Physics of Sedimentology

Textbook and Reference

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DIE FACHBUCHHANDLUNG

Sorting Out and Mixing

2.1
Bulk Minerals

Sedimentary particles come mainly from the lithosphere, the hydrosphere, and the biosphere, and they are detrital, chemical, and biogenic in origin.

All rocks in the lithosphere could yield sedimentary detritus. Where mechanical erosion is dominant, sedimentary particles are rock fragments, also called *lithic* grains. Fine-grained rocks, such as chert and andesite, make good rock fragments. Sediments containing abundant lithic grains are commonly considered *immature*; the term immaturity refers to the fact that the detritus has not undergone extensive "wear and tear". A rock consisting of chert detritus records, however, a very different history from the rock consisting of andesite detritus. Chert-pebble conglomerates are not considered immature. In fact, the presence of chert grains to the exclusion of other more easily weathered grains testifies to intense chemical weathering in the source terrane. Only rock fragments consisting mainly of easily weathered minerals, such as feldspars, make immature sediments.

Perfectly *mature* detrital sediments are quartz sandstones, which are made up almost exclusively of quartz. Some have been derived from older quartz-rich sandstones; they are *polycyclic*, referring to the "reincarnation" of old detritus in newer sediments. Others owe their origin to the elimination of less resistant minerals in source areas, during transport, and/or after deposition.

Francis Pettijohn suggested the idea that the relative abundance of feldspars (F) and quartz (Q) is a *maturity index*. Igneous rocks have more feldspar than quartz, and their ratio $F/(F + Q)$ is more than 50. Most sedimentary rocks, with their detritus derived from weathered terranes, have a feldspar content considerably less than 50. Feldspar-rich sandstones are immature. They are called *arkoses*, if their $F/(F + Q)$ is greater than 20 or 25; those containing less feldspars are *feldspathic* sandstones.

Almost a century ago, an English geologist William Mackie studied the percentage of feldspar in river and beach sands. He found a downstream

decrease in sands of River Findhorn (Scotland). The percentage of feldspar is at

- Dulsie Bridge   42%
- Logie Bridge   31%
- Ferness   21%
- Culbin at sea   8%

This dramatic decrease within a short distance downstream was once considered evidence of elimination of feldspar by abrasion during river transport. The deduction seemed logical and reasonable. Another explanation is that the decrease of the feldspar content has resulted from dilution by quartz-rich sands transported down the tributaries.

Several sedimentologists investigated the problem during the following decades, and the final verdict was handed down by R. Dana Russell in 1937, when he made a systematic study of the mineralogy and texture of the Mississippi River sediments. His results are illustrated in Fig. 2.1. The decrease of the feldspar content in Mississippi River sands down the more than 1 700-km-long course is trivial, and this decrease can be explained by the dilution effect. Russell concluded, therefore, that the selective destruction of less resistant minerals during river trans-
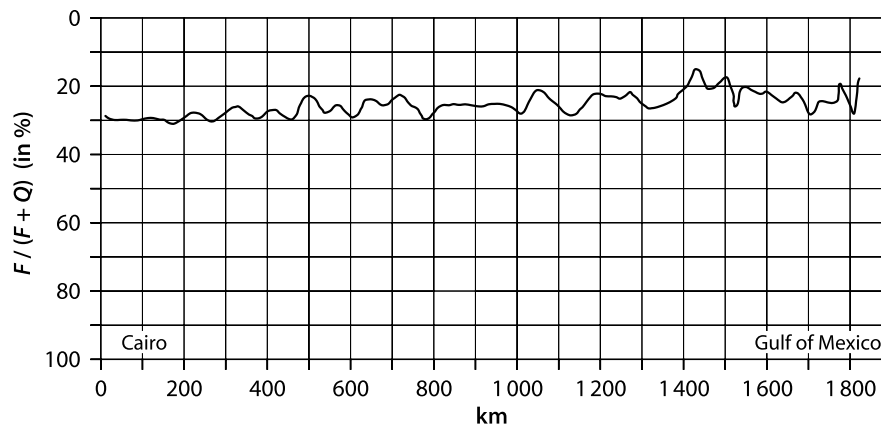
Fig. 2.1. Downstream variation of the feldspar content in the Mississippi River sands (modified after Russell 1937). The feldspar content of the river sands has changed very little, from about 30% to about 25%, in the 1 700-km plus course of transport from Cairo, Illinois to the river mouth. The slight variation has been explained by the dilution effect, when the sands from the Upper Mississippi are mixed with those poor in feldspar derived from the coastal tributaries of the Mississippi. This study by R. Dana Russell falsifies the assumption that the mineral composition of a sand is modified by abrasion during river transport

port is insignificant. Quartz, the most persistant detrital mineral, is common in mature sands not because of exceptional resistance to abrasion during transport, but because of susceptibility of other minerals to chemical weathering in source terranes.

So the pounding and grinding during river transport did little to eliminate the less resistant minerals such as feldspars. What was then the effect of wave actions on a beach. When I left the university in 1954, my first professional job was to compare the mineral composition of beach sands at various parts of the Gulf Coast, in order to evaluate the influence of abrasion during marine transport. This was my first introduction to process-oriented geology. The results of my investigations are shown in Fig. 2.2.

A first glance seems to support the postulate of feldspar destruction during longshore transport. The beach sands at the mouth of the Mississippi Delta have about the same composition as river sands of the lower Mississippi, and the feldspar content decreases westward, in the direction of transport. Such a decrease could be attributed to mechanical attrition. A close analysis revealed, however, that the decrease of the feldspar content, as expressed by the $F/(F + Q)$ value, is a manifestation of dilution. By analyzing the composition of the various size fractions of the Texas beach sands, it was found that the coarser fractions, having been derived from the Mississippi, have about the same feldspar percentage as that of the sand in the delta area, only the finer fractions, having been derived from the Tertiary quartz sandstones and carried down by small coastal streams of Louisiana and Texas, are deficient in feldspar. This precise analysis has revealed that the westward decrease of $F/(F + Q)$ value in beach sands is not caused by attrition, but is a manifestation of dilution.

The postulate that the mineral composition of sands is little changed during transport suggests that chemical weathering must have played a significant role. This idea is best illustrated by the results of studying the river and beach sands of Florida: Detritus derived from source terranes where the climate is favorable for deep chemical weathering is mature and quartz-rich. The sands of West Florida beaches, for example, are derived from the weathered terranes of the southern Appalachian Mountains. The sand grains are still very angular, a testimony of their "youthful" history, having just been swept away from the red-earth hilly country of Alabama. Yet the sand consists almost exclusively of quartz, because feldspars have been weathered in the source areas and are converted into clay minerals.

We now believe that the composition of a detrital sediment is a fairly good indicator of past climate. Quartz sandstones are not uncommon in Switzerland; those of Eocene age are present in the Jura Mountains. Could we postulate that the Eocene climate was warm and humid in Switzerland so that feldspars were eliminated by chemical weathering in the source terranes? Yes, we can, and this postulate is confirmed by fossil fauna and flora evidence.
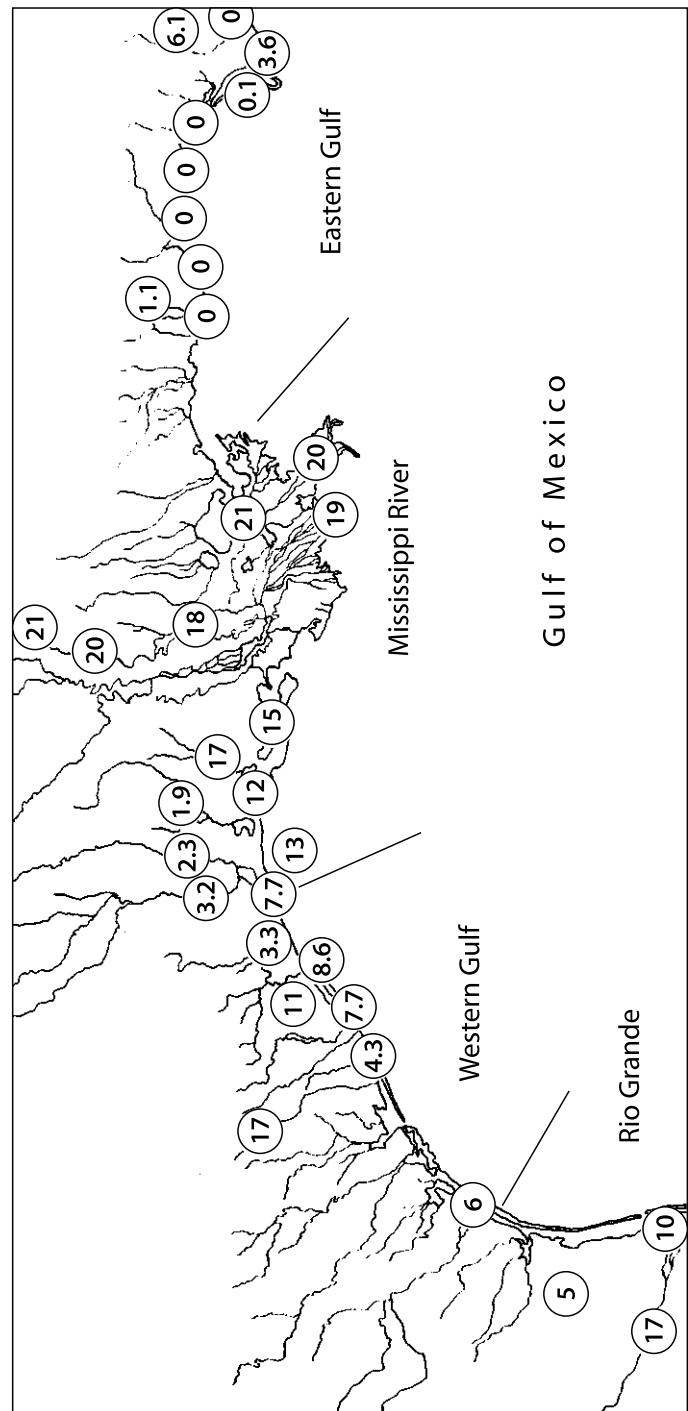
Fig. 2.2. Variation of feldspar content in the beach sands of the Gulf Coast (modified after Hsü 1964). The beach sands in the Mississippi Delta region have a feldspar content of about 20%, virtually the same as that in the river sands of the region. The feldspar content in beach sands decreases westward to a minimum of less than 5% in southwest Texas. A systematic study by Hsü in 1964 indicated, however, that the decrease is not caused by mechanical abrasion during transport, but is a manifestation of mixing of sands from different sources

2.2
Heavy Minerals

Another component of a sandstone consists in minerals denser than quartz, and they have been referred to as *heavy minerals*. Heavy is, of course, the wrong word; those minerals are not heavier, but denser than quartz or feldspar. Heavy minerals are minor constituents of sandstones, constituting commonly less than 1% of the bulk, but the presence of various species could yield significant information.

Individual heavy minerals are separated from a concentrate of sand, after the lighter particles (quartz, feldspar, etc.) have been removed by flotation on heavy liquids. H. B. Milner was one of the pioneers to use binocular microscope to identify those minerals. This kind of study was once very fashionable. My father-in-law, Hermann Eugster, remembered his postdoctoral sojourn to the Imperial College of London in the early 1920s, to study with H. B. Milner, the author of *The Principles and Practice of Correlation of Sediments by Petrographic Methods.*

Milner and his colleagues discovered a *heavy-mineral zonation* in sedimentary sequences. Pyroxenes are commonly found only in Recent sediments, amphiboles in young, near-surface sandstones, the heavy-mineral assemblage in progressively deeper sedimentary formations is characterized by successive dominance of epidote, garnet, and zircon. Eventually such zonal arrangement has been identified not only from Europe and North Africa, but also in various parts of North America (see Fig. 2.3).

Eugster worked for an oil company in Colombia, and the dating and correlation of geologic formations were of prime importance to exploration. Foraminiferas and other microfossils had been found in marine sediments, but their stratigraphic significance was not well known. Much hope during the 1920s was placed on the use of heavy minerals for stratigraphical correlation. The Society of Economic Paleontologists and Mineralogists, SEPM, the earliest sedimentological society, was founded in 1930, when both paleontologists and (heavy-) mineralogists served the oil industry for the purpose of making correlations.

Paul Krynine, in a series of talks given at the Annual Meeting of the Geological Society of America in 1941, was an enthusiastic proponent of the idea that the vertical zonation of heavy minerals reflects the history of erosion of source areas. The zircon suite consisting of zircon, rutile, monazite, etc., is commonly found in older sedimentary rocks. These minerals are considered polycyclic, having been derived from the sedimentary cover of the basement in the source terrane. As the cover was eroded first, these stable minerals were deposited as the heavy-mineral suite (Fig. 2.4 *A*) of the oldest sediments in a basin. With continuing uplift, metamorphic rocks with garnet and epidote (Fig. 2.4 *B*) were successively eroded. The heavy-mineral suite of the middle

Maryland coastal plain sediments

	Trias	Lower Cretac.	Upper Cretac.	Eocene-Miocene	Miocene	Pleistoc.
R						
Z						
T						
G						
St						
Chl						?
Ep-Zo						
Ti				?	?	?
Ky						
Si						
Hb						

Egyptian sediments

	Nubian	Eocene	Oligocene	Miocene	Pliocene	Modern Nile
R						
Z						
T						
Ky						
St						
G						
Ep						
Si						
Hb						
Pyrox						
Ol						

Tertiary

	Staurolite Zone	Kyanite Zone	Epidote Zone	Hornblende Zone
Z				
T				
G				
R				
St				
Ky				
Ep				
Ti				
Hb				

formation consists thus of a mixed assemblage. Finally the basement composed of rocks rich in amphiboles and pyroxenes is bared by erosion, so that the youngest sedimentary strata are characterized by a suite that includes all heavy minerals (Fig. 2.4 *A*, *B*, *C*).

The hypothesis of relating heavy-mineral zonation to erosional history encouraged "economic mineralogists". At the same time "economic paleontologists" were making great strides in their correlation of microfossils. Soon friends in SEPM became enemies when the surfaces of *isochrone* (equal-age) zones determined by faunal correlation were shown by economic paleontologists to cut across those separating heavy-mineral zones. It is true that more stable minerals occur in deeper rocks and they are on the whole older, but stratigraphical correlation by mineralogical studies are not very precise. Paleontologists eventually were triumphant; many mineralogists in the petroleum industry had to abandon their heavy minerals and used the same microscopes to identify microfossils.

When I went to Houston in 1954 to work with the Shell Development Company, my boss gave me several boxes of heavy-mineral data, representing several 100 man-years of diligent work during the 1920s and 1930s. By then, the battle for stratigraphical correlation had been won by the paleontologists. But, as I found out from the files, the mineral zonation is there (Fig. 2.4), even though its stratigraphical value is questionable. This vertical zonation requires nevertheless an explanation.

Francis Pettijohn, among others, had noted that the heavy minerals have varied resistance to weathering or to chemical dissolution. The order of increasing resistance is pyroxenes, amphiboles, epidote, garnet, kyanite, staurolite, zircon, etc. That the zonation was caused by differential dissolution of less stable heavy minerals by groundwater was proposed.

I worked then with my late friend James Taylor to study the heavy minerals of Late Cenozoic sandstones of southern California. The bulk composition of the sandstones and the geologic history of the region are such as to indicate that the heavy mineral composition of the sands should have been the same

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◄ **Fig. 2.3.** Heavy-mineral zones (modified after Pettijohn 1957). The diagrams illustrate that rutile (*R*), zircon (*Z*), and tourmaline (*T*), the so-called stable heavy minerals, are present in all sandstones, whereas olivine (*Ol*), pyroxenes (*Pyrox*), and amphiboles (*Hb*) are present only in the youngest. Other minerals of intermediate stability include garnet (*G*), kyanite (*Ky*), sillimanite (*Si*), chlorite (*Chl*), epidote-zoisite (*Ep-Zo*), titanite (*Ti*).

Zonations, such as that in the Cenozoic formations of the Gulf Coast region, were recognized, and heavy minerals were used as "index fossils" for correlation. We now believe, however, that the zonations have resulted from dissolution of less stable heavy minerals in deeper or older rocks
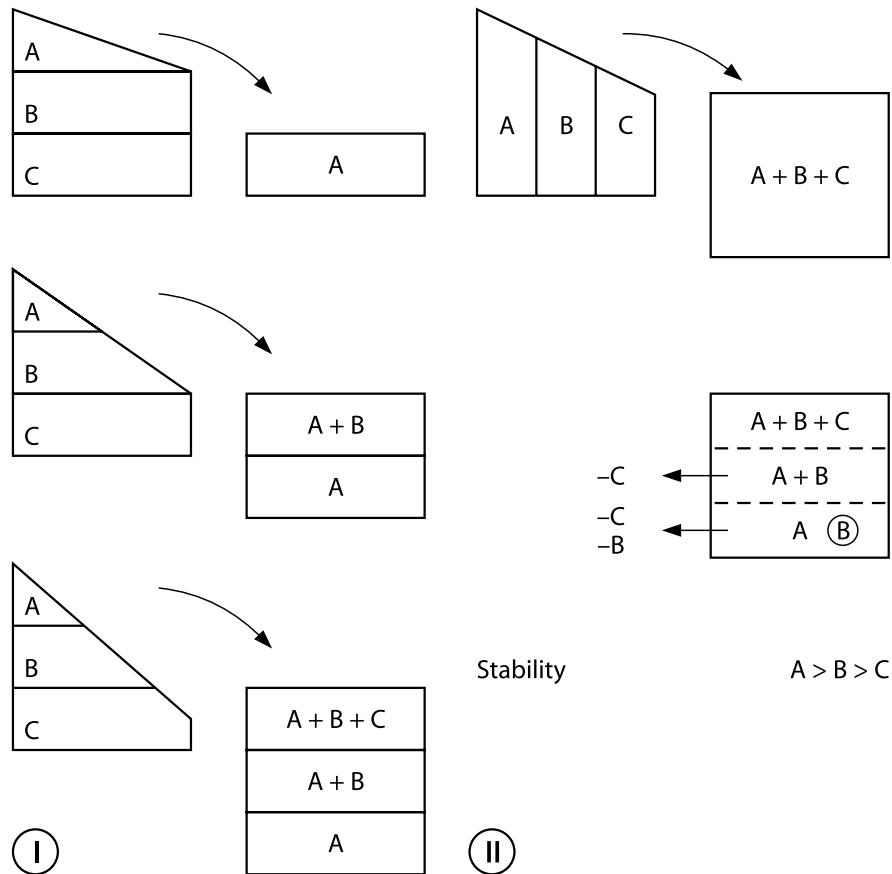
Fig. 2.4. Hypotheses of heavy-mineral zonation. Two different schools of thought have developed regarding the heavy-mineral zonation. Krynine assumed that the heavy minerals in sedimentary rocks are all stable, and the zonation is a manifestation of the changing input of source materials (*Model I*). Pettijohn postulated dissolution of less stable heavy minerals in more deeply buried rocks (*Model II*): for explanation of *A*, *B*, *C*, see text

from the top to the bottom of the sedimentary sequences. Yet, Taylor found a heavy-mineral zonation, similar to that found in the Gulf Coast: the oldest suite consists of zircon and rutile, and the youngest consists of all heavy minerals. He also observed that the weight percent of the total heavy-mineral suite becomes less and less in deeper and deeper formations, and that this change can be explained if we assume the dissolution of less stable heavy minerals in deeper formations. After this exercise, I found little reason to question Pettijohn's postulate.

To draw geological conclusions on the basis of sedimentary petrology is a "natural-history approach". Syntheses are made on the basis of direct geological observations, and the recourse to the relationships established in other sciences is vague and not quantitative. We have no physical law, which states that change of mineral composition by abrasion during transport is impossible. We have made no chemical experiments to verify the dissolution of the less resistant heavy minerals. As M. King Hubbert pointed out, the natural-history approach in geology is necessary, but insufficient. The "Earth Science Revolution" of the 1960s came only after the "physical science approach" had been adopted to investigate the physics and chemistry of the earth's phenomena.

Traditional approaches were conserved in central Europe, however, when I was called to ETH Zurich in 1967. Sedimentology was then taught in the form of studying heavy minerals, and only to a few students who happened to work on the Molasse formations. Thanks to a revolt by students, the course on the physical principles of sedimentology is now obligatory for our geology majors; this is the course I am now teaching. I have made, however, this lesson in sedimentary petrology my first lecture, because I do not recommend that the "natural-history approach" be abandoned. Studies of heavy minerals could yield valuable information on the provenance of detritus. For example, the discovery in Alpine Cretaceous Flysch of heavy minerals derived from ophiolites told us that the Cretaceous Tethys Ocean was bounded on the south by a coast range, where *ophiolite melanges* were exposed. We now have evidence that the ocean crust was being consumed long before the Early Tertiary continental collision which formed the Alps. A proper interpretation of sedimentary petrology has thus made an important contribution to our understanding of the geologic history of Switzerland.

2.3
Size and Sorting

We have so far been discussing separation by chemical processes; such sorting leaves an imprint on the composition of a detrital sediment. Sorting by mechanical processes determines its texture.

The grain-size distribution of a detrital sediment is commonly determined by sieve analysis. A series of sieves is used, each successive one has an opening half as large. The weight of the sedimentary particles left in each sieve constitutes the *sieve fractions* or the weight fraction of a grain-size class. The median diameter of a sediment is the average diameter, which is larger than 50% of the grains and smaller than the other 50%. The sorting of a sediment can be expressed by noting the distribution of components in various sieve fractions. If all of the detrital particles of a sediment are caught in the same sieve frac-

tion, the sediment is well sorted. If its detrital grains are found in several sieve fractions, the sediment is not so very well, or poorly, sorted.

Standard sieves are made such that each successive sieve opening is only half as large. Sieve fractions are thus expressed as powers of ½. Mathematically minded sedimentologists invented phi units, and ϕ is a dimensionless number defined by

$$\phi = -\log\left(\frac{1}{2^n}\right) \tag{2.1}$$

where ($\frac{1}{2^n}$) is the median diameter (in mm) of a sand, with $n = 0, 1, 2, \ldots$ A sediment with a median diameter of 1 mm ($n = 0$) has a phi value of 0. One with a median diameter of 0.125 or $\frac{1}{2^3}$ mm ($n = 3$) has a phi value of 3. A clay with a median diameter of 0.002 or $\frac{1}{2^9}$ mm ($n = 9$) has a phi value of 9.

Opinions have varied on the definition of sand, silt, and clay; European and American usages are different (Fig. 2.5). The North American practice advocated by Udden has been adopted by many, if not most, of the sedimentologists.

Unsorted sands have nearly equal weight percentages in numerous sieve fractions. Mechanical sorting results from the fact that a river, or a marine current, has a range of speeds which could erode or transport detrital particles of certain size. Well-sorted sands have thus sand grains which almost all belong to the same phi. Such good sorting is evidence that the velocity of the current passing through the site of deposition varied within a narrow range. Coarser sediments had all been left behind before the current reached the site of deposition; finer particles remained in suspension and were carried away. Only sediments of a given size fraction were too coarse to be transported farther. In Chapt. 4 this matter of sorting during sediment transport will be discussed.

2.4
Exclusion Principle

Sediments of different origins can also be separated from one another because their paths of sediment transport are different. Coastal marine current, also known as longshore current, tends to flow in a certain direction so that the detritus transported by this current system would be excluded at sites in the opposite direction. On the Gulf Coast, for example, the beach sands east of the Mississippi River delta contain little feldspar (Fig. 2.2), because the detritus from the river have all been carried westward by longshore currents. The quartz sands on Florida beaches have been derived from the weathered terranes of the southeastern United States.

Hopkins 1889		Atterberg 1903		Udden 1914		Wentworth 1922		Cailleux 1929	US Bureau of Soils	
		Block				Boulders		Blocs		512
				Boulders	vc					256
		Sten			c	Cobbles		Galets		128
					f					64
					vf					32
		Grus		Gravel	vc	Pebbles		Graviers		16
					c					8
					f					4
	Gravel				vf	Granules			Gravel	2
		Sand		Sand	vc		vc	Sables		1
Sand	c				c	Sand	c		c	1/2
	m				f		m		m	1/4
	f	Mo	Fimma		vf		f		f	1/8
	c			Silt	vc		vf		vf	1/16
			Mjäla		c			Poussières et Boues	Silt	1/32
		Lättler	Vesa		f	Silt				1/64
Silt	m				vf					1/128
			Mjuna		vc					1/256
	f			Clay	c	Clay			Clay	1/512
		Ler			f					1/1024
	Clay				vf					1/2048

Fig. 2.5. Classifications of detrital sediments (modified after Pettijohn 1957). Detrital sediments can be classified on the basis of grain size into clay, silt, sand, gravel, etc. It is a sad commentary on the triviality of scientific endeavor when scientists found little better to do than to argue if a clay-sized particle is less than 0.001, 0.002, or 1/256 mm.

Despite the difference in opinions, the one central feature common to all the classifications is the fact that size classes are geometrical progressions. Such schemes have been proposed because of their practicality. I have analyzed the grain-size distribution of unsorted sediments, and found that the weight percentages of all sieve fractions, with the size of sieve openings in geometrical progression, are the same for a perfectly random grain-size distribution. Unsorted sediments, in the new mathematic language of Mandelbrot (1982), have a fractal distribution of grain size

Exclusion could be a consequence of geographic isolation. The sands on Bahama Islands, for example, have neither feldspar nor quartz; the Florida Strait has served as a barrier to "filter out" all terrigenous detritus.

Where the *siliciclastics*, i.e. silica and silicates, are "filtered" out, the streams draining a carbonate terrane could carry down limestone and dolomite de-

bris to marine realms to form carbonate sediments, such as lime sands or *calcarenites*.

More commonly, however, calcium carbonate sediments are derived from skeletal debris of organisms. The Recent carbonate sediments on the shallow marine Great Bahama Bank consist mainly of fossil skeletons or debris. Oozes on the bottom of open oceans are also mainly biogenic. They are derived from skeletons of nannoplankton, foraminiferas, radiolarias, and diatoms; the detritus from land have been deposited nearer to shore.

Sedimentary particles can originate from chemical precipitation, and they form chemical sediments if terrigenous detritus are excluded. Chalk sedimentation in Lake Zurich is a good example. The suspended particles from the Linth, its main tributary, have been filtered out before the river water leaves the Lake of Walenstadt, while the debris from smaller tributaries are deposited behind flood-control constructions. As a consequence, a chalk, not a marl or clay, is now deposited in Lake Zurich.

Carbonate muds in marine environments were once thought to be chemical precipitates. Work by Robert Ginsburg and others during the 1950s have shown that they are in fact mostly biochemical precipitates by green algae.

Chemical precipitates from lakes and oceans include not only carbonates, but also sulphate and chloride *evaporites* (anhydrite, gypsum, halite, etc.) as well as phosphates and other important economic minerals. Whereas the genesis of siliciclastics involves mainly physical processes, the origin of carbonates, evaporites and other monomineralic deposits are problems of biomass production and chemical reactions, which will be discussed later.

Sorting by chemical processes leaves an imprint on the mineralogical composition of a sediment, sorting by mechanical processes determines grain size. The mechanical sorting is done by physical processes, governed by physical laws. I shall start my discussion of those principles in the next chapter with Newton's First Law of Motion.

2.5
Suggested Reading

The natural-history approach in geology is inductive, and induction means "the bringing forth of facts to prove something". Philosophers of science, in their jargon, tell us that you cannot "prove", you can only falsify. In other words, no accumulation of facts suffice to prove the truth, but a single fact can prove an assumption wrong. Therefore, I have referred to two studies (Mississippi River and Gulf Coast), which falsified the assumption that the composition of a sediment is changed by abrasion during transport, and I have not tried to prove, by citing many case histories, that mineralogy indicates provenance.

Many excellent studies on sedimentary petrology have been published, and they give us an appreciation of the complexity of interpreting sediment composition and texture. Undergraduate students could begin by reading Francis Pettijohn's *Sedimentary rocks* (Harper, New York, 1957), especially Chapters 2, 3, 11, and 12. Advanced students writing a term paper, or doing a dissertation on physical sedimentology may wish to dig deeper into the classic papers by William Mackie on *The sands and sandstones of eastern Moray* (Trans Edinburgh Geol Soc 7:148–172, 1896), by R. Dana Russell on the *Mineral composition of Mississippi River sands* (Bull Geol Soc Am 48:1306–1348, 1937), and other papers cited by Pettijohn in his book.

The major conclusions on mineralogy, as summarized in this chapter, came as a revelation to me, when I had to synthesize my data for an article on *Texture and mineralogy of the recent sands of the Gulf Coast* (J Sediment Petrol 30:380–403, 1980). I owe much to Robert Ginsburg, however, for having taught me the fundamentals of carbonate sedimentation. Much of his wisdom can be found in his article on *Environmental relationships of grain size and constituent particles in some South Florida carbonate sediments* (Bull Am Assoc Petrol Geol 40:2384–2427, 1956).

Francis Pettijohn has personified the natural-science approach to sedimentology. For those endeavoring to obtain a deep appreciation of what we have learned in sedimentology with this approach over the past 70 years, they should secure a copy of the Pettijohn Festschrift *Evolving concepts of sedimentology*, edited by Robert Ginsburg (Johns Hopkins Univ Stud Geol No 21, 1973).