating younger from older strata along which there is evidence of subaerial exposure; it will pass laterally (basinwards) into a *correlative conformity (cc)*. Major drowning surfaces have also been interpreted as sequence boundaries, notably in the third model, the Genetic Sequence, consisting of a RST-TST (Figure 1.5), since in some data sets, they are quite easy to recognise.

The *systems tracts* (a linkage of contemporaneous depositional systems and their sediments) are deposited during a specific part of a cycle of change in accommodation,

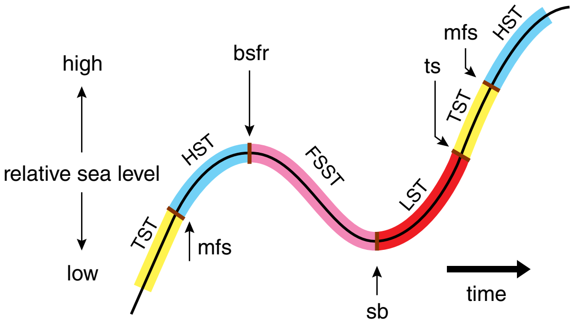

Figure 1.6 The systems tracts and key surfaces of a cycle of accommodation/relative sea-level change as used in the Depositional Sequence model. Systems tracts: LST – lowstand, TST – transgressive, HST- highstand, FSST – falling stage. Key surfaces: sb – sequence boundary, ts – transgressive surface, mfs – maximum flooding surface, bsfr – basal surface forced regression.

namely, the lowstand (LST), transgressive (TST), highstand (HST) and falling stage (FSST, also called forced regressive, FRST) systems tracts (see Figures 1.5, 1.6 and 1.7a). In the T-R sequence model, the HST+FSST+LST constitutes the regressive systems tract (RST) (Figure 1.5). Apart from the unconformity–correlative conformity (usually taken at the base of the LST), other key surfaces are the *transgressive surface* (ts), which may be coincident with the subaerial unconformity in more proximal (landward) parts of a basin, at the base of the TST; the *maximum flooding surface* (mfs), that separates the TST from the HST, and the *basal surface of forced regression* (bsfr), between the HST and FSST, at the start of sea-level fall/decreasing accommodation, i.e. forced regression (Figure 1.6). In more distal parts of a basin, there is commonly a *condensed section* (CS), equivalent to the upper part of the TST, the mfs and the lower part of the HST, as a result of sediment starvation there (Figure 1.7a).

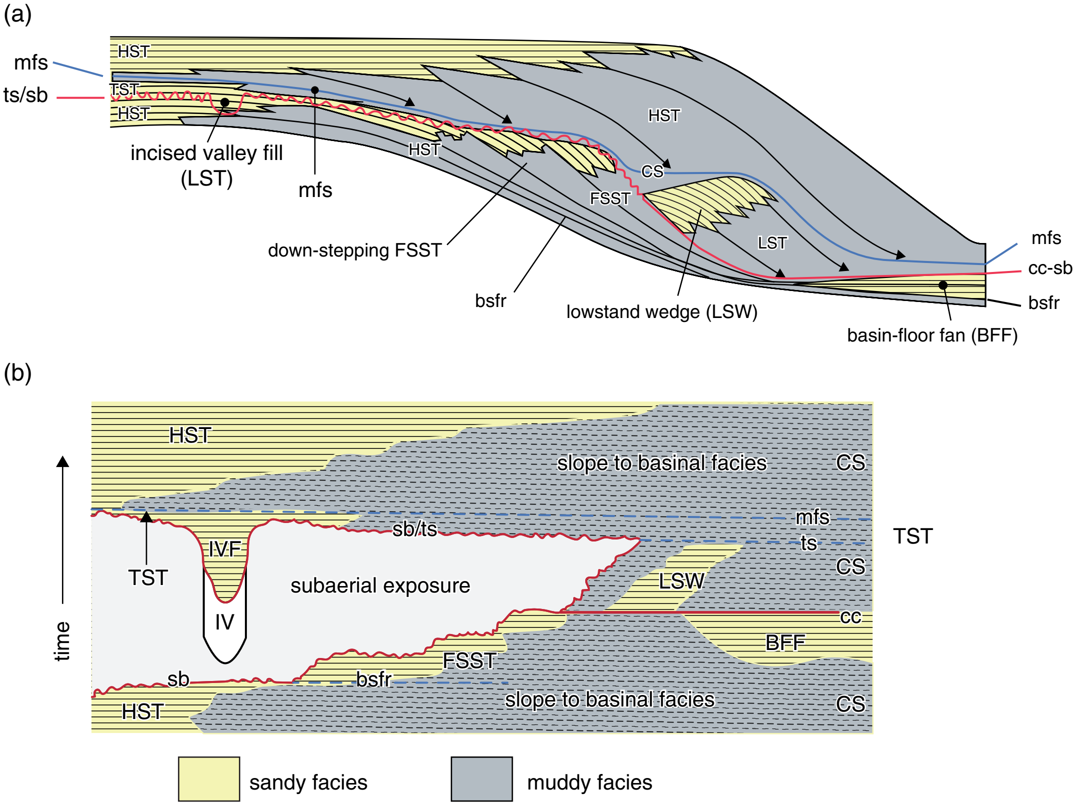

Figure 1.7 (a) Schematic Depositional Sequence model showing the arrangement of systems tracts and key surfaces, and typical location of sand (yellow) and mud (grey). However, in reality, there are many other possible patterns, some particular to clastic and others to carbonate and mixed successions. Systems tracts: LST, TST, HST, FSST = lowstand, transgressive, highstand and falling stage; IVF = incised valley fill, cut during the FSST, filled during the LST; CS = condensed section. Key surfaces: sb = sequence boundary and its correlative conformity, cc; ts = transgressive surface; mfs = maximum flooding surface; bsfr = basal surface forced regression. *Source:* Modified from Tucker (2011). (b) Chronostratigraphic diagram for the succession shown in Figure 1.7a. This diagram shows the distribution of sediment in time and space, which brings out the interval of subaerial exposure. Note the incised valley (IV) is shown cut during the sea-level fall (forced regression) and filled (IVF) during the lowstand to transgressive phase. Abbreviations as in Figure 1.7a. *Source:* Modified from Tucker (2011).

In a normal regression, also called depositional regression, a shoreline-tidal flat or shelf margin migrates seawards/basinwards (i.e. progrades) creating a shallowing-upward (regressive) sediment package. This is typical of the LST and HST, and sediments could exhibit an offlapping–downlapping geometry with clinoforms. In a forced regression, relative sea level is falling, so erosion takes places and incised valleys may be cut (and later filled, an IVF), but if there are pauses during the fall, then new shorelines may be established so that sediments are deposited and they may be preserved (i.e. the FSST). These would show a down-stepping geometry (as in Figure 1.7a). During a transgression, a relative sea-level rise, shorelines backstep; a shelf is flooded, sediments may show retrogradation; onlap and deepening up (TST) or there may be no sediments deposited, i.e. drowning, if the transgression is rapid. Sediments deposited may be thin, the result of reworking, or they may aggrade (as reefs can), all depending on the ratio of sea-level rise (accommodation increase) to sediment input/production (the A/S ratio).

Figure 1.7a presents a model for a 4-systems tract Depositional Sequence. However, not all systems tracts are developed in every case, and thicknesses may vary significantly. In both clastics and carbonates for example, TST sediments may be thin from rapid flooding (but in carbonates, they could be thick from upward reef growth!); FSST sediments may be absent; lowstand deposits may be restricted to IVFs or there could be a huge megabreccia, usually in carbonates, from shelf-margin collapse from the sea-level fall. With clastics, much sediment is deposited at the shelf margin-slope during the LST, as rivers supply sediment farther out on to the shelf and turbidites are deposited in the basin. By way of contrast, with carbonates formed in a tropical factory, more sediment is commonly deposited during the highstand (‘highstand shedding’) as a result of a productive factory on the flooded shelf. For two outcrop examples: Figure 1.8 shows a section in the Cretaceous of eastern Spain where all four systems tracts of a sequence can be recognised from the facies geometries and key surfaces clearly displayed there; and Figure 1.9 shows a transgressive to highstand to falling stage to lowstand channel (IVF) to the next transgressive package in a mid-Carboniferous mixed clastic-carbonate succession from NE England. See Sections 2.13 and 4.14 for further information.

1.2.5.5 Metre-Scale Cycles, High-Frequency Sequences, Parasequences

Many sequences, especially in platform carbonates and shoreline-shelf clastics, are composed of several to many *metre-scale cycles*, termed *parasequences* (originally defined by *flooding surfaces* at their bases), also referred to as

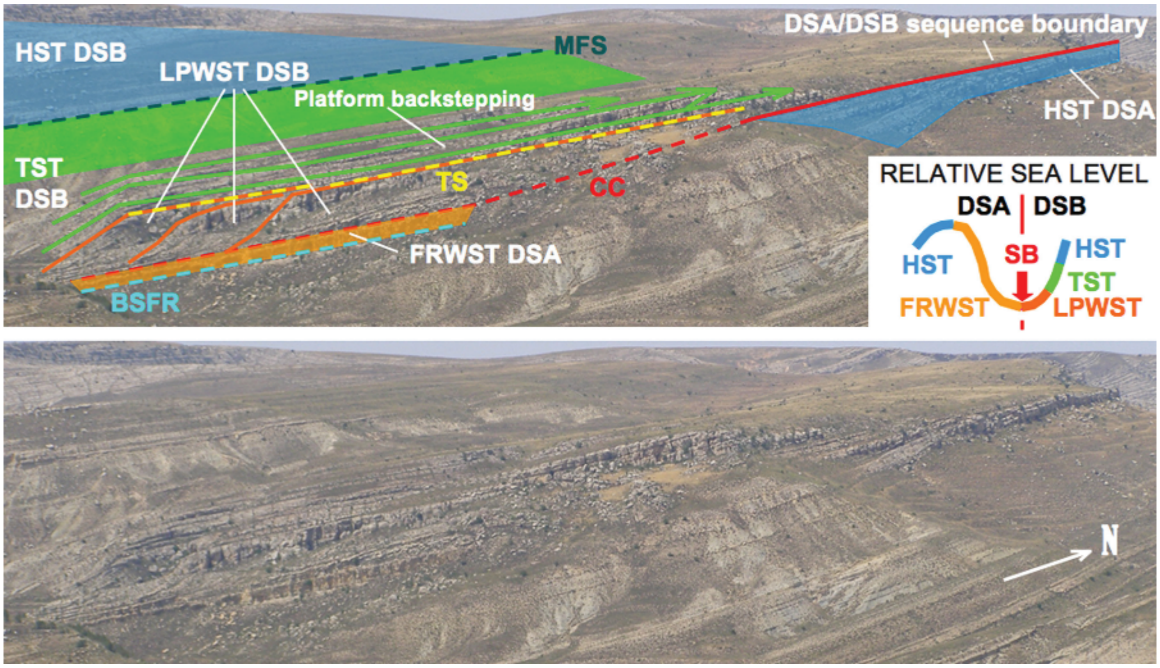

Figure 1.8 Sequence stratigraphy in the field: two middle Cretaceous carbonate depositional sequences (DSA and DSB) from the Maestrat Basin, eastern Spain. Abbreviations: ST – systems tract; LPW – lowstand prograding wedge; T – transgressive; H – highstand; FRW – forced regressive wedge; BSFR – basal surface of forced regression; CC – correlative conformity; TS – transgressive surface. See Bover-Arnal et al. (2009) for further information. Image courtesy of Telm Bover-Arnal.

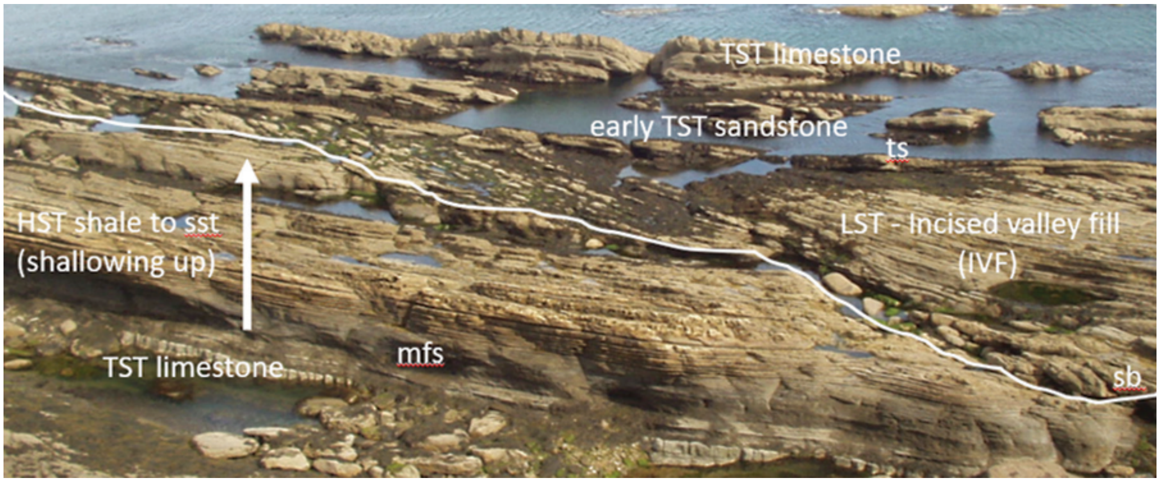

Figure 1.9 Sequence stratigraphy in the field: a view of mid-Carboniferous strata showing a lower transgressive limestone overlain by a highstand shale to sandstone coarsening-upward package from a prograding shoreline, into which a clear fluvial channel (an incised valley) has cut down during a forced regression/sea-level fall. This channel was then filled with a lowstand coarse sandstone, an IVF, overlain by a laterally extensive early transgressive sandstone which passes up into the upper transgressive limestone. Howick, Northumberland, UK.

Figure 1.10 Metre-scale parasequences (the beds, a), cliff 7 m high, bundled into parasequences sets in (b), shown by the arrows and highlighted by the lines of snow. Triassic, Brenta Dolomites, Italy. Cliff 200 m high.

(a)

(b)

high-frequency sequences, deposited over 10s to 100s of 1000s of years. Systems tracts can be defined by the *stacking patterns* of the parasequences, e.g. whether they show a thinning-up trend, which would indicate a TST, or a thickening-up trend, typical of a HST, along with lateral and vertical facies and grain-size changes, all reflecting the longer term pattern of accommodation/relative sea-level change (as in *composite eustasy,* Figure 1.2). In some cases, parasequences are bundled into groups of several to up to five cycles; such *parasequence sets* could reflect the interaction of two sea-level rhythms, such as produced by orbital forcing from the precession (20 kyr), obliquity (40 kyr) and eccentricity (100 kyr) astronomic Milankovitch rhythms. See Figure 1.10 for an example from the Triassic of the Brenta Group, Dolomites, Italy. However, internal processes of deposition (autogenic/autocyclic) can also produce these patterns (see Section 4.14.4).

The filling of accommodation space is determined by *base level*. Base level controls the depth down to which erosion occurs and thus controls the position of sequence boundaries. Base level determines the upper surface of deposition. In marine successions, sea level is generally base level, so sequence boundaries usually show the effects of subaerial exposure or soil formation. However, in high-energy shelf/ramp locations (shaved shelves), fairweather wave base (FWWB) or storm wave base (SWB) is base level, so that the sequence boundary is developed in shallow-to-moderate depth facies; this may well then be a hardground, overlain by deeper-water deposits.

1.2.6 Diagenesis

Considerations of sedimentary rocks do not stop with environmental interpretations. There is a whole story to be told of events after deposition, that is during *diagenesis*. It is during diagenesis that an indurated rock is produced from an unconsolidated, loose sediment. Diagenetic processes begin immediately after deposition and continue until metamorphism takes over; this is when reactions are due to elevated temperatures (in excess of 150–200 °C) and/or pressures. A distinction is made between early diagenetic events, taking place from sedimentation until shallow burial, and late diagenetic events occurring during deep burial and subsequent uplift.

Diagenetic processes which can be introduced here but which are considered further in later sections (see Sections 2.9, 3.6 and 4.9) are compaction, recrystallisation, dissolution, replacement, authigenesis and cementation. Compaction is both a physical and chemical process arising from the mass of the overlying sediment, which causes water to be squeezed out and grains to become closer packed. Some grains and minerals deposited in a sediment or forming a sediment are unstable and during diagenesis they may recrystallise (i.e. their crystal fabric changes but the mineralogy is unaltered) or they may undergo dissolution and/or be replaced by other minerals. The effects of dissolution and replacement are common in limestones, sandstones and evaporites. The formation of dolomite largely takes place by replacement of limestone. The precipitation of new minerals within the pore spaces of a sediment is referred to as authigenesis, and if precipitated in sufficient quantity, then cementation of the sediment results. Concretions and nodules such as commonly occur in mudrocks form through localised mineral precipitation. The ions for cementation are derived from pore waters and grain dissolution.

In the same way that relative sea-level changes and global sea-level stand are a fundamental control of many aspects of the deposition of sedimentary rocks, they can also account for the major diagenetic events. Much early diagenesis relates to sequence boundaries, produced by second- to third-order sea-level fluctuations, but climate (arid vs humid) is important at this stage too. The nature of near-surface diagenesis very much controls the path of later (burial) diagenesis.

Diagenetic processes are important for several reasons. They can considerably modify a sediment, both in terms of its composition and texture, and in rare cases, original structures are completely destroyed. Diagenetic events also affect a sediment's porosity and permeability, properties which control a sediment's potential as a reservoir for oil, gas or water and for carbon dioxide or hydrogen storage.

1.3 Methodology

The study of sedimentary rocks invariably begins in the field but after that there are several avenues which can be explored, depending on the objectives of the study and the interests of the investigator. Samples collected can be examined on a macro-, micro- and nano-scale. Sophisticated techniques and machines can be used to discover a sediment's mineralogy and geochemistry. Experiments can be devised to simulate the conditions of deposition. Data collected in the field or laboratory can be subjected to statistical tests and computer analysis. Computer modelling can be used to simulate deposition and diagenesis. Account should be taken of any existing literature on the rocks being studied and of descriptions of similar rocks and facies from other areas, together with their probable modern analogues. With all this information at hand, the rocks under consideration can then be interpreted with regard to origin, depositional process and environment, palaeogeography, diagenetic history and possible economic significance and potential.

1.3.1 In the Field

The main point about fieldwork is being able to observe and record accurately what you see. With a little field experience and some background knowledge, you will soon know what to expect and what to look for in a certain type of sedimentary rock or particular facies. It is obviously important to appreciate the significance of the various sedimentary features you see, to know which are environmentally diagnostic, for example, and also to know how they can be used to get maximum information: what to measure, what to photograph, what to collect. The field study of sedimentary rocks is discussed in Coe (2010) and Tucker (2011); the description and interpretation of sedimentary structures are covered in Collinson and Mountney (2019) and the statistical analysis of Earth Science data sets is covered by Davis (2002) and Borradaile (2003).

The study of sedimentary rocks in the field requires the initial identification of the lithology (often with the aid of a hand-lens) in terms of composition, grain size, texture and fossil content (see Table 1.6). These attributes can be confirmed and quantified later in the laboratory. Sedimentary

Table 1.6 Scheme for the identification and description of sedimentary rocks in hand specimen.

Hand-specimen description of sedimentary rocks

Examine the rock for colour, texture, composition, sedimentary structures and fossils and then identify the sedimentary rock type. If there is enough evidence, give an interpretation of the depositional environment and diagenesis of the sediment.

Colour:

It should be easy to describe the colour. The colour is usually a reflection of the organic content (grey to black with increasing organic matter) and oxidation state of iron: ferrous iron, occurring in clay minerals (e.g. chlorite) and iron minerals (such as berthierine-chamosite) gives a green colour; ferric iron, occurring in iron minerals, gives red (in hematite) and yellow-brown colours (in goethite-limonite and ferrihydrite). Some sedimentary minerals may have a particular colour, such as the white of pure anhydrite and gypsum.

Texture:

Determine the grain size of the rock with a hand-lens; look at the grain shape: rounded or angular? Look at the grain sorting, well or poorly sorted. Look for the nature of the contacts between the grains (if visible), and for any preferred orientation of the grains (fabric).

Composition:

Identify the composition of the sediment using a hand-lens.

Is it sandstone? – made of quartz, feldspar, rock fragments; if so, is it a quartz arenite, litharenite, arkose or greywacke (the 4 common types)?

Is it a limestone (fizzes with acid)? – made of bioclasts (fossils), ooids, peloids; if so, is it a grainstone, packstone, wackestone, mudstone or boundstone?

Is it a dolomite (dolomitised limestone, fizzes little)? crystalline, poorly preserved fossils and structures, pale brown-buff colour.

Is it a mudrock? If so, is it fissile (a shale) or not (mudstone). Any nodules present? Composition?

Is it a conglomerate? Determine whether monomictic or polymictic (from clast composition), orthoconglomerate or paraconglomerate (from texture).

Less common sedimentary rock types are evaporites (may be salty or soft), cherts (hard and splintery) and ironstones (red or green, heavy, oolitic).

Sedimentary structures:

Look for structures such as bedding, lamination, cross-bedding, cross-lamination, parting lineation, sole structures, burrows, nodules, stylolites etc.

Fossils:

If present (hand-lens may be needed to see them), try and identify them to phylum level (further if you can). Also look for the preservation of the fossils (shells articulated, broken, bored, dissolved etc.).

Interpretation:

From all the evidence gathered, suggest a rock type and possibly depositional environment. There may be several alternatives. Comment on the rock's diagenesis: cementation, compaction, replacement etc., and near-surface versus burial diagenetic effects.

structures are usually described and measured in the field because of their size. It is relatively easy to see structures in hand specimen or block, but those on the scale of a quarry or cliff face are easily overlooked. So, observe on all scales. It is important to note the size and orientation of structures. Many sedimentary structures can be used for palaeocurrent analysis and these and others reflect the processes operating in the environment (see Sections 2.3, 2.4, 3.2 and 4.8). Sedimentary structures should be described within their lithological context; many are related to grain size or composition, for example. These days, considerable emphasis is being placed on the larger scale geometric relationships of sedimentary strata, seeking the onlap, offlap, downlap (etc.) arrangements (see Figure 1.4), which reflect long-term relative sea-level changes. In mountainous regions of good exposure, these seismic-scale relationships can be observed directly; in other instances, they may need to be mapped out. The identification of sequence boundaries is also important, since many vertical and lateral facies patterns can be explained by a sequence stratigraphic approach, and much diagenesis ties into these boundaries too.

One of the best methods of recording sedimentary rocks is to construct a log of the section. Basically, measure the thickness of each bed or facies unit, note its composition, grain size, colour, sedimentary structures, fossils and any other features. If a palaeocurrent measurement can be taken, record this too. A *graphic log* can be drawn up in the field using an appropriate vertical scale for the sediment thickness and a horizontal scale for the sediment grain size (for examples, see Figures. 2.64, 2.66, 2.68 and 2.74). Different types of shading can be used for the various lithologies and symbols and abbreviations for the sedimentary structures and fossils (see Coe 2010; Tucker 2011). The value of such graphic logs lies in the immediate picture which is obtained of the vertical succession of facies. In logging a section, the lateral extent and continuity of beds must be taken into account. Many beds are actually lenticular.

Although in the field study of sedimentary rocks, it is likely that a geological map will be at hand, some detailed mapping of small areas could well be required to ascertain the relationships between facies and facies packages, and the effects of local structural complications.

In many cases, the interpretation of sedimentary rocks hinges on the fieldwork, so much care and attention should be paid to it. Localities need to be visited several times; it is amazing how many new things you can see at an exposure on a second or third visit.

1.3.2 In the Laboratory

A great deal can be done with sedimentary rocks in the laboratory. Starting with a hand specimen, cutting and polishing a surface may reveal sedimentary structures poorly displayed or invisible in the field. With limestones, etching with acid and staining a surface may further enhance the structures. With unconsolidated sediments and sedimentary rocks that are readily disaggregated, sediment grain size can be measured through the use of sieves and sedimentation chambers (see Section 2.2.1). The heavy minerals (Section 2.5.6) can be extracted from loose sediment using heavy liquids, but this can be hazardous; take care!

Much detailed work is undertaken on thin-sections cut from sedimentary rocks or resin-impregnated unconsolidated sediments. With limestones, acetate peels are frequently used and the staining of these and thin-sections with Alizarin Red S and potassium ferricyanide helps identify the carbonate minerals present. Stains can also be used for feldspars in terrigenous clastic sediments. There are a relatively small number of common minerals in a sedimentary rock and with a little experience, it is not necessary to examine their optical properties to identify them each time. The properties of the common sedimentary minerals are given in Table 1.7. The precise composition of many sedimentary rocks (the sandstones and limestones in particular), which enables then to be classified, is obtained from microscopic studies by the use of a point counter. Several hundred grains are identified as the thin-section is systematically moved across the microscope stage. Grain sizes of indurated silt- to sand-sized rocks are measured from a thin-section or peel using a calibrated eye-piece graticule. Grain shape and orientation can also be assessed. Many aspects of diagenesis in sandstones, limestones and evaporites are deduced from thin-section studies. Use of a cathodoluminoscope, wherein a rock slice is bombarded with electrons which cause luminescence, can reveal details of cements and overgrowths (see Figures 4.82 and 4.92 for examples), and UV fluorescence is also useful for identifying organic matter as well as revealing 'hidden textures'. In view of the interest in porosity and reservoir potential, many sedimentary rocks are now routinely impregnated with a resin containing a blue dye before they are sectioned (e.g. Figures 2.75a and 4.18). See chapters in Tucker (1988) for details of these techniques.

In recent years, much sedimentological work has been carried out with the scanning electron microscope (SEM). This instrument allows examination of specimens at very high magnifications; features down to 0.1 μm (i.e. 100 nm) can be seen. The SEM is especially useful for fine-grained sedimentary rocks, such as mudrocks and cherts, and for cements in sandstones and limestones; in some cases, relics of microbes can be seen. For examples, see Figures 2.86, 2.89, 4.43 and 4.44. There are two modes of SEM operation: SE (secondary electrons) and BSE (back-scatter): the first provides a straightforward view of the sample; the second reflects the atomic number of the material, giving an image with shades of grey (lighter colour = higher atomic no.), such that minerals can be distinguished, e.g. calcite from dolomite. Bacteria, composed of light elements (C, H, O), are well seen in SE, but do not appear with BSE, unless mineralised. The BSE mode is useful for textural studies of mudrocks in particular (see Figure 3.11). Recently, new generations of SEM with energy dispersive X-ray analysis (EDX) tools, such as QEMSCAN and Mineralogic, have been developed permitting automated mineral identification and detailed quantitative mapping of areas of interest (see Fig. 2.75a and b).

For mineral identification in fine-grained sediments and sedimentary rocks, X-ray diffraction (XRD) is widely used. Clay minerals in mudrocks are invariably analysed in this way.

Geochemical analyses of sedimentary rocks, especially limestones and mudrocks, can give useful and vital information on the environment of deposition and path of diagenesis. Major and minor elements, including rare

Table 1.7 Optical properties of common minerals in sedimentary rocks as observed with the petrological microscope.

Mineral	Chemical formula	Crystal system	Colour	Cleavage	Relief
Quartz	SiO_2	trigonal	colourless	absent	v. low (+)
Microcline	$KaAlSi_3O_8$	triclinic	colourless	present	low (−)
Orthoclase	$K(Na)AlSi_3O_8$	monoclinic	colourless	present	low (−)
Albite	$Na(Ca)AlSi_3O_8$	triclinic	colourless	present	low (−)
Muscovite	$KAl_2(OH)_2AlSi_3O_{10}$	monoclinic	colourless	planar	moderate
Biotite	$K_2(Mg,Fe)_2(OH)_2AlSi_3O_{10}$	monoclinic	brown to green	planar	moderate
Chlorite	$Mg_5(Al,Fe)(OH)_8(AlSi)_4O_{10}$	monoclinic	green	planar	low
Kaolinite	$Al_2O_32SiO_2.2H_2O$	triclinic	colourless-yellow	planar	low (+)
Illite	$KAl_2(OH)_2[AlSi_3(O,OH)_{10}]$	monoclinic	colourless-yellow	—	low (+)
Montmorillonite	$(MgCa)O.Al_2O_3.5SiO_2.nH_2O$	monoclinic	colourless-pink	—	low (−)
Berthierine -Chamosite	$Fe_3^{2+}Al_2Si_2O_{10}.3H_2O$	monoclinic	green	—	moderate
Glauconite	$KMg(Fe,Al)(SiO_3)_6.3H_2O$	monoclinic	green	planar	moderate
Aragonite	$CaCO_3$	orthorhombic	colourless	rectilinear	moderate
Calcite	$CaCO_3$	trigonal	colourless	rhombic	low to high
Dolomite	$CaMg(CO_3)_2$	trigonal	colourless	rhombic	low to high
Siderite	$FeCO_3$	trigonal	colourless	rhombic	low to high
Gypsum	$CaSO_4.2H_2O$	monoclinic	colourless	planar	low
Anhydrite	$CaSO_4$	orthorhombic	colourless	rectilinear	moderate
Halite	NaCl	cubic	Colourless	rectilinear	low
Collophane	$Ca_{10}(PO_4,CO_3)_6F_{2\text{–}3}$	a mineraloid	shades of brown	—	moderate
Pyrite	FeS_2	cubic	opaque	—	—
Hematite	Fe_2O_3	hexagonal	opaque	—	—
Magnetite	Fe_3O_4	cubic	opaque	—	—

earth elements (REEs) are mostly determined by inductively coupled plasma optical-emission spectroscopy (ICP-OES) or mass spectrometry (ICP-MS) and X-ray fluorescence (XRF). On the scale of individual grains and crystals, the electron microprobe or laser ablation with ICP-MS is used to determine trace elements on areas only a few microns across. A consideration of the isotopes of such elements as oxygen and carbon, measured with a mass spectrometer, is a powerful tool in the study of limestone and chert diagenesis. Isotopes of other elements (e.g. Mg, Fe, S and Sr) are increasingly used as well. Analysis of fluid inclusions in calcite, quartz and halite crystals also provides important data on the temperature and salinity of pore waters from which the minerals were precipitated.

One further laboratory approach has been to carry out experiments to determine the conditions under which sedimentary structures, grain types, minerals, etc., were formed. Perhaps the best known are those involving laboratory channels or flumes, where the effects of water flowing over sand have been monitored (Section 2.3.2), and the attempts to precipitate dolomite and $CaCO_3$ using microbes.

Once the data on the sedimentary rocks under investigation have been gathered, then the interpretations can begin. Information on sediment composition and microfacies can be combined with field data to deduce the environment and conditions of deposition. Petrographic studies of sandstones can give information on the geology of the source area (its provenance) and the plate-tectonic setting. Diagenetic studies can be integrated with facies and burial history to account for the patterns of cementation and dissolution, and porosity evolution. Statistics are being increasingly used to evaluate interpretation of sedimentological, petrographic and geochemical data. Stratigraphic forward modelling of successions and simulations of depositional and diagenetic processes are increasingly used to further unravel the controlling factors.

Birefringence	Other features	Form and occurrence	See sections
weak		as detrital grains (monocrystalline and polycrystalline types), cements and replacements: fibrous quartz (chalcedony), microquartz, megaquartz	2.5.2, 2.9.2 4.11, 9.2
weak	grid-iron twinning	as detrital crystals, also authigenic,	2.5.3
weak	simple twinning (Carlsbad)	commonly altered to clays, so appearing dusty	2.9.4
weak	multiple twinning		
strong	parallel extinction	common detrital minerals occurring as flakes	2.5.4
strong	parallel extinction		3.4.3
weak	best identified through X-ray diffraction since usually so fine-grained	occur as detrital minerals, particularly in mudrocks, also as cement (as in sandstone) and replacements, such as of feldspars and volcanic grains	2.9.5
weak			3.4.1
strong			
moderate			
weak		ooids and mud in ironstones	6.4.4
moderate		forms synsedimentary grains	6.4.4
moderate	can be distinguished by staining (Section 4.2.2)	forms grains, matrix, cement and replacements in limestones, dolomites, sandstones (etc.)	4.3, 4.9, 4.10, 2.9.3
extreme			
extreme			
extreme	alters to brown colour	fine and coarse crystals in ironstones	6.4.2
weak		anhedral to euhedral crystals	5.3
strong	parallel extinction	equant to lath-shaped crystals	
—	may have fluid inclusions	may be coarsely crystalline	5.4
isotropic or weak	if bone – organic structure	forms ooids, pellets, bones, some shells	7.2
—	yellow in reflected light	aggregates and cubic crystals, authigenic	6.4.3
—	red-grey in reflected light	cryptocrystalline, a pigment and replacement	6.4.1, 2.9.6
—	grey-black in reflected light	cryptocrystalline, detrital	6.4.1

1.3.3 The Sedimentological Literature

However good your field and lab work, it needs to be supported with a knowledge of the literature on the subject. Publications on the petrology of sedimentary rocks go way back into the nineteenth century, but most advances have come in the past five decades and in fact the literature has ballooned in the last decade. There are many textbooks available on particular aspects of sedimentary petrology in print and some of the more recent ones are in digital format. Collections of papers on specific topics within sedimentology are published by the learned societies, notably the Special Publications of the Society of Sedimentary Geologists (formerly Society of Economic Paleontologists and Mineralogists, SEPM), the International Association of Sedimentologists (IAS), and the Geological Society of London; also check the Memoirs of the American Association of Petroleum Geologists (AAPG).

Most research papers, of course, are published in the learned journals. Interested students should set up alerts for papers as they are published in the various journals. The three principal periodicals are the *Journal of Sedimentary Research (formerly Journal of Sedimentary Petrology)*, *Sedimentology* and *Sedimentary Geology*, published by SEPM, IAS and Elsevier, respectively. Other journals devoted to sediments or containing many sedimentological papers are: *Basin Research*, *Bulletin of the Geological Society of America*, *Bulletin of the American Association of Petroleum Geologists*, *Earth-Science Reviews, Facies, Frontiers in Earth Sciences, Geology, Journal of Geology*, *Marine Geology*, *Marine & Petroleum Geology*, *Petroleum Geoscience, Palaeogeography Palaeoecology Palaeoclimatology*, *Palaios* and *The Depositional Record*. In addition, there are many other journals which often contain relevant articles. Most journals are available *online* through a library's website and many individual papers are simply available on the internet through Google Scholar or similar search engines.

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