Chapter 4
SILICICLASTIC ROCKS

1. SANDSTONES

1.1 Introduction

1.1.1 Sandstones are an important group of sedimentary rocks. I suppose a good estimate of the percentage of sedimentary rocks that would be classified as sandstones is about 25%.

1.1.2 Defining what's meant by the term sandstone turns out not to be easy. Recall from Chapter 1 that *all sedimentary particles between 1/16 mm and 2 mm* should be called ***sand***, regardless of composition. But terminology for a sand *deposit*, as distinct from sand *grain size*, is more difficult. For a deposit to be called a sand, "most" of the particles must be in the sand size range. But *how much is "most"?* How much finer and/or coarser material can there be in a sand deposit? Various attempts have been made to erect terminology for mixtures of sand and finer/coarser sediment, with quantitative boundaries. There's no standard classification, but nobody seems to worry much about that. Figure 4-1 shows two ways of dealing with mixtures of sand and mud, one "rational", seemingly composed with logicality and symmetry in mind, and the other reflecting marine-geological practice. And 4-2 shows two ways of dealing with mixtures of sand and gravel, the first idealized and symmetrical, and the other reflecting field usage. The same difficulties in distinguishing between a sandstone and a conglomerate, at the one end, and between a sandstone and a siltstone, on the other end, are similar. If the rock has a lot of silt in it as well as sand, you can call it a *silty sandstone*, and if it has a lot of gravel in it was well as sand, you can call it a *gravelly (or pebbly) sandstone or a conglomeratic sandstone*. But note this: the rock doesn't have to have much gravel in it, perhaps 10-20%, or even less in the view of some people, before it starts to get called a conglomerate, because of the prominence and (presumably) significance of that small percentage of gravel. But, with all that said, this whole matter isn't something you have to worry much about when you're in the field actually working with sandstones.

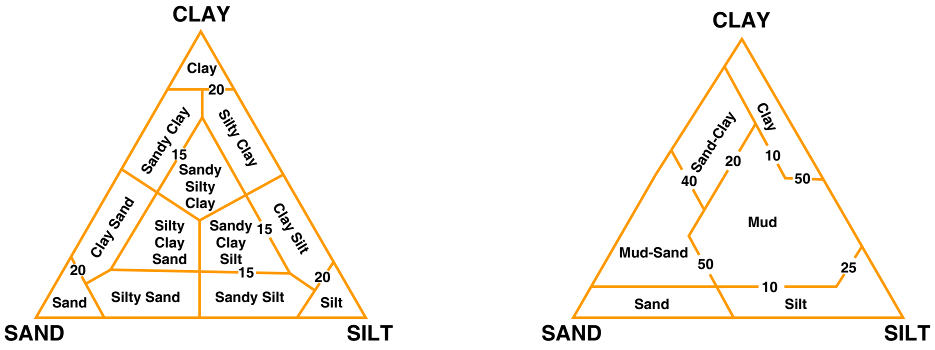


Figure 4-1: Two classifications of mixtures of sand, silt, and clay

Figure by MIT OCW.

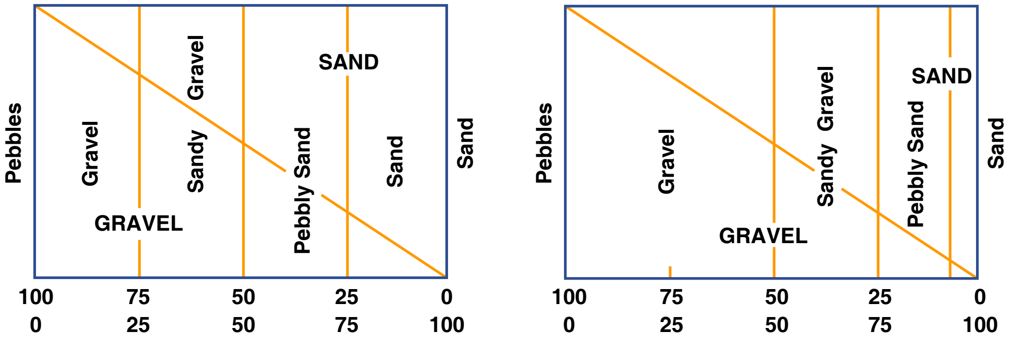


Figure 4-2: Two classifications of mixtures of sand and gravel

Figure by MIT OCW.

1.1.3 *Sands (sand deposits) can be of any composition: siliciclastic, carbonate, or even evaporitic*, in the case of wind-blown or water-transported gypsum particles on playa surfaces in deserts. But once the deposit is lithified enough to be called a sandstone (and you should realize that the boundary between sand and sandstone is broadly transitional and not conventionally established in any way), the term sandstone is applied only to *siliciclastic* rocks, not to *carbonates*; in the case of clastic carbonate rocks whose particles are of sand size, the term *limestone* takes precedence over the term *sandstone*.

1.1.4 Miscellaneous comments about sandstones:

θ *Sandstones show an extremely wide range of framework composition*, from all quartz to not much quartz and lots of feldspar and/or rock fragments.

θ *Sandstones also show an extremely wide range of textures*, from very well sorted and well rounded to very poorly sorted and subangular.

θ *Sorting and rounding of the framework grains tend to vary together*, but there are important exceptions.

θ *Framework composition and framework texture are strongly correlated*: sandstones with varied framework composition tend to have poorly sorted and poorly rounded framework grains, and sandstones with all-quartz framework composition tend to have well sorted and well rounded framework grains—but again there are important exceptions.

θ *Sedimentary structures in sandstones, both primary and secondary, are common, prominent, and extremely useful in interpreting depositional environments*—more so than in other rocks.

1.2 How Do You Know It's a Sandstone?

1.2.1 Seems like a silly question, I suppose. Usually the situation is clear, but the question is sometimes not a trivial one when you're on the outcrop. And it's especially acute when someone hands you a little out-of-context hand specimen and you have to perform. I don't want to be too cookbookish, but here are some considerations:

θ *Look for detrital grains of sand size.* Even in the finest sandstones, mineral oil and a hand lens usually do a good job. If the sandstone is fairly fine and very matrix-rich, this may be difficult or impossible, especially if the rock is on its way toward metamorphism.

θ *Be cautious about calling it a limestone just because it fizzes in acid.* That may well be carbonate cement or a small percentage of carbonate grains or fossils in a true sandstone.

θ *In really difficult situations, overall bedding may suggest a sandstone* rather than some other kind of rock—but you may still be dealing with a volcanic igneous rock.

1.2.2 Here's an annotated list of other rock types with which you might confuse sandstone on occasion:

θ **volcanics**: in the case of *felsic volcanics*, there's a true gradation in the first place (see later section on volcaniclastic rocks), and many felsic volcanics look superficially like certain "ordinary" sandstones. In the case of *mafic volcanics*, some dark graywackes look a lot like basalts/andesites.

θ **limestones**: aside from the fact that there are truly intermediate cases, in which some of the framework is carbonate and some is siliciclastic, certain *dark unfossiliferous limestones look superficially like sandstones*. But if you use the right techniques you shouldn't have much trouble with this.

θ **granites**: in some cases, *coarse well cemented feldspar-rich sandstones can look a lot like granites* (from which they probably were derived in the first place). Careful examination of texture, and a chance to see bedding, usually takes care of this confusion.

θ **low-grade metamorphics**: here the problem is one of judgment about where to draw the line. If you want to claim it as a sandstone, go ahead.

1.2.3 Here's a list of the properties of a sandstone you could measure or describe.

"fundamental":

"component" composition (minerals, rock fragments, fossils, organic matter)
texture (grain size grain shape, grain arrangement)
sedimentary structures

"derived":

chemical composition
bulk density
color
strength (tensile, compressive, shear)
porosity
permeability
elastic wave velocity
electrical properties
heat capacity
thermal conductivity
etc.

1.2.4 In addition to these, there are a number of other important things you can describe that don't fit neatly into the above list:

friability (degree of induration or lithification)
parting characteristics
development of rock cleavage
weathering characteristics
ledge/cliff-forming tendency

1.3 Constituents of Sandstones (Partly Review)

framework grains:

quartz (usually dominant)
feldspar (Kspar >> plag; usually partly altered; microcline > orthoclase)
rock fragments (chert/quartzite act like quartz; others nonresistant)
heavy minerals (varied; most of minerals; seldom abundant)
micas (common, never high %; muscovite >> biotite)
clastic carbonates (mixtures less common than ends)
glauconite (local, sometimes abundant in quartz-rich ss)

void filler:

quartz (as secondary overgrowths)
quartz (as recrystallized amorphous silica)
chert (amorphous silica)
calcite (dolomite less common)
hematite (primary? secondary?)
exotica (anhydrite, gypsum, barite, halite, siderite, etc.)

matrix (fine material, not authigenic):

fine detrital nonphyllosilicates (quartz, feldspar, carbonates)
fine detrital phyllosilicates (starts as clay-mineral mud, gets recrystallized to "sericite", "white mica", chlorite)
reorganized phyllosilicate-rich coarse rock fragments

1.4 Classification

1.4.1 A lot of effort has gone into devising rational classifications of sandstones—more than for other sedimentary rocks. Everyone agrees that classifications are important and useful, not only for communication but also for organization of thought; a good classification can help reveal underlying regularities that need to be explained.

1.4.2 There are many different kinds of classification. Usually a distinction is made between a *genetic* classification and a *descriptive* classification. In classifying rocks, there's general agreement that *the best classification is one that's descriptive but with a genetic basis*; such a classification has the advantage of being objective but at the same time oriented toward the genesis of the rock. (The trouble with classifying a sandstone as eolian, say, is that your interpretation of the depositional environment is built in, and you may be wrong.)

1.4.3 Here are some of the important genetically based defining parameters that could be used:

provenance
mineralogical maturity
textural maturity
depositional environment
diagenesis

Almost without exception, classifications have made use of *the first three of these*.

1.4.4 A large number of classifications have been formally proposed, in print. All but a handful of these have seen little use. Most are of no more than historical interest at this point. Probably the most widely used classification now is that of Pettijohn, Potter, and Siever. It's shown as Figure 4-3, in a three-dimensional sketch.

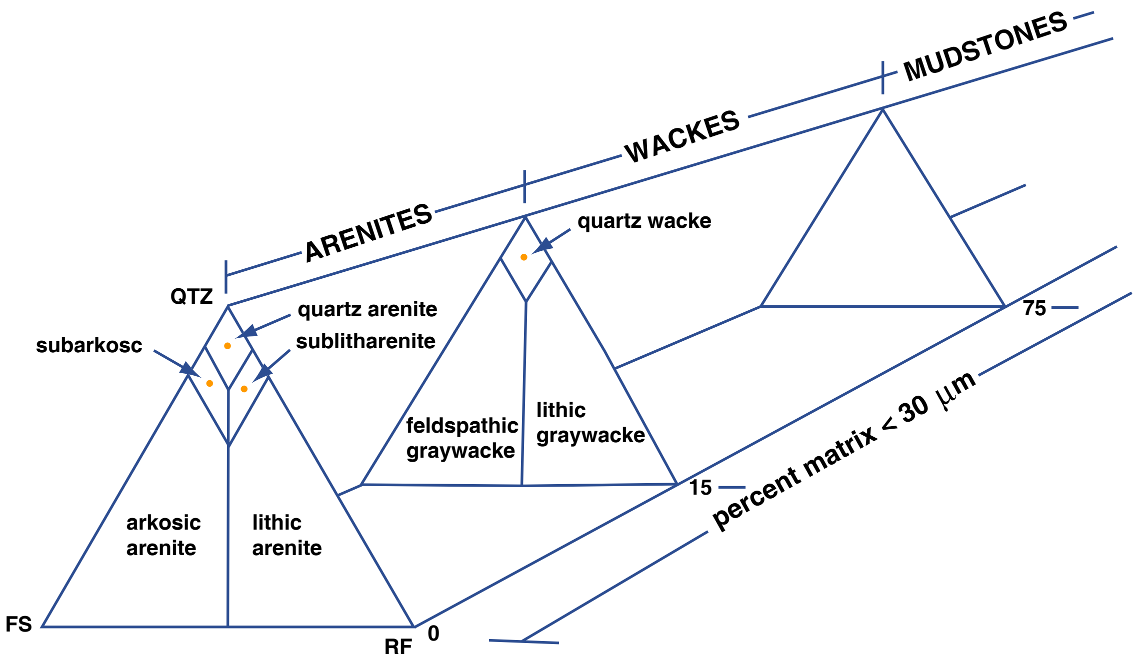


Figure 4-3: The Pettijohn/Potter/Siever classification, of sandstones

Figure by MIT OCW.

1.4.5 The main idea behind the classification is that there are *two broad textural kinds of sandstones*—those, called ***arenites***, without appreciable fine matrix along with the framework grains, and those, called ***wackes***, with appreciable fine matrix along with the framework grains. Within each of these sandstone classes, names are assigned on the basis of the percentages of three major framework constituents: *quartz*, *feldspar*, and *rock fragments*.

1.4.6 I should emphasize that this the classification in Figure 4-3 can be used only to a limited extent in the field. It's designed for thin-section work. It'll be useful to you in the field only if the sandstone is fairly coarse. If you find you can't apply it in the field, don't worry.

1.4.7 Sandstone petrologists play lots of games beyond just this classification. They love to make triangular composition diagrams. To do this, you have to make careful and tedious point counts in thin section. Figure 4-4 shows some examples.

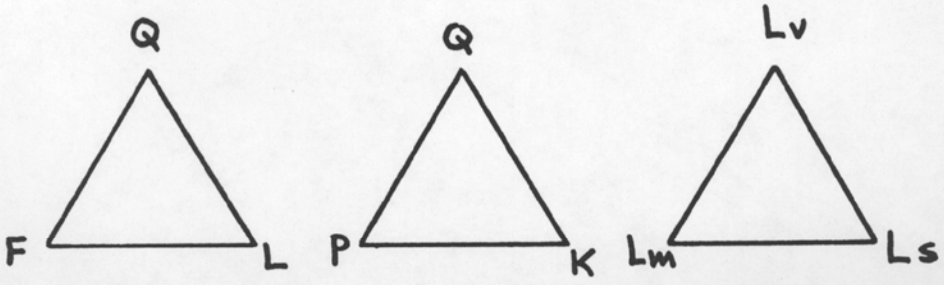


Figure 4-4 Kinds of ternary composition diagrams used in expressing the framework composition of sandstones. See Paragraph 4-6 for key.

Key:

Q	quartz
F	feldspar
L	rock ("lithic") fragments
P	plagioclase
K	Kspar
Lv	volcanic rock fragments
Lm	metamorphic rock fragments
Ls	sedimentary rock fragments

1.5 Kinds of Sandstones

1.5.1 Even aside from rational pigeonhole classifications like the one presented above, most people would agree, at least in a general way, that there are *"kinds" or fairly natural groupings of sandstones*, albeit with very broad and blurred boundaries among them. Thinking about sandstones like this is often useful in making broad interpretations of geological setting, but it can be misleading. So I want you to be cautious about what I'm going to say next.

quartz arenites:

Almost all quartz plus a little chert and resistant heavies in the framework; silica or carbonate cement; no matrix; very well sorted and rounded; lightest color of sandstones; planar lamination or large-scale cross-lamination; section thickness low; thin, widespread, patchy blankets; associated with limestone and shale; usually marine, craton to miogeocline.

feldspathic sandstones:

Quartz variable but feldspar abundant in the framework, mostly Kspar, rock fragments subordinate, coarse detrital mica common; silica and secondary feldspar cement common; some matrix but not a lot, mostly kaolinite; coarsest of sandstones; tends to be reddish; large-scale cross-stratification common; section thin to thick; blankets like quartz arenite, or thick wedges and prisms; associated with either quartz arenite or red shale, conglomerate, volcanics; craton to miogeocline (marine), or fault-block basins (nonmarine).

lithic sandstones:

Quartz abundant, rock fragments second, feldspar variable but third; variable amount and composition of matrix; silica or carbonate cement; color variable, often salt-and-peppery; fine-medium sand size common; cross-stratification prominent; section thickness middling; tabular, lenticular, shoestring shapes; associated with shale, conglomerate, not much limestone; fluvial or shallow marine; miogeoclinal and post-tectonic basins.

graywackes:

Quartz variable, often less than 75%, feldspar and rock fragments variable; matrix prominent; usually poor sorting and rounding; color gray, darkest of sandstones; pelagic marine fossils; graded bedding, sole marks, small-scale cross-stratification; section thickness large; thick lenticular shapes; associated with shale, bedded chert, submarine volcanics; deeper marine trough fillings in mobile belts (eugeoclinal).

2. CONGLOMERATES

2.1 Introduction

2.1.1 Conglomerates are far less abundant in the sedimentary record than sandstones. But they're important far beyond their abundance. Why? For three reasons:

θ Because of *what they tell us about depositional environment*: if you can be sure that the gravel was actually transported (rather than being just the in-place residuum of weathering) then *the presence of gravel-size material indicates strong currents*. That's one of the firmest interpretations you can make in sedimentary petrology.

θ Because of what they tell us about provenance: *to get gravel-size material coming out of the source area, there must have been high relief, and therefore strong uplift*. So the presence of gravels in the sedimentary record is a good indication of tectonism in the source area. Here's another one of those important first-order interpretations that are generally accepted to be fairly reliable.

θ Because *conglomerates present a record of the rock types present in the source area*. It's sort of like having little source-area outcrops delivered to your door. There's still the problem of *representativeness* (some rock types are less likely to produce gravel-size debris than others), but the problem is not nearly as severe as for sandstones.

2.1.2 With regard to the first point, *the physical mechanisms involved in deposition of gravels are not well understood, so detailed interpretations of depositional mechanisms based on study of conglomerates is much less advanced than for sandstones*.

2.2 Terminology

2.2.1 *A rock containing as little as 10-20% gravel-size clasts is usually called a conglomerate*, although actually it should be called a conglomeratic sandstone or even a conglomeratic mudstone; see the chapter on sandstones.

2.2.2 Technically, terminology differs depending on clast roundness (Figure 4-5). *A conglomerate with angular clasts* is called a ***breccia*** (watch out; there are lots of other kinds of breccias besides sedimentary breccias), and the unconsolidated equivalent is called ***rubble***. Breccia is also called ***sharpstone conglomerate***, in contrast to ***roundstone conglomerate***. But this is not a big deal, because *sedimentary breccias are a lot less common than conglomerates*. Also keep in mind that breccia is a more general term for fragmental rock consisting of angular fragments. There are many kinds of breccia, depending upon how the fragmentation developed:

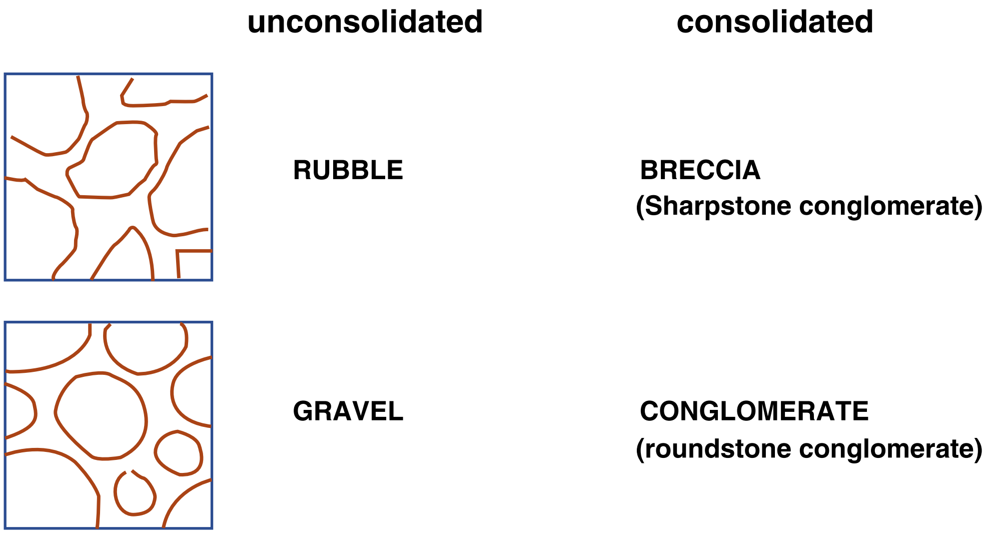


Figure 4-5: Terminology for gravels and conglomerates

Figure by MIT OCW.

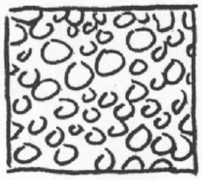
volcanic breccia
tectonic breccia
intrusion breccia
sedimentary breccia
solution-collapse breccia
landslide breccia
meteorite-impact breccia

How do you tell all of these apart? It's often very difficult.

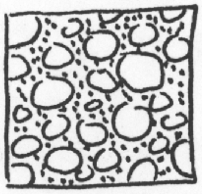
2.3 Descriptive Stuff

2.3.1 Figure 4-6 shows an unofficial list of *size-distribution types* in conglomerates you're likely to see. Remember that there are three different grain-size components (gravel, sand, mud), presumably with different hydrodynamic significance. (Never mind that these are to a great extent arbitrary categories.) The things you have to worry about are *sorting*, *number of modes*, and *clast support vs. matrix support*.

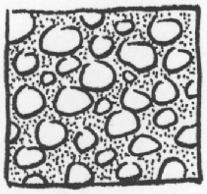
Unimodal clast-supported (= openwork):



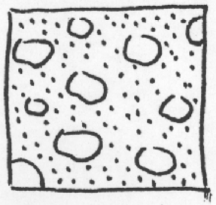
Bimodal clast-supported with sand matrix:



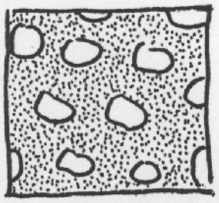
Bimodal clast-supported with mud matrix:



Bimodal matrix-supported with sand matrix:



Bimodal matrix-supported with mud matrix:



Unimodal poorly sorted:

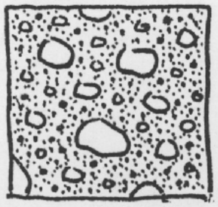


Figure 4-6 Unofficial catalog of size-distribution types in gravels and conglomerates

2.3.2 I think the three most common textural categories are:

bimodal clast-supported with sand matrix
bimodal matrix-supported with sand matrix
unimodal poorly sorted (with abundant mud)

2.3.3 In terms of *fabric*, think about tendencies toward *preferred orientation* of crudely triaxial-ellipsoid gravel clasts. Here are the commonest fabric types (*a* axis is longest, *c* axis is shortest, *b* axis is intermediate):

a axis flow-parallel, *ab* plane imbricated
a axis flow-transverse, *ab* plane imbricated
a axis unordered, *ab* plane horizontal
no strong preferred orientation

2.3.4 In terms of *stratification*, keep in mind that *conglomerates tend to be less well stratified than other kinds of sedimentary rocks*. Conglomerates can show *planar stratification* or *cross-stratification*, or they can be *unstratified* (Figure 4-7). Planar stratification in conglomerates tends to be crude, and often indistinct. Cross-stratification in conglomerates is always on a fairly large scale (a few tens of centimeters normal to overall stratification), and it's not nearly as common as in sandstones. It's much more common for conglomerates to be unstratified than for sandstones.

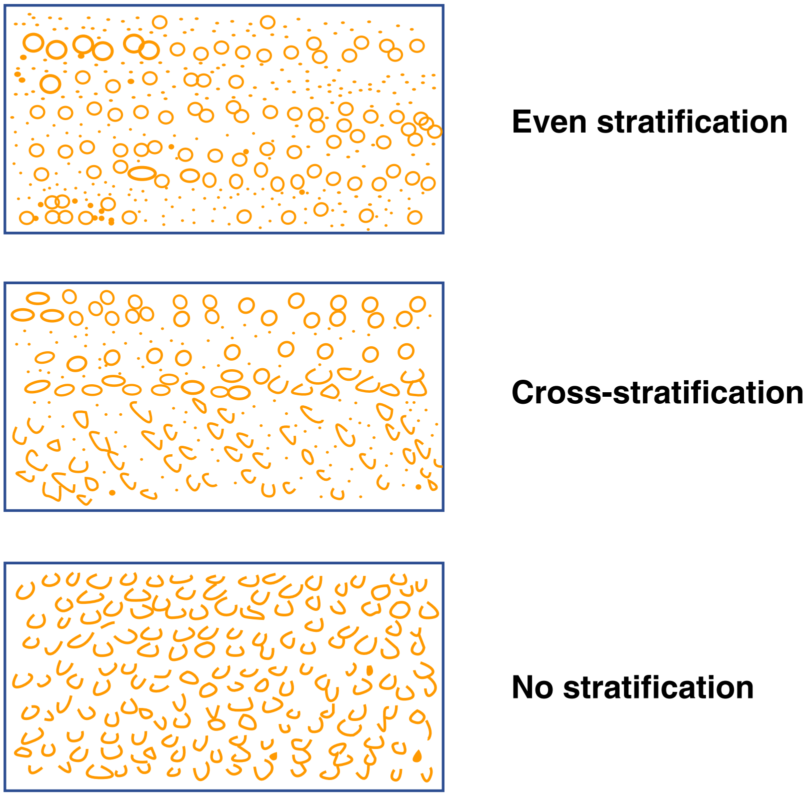


Figure 4-7: Kinds of stratification in gravels and conglomerates

Figure by MIT OCW.

2.4 Where Are Modern Gravels?

rivers: especially high-gradient rivers draining mountainous areas; usually but not always braided; grade over into sand-bed rivers with only a small percentage of gravel in the system. Typically gravel plus sand, bimodal, with sand the secondary mode; fairly well sorted but not nearly as well as beach gravels.

alluvial fans: just another kind of braided-stream environment, but the geographic setting and the geometry of the depositional body are different. In addition to the stream gravels (fanglomerates) there are debris-flow deposits on many fans. Debris-flow deposits are very poorly sorted mixtures of gravel, sand, and mud.

talus slopes: local, not very important

beaches: high-wave-energy coasts, supply of coarse clasts from marine abrasion/shore erosion or fluvial source. Typically well sorted, well rounded, unimodal

glaciers: tills, deposited directly from moving ice, and glaciofluvial deposits, from meltwater. Tills are very poorly sorted mixtures of gravel, sand, and mud, hard to tell from debris-flow deposits; glaciofluvial gravels are largely the same texturally as nonglacial fluvial gravels.

deep ocean: both tractional deposits, not greatly different from fluvial gravels, and sediment-gravity-flow deposits, not greatly different from subaerial debris-flow deposits. We don't have a good understanding of either of these kinds of gravels, because we don't know where and when to look. Also glaciomarine deposits with dropstones.

2.5 Gravels vs. Sands

2.5.1 *Gravels and sands have a lot in common*. We think of them in the same way and in terms of both texture and significance (provenance, transport, deposition). Both are *washed and physically transported residues of rock weathering*. But there are *some characteristic differences*:

Composition: gravels are dominantly rock fragments, sands are dominantly mineral grains

Size distribution: the most common gravels are bimodal, the most common sands are unimodal.

Rounding: gravels have better rounded clasts, because gravel clasts wear down faster than sand clasts

Size trends: in most transport systems, gravels show much stronger downcurrent size decrease than sands

Stratification: sands commonly show cross-bedding and/or well developed even bedding; gravels seldom show cross-bedding, and are much less commonly well bedded than sands.

Abundance: gravels are much less abundant than sands

Extent: gravels are more restricted in areal extent than sands

2.6.1 Table 4-1 shows a classification of conglomerates. Keep in mind that extraformational epiclastic conglomerates are by far the most abundant deposits in Table 4-1. Here are some comments on them.

INTRAFORMATIONAL		
EXTRAFORMATIONAL	ORTHOCONGLOM. (matrix < 15%)	OLIGOMICT (unstable clasts minor)
		PETROMICT (unstable clasts major)
	PARACONGLOMERATE (matrix > 15%)	

Figure by MIT OCW.

Table 4-1: Classification of conglomerates

oligomict orthoconglomerates: simple composition. The only pebbles are those with very resistant lithologies (mainly vein quartz, chert, quartzite). Residuum derived from destruction of a much larger volume of rock (all the rest went somewhere as sand or mud or dissolved material). Very common in the geologic record but not volumetrically abundant. Thin discontinuous beds and stringers and lenses at the base of a sedimentary section (basal conglomerate) and at various points within a sequence. The rest of the section is typically sands, often pebbly and cross-stratified. Environments: fluvial, beach.

petromict orthoconglomerates: Most of the great conglomerates of the past. Tend to be thick wedge-shaped basin-margin accumulations shed from high-elevation, high-relief areas, tectonically rising. Usually form a substantial percentage of the section. Conglomerate equivalents of arkosic and lithic sandstones. Main constituents are potentially unstable rock fragments, usually several kinds. Tend to be coarse and thick. Clast rounding fair to good (but remember that it takes only kilometers to tens of kilometers for good clast rounding). Largely alluvial-fan or fluvial (meandering or braided). Some are deep-water conglomerates, apparently deposited in channels by sediment gravity flows, analogous to turbidite sandstones.

paraconglomerates (also called ***diamictites***): Larger clasts "float" in a poorly sorted matrix of mud plus sand plus finer gravel. Almost always unstratified, except for glaciomarine deposits. Important kinds genetically: glacial, nonglacial. Nonglacial paraconglomerates are often difficult to tell from tillite: typically unstratified, ungraded, very poorly sorted, subangular-subrounded clasts. Most seem to be sediment-gravity-flow deposits (high-concentration, slurrylike mixture of sediment and water, flowing under influence of gravity, on land and under water). These are the least well understood of conglomerates. The marine kinds are typically associated with marine sandstone and shale.

2.6.2 *Intraformational conglomerates are common too, but never very voluminous*. Intraformational conglomerates are formed by *fragmentation and redeposition of sedimentary material only shortly after deposition* (at least geologically shortly, if not in terms of human time scales), while the sediment is unlithified or only partly lithified. Minor episodes of stronger current, possibly also uplift to subaerial situation. Debris very local, little or no transportation. You can see all gradations between unimportant ripping up in place to total dispersal. The two commonest types are: Clasts of shale in sandstone; clasts of fine-grained carbonate rock in coarse-grained carbonate rock.

3. SHALES

3.1 Introduction

3.1.1 This section really should be entitled **fine-grained detrital rocks**; see the section on terminology below. Here we're dealing with everything *from freshly deposited muds to phyllites, and grain sizes from silts to the finest clays*.

3.1.2 *Shales are the most abundant of sedimentary rocks*, 40-70% by various estimates. And you can easily see why, by considering the products of weathering of source rocks: clay minerals and fine-grained quartz form a very high percentage of everything.

3.1.3 *Shales tend not to be as well exposed as sandstones, limestones, and conglomerates*, because they're softer and more easily weatherable. And *they're much harder to study*, because they're fine-grained and complex in composition. Only the coarser fraction can be studied easily under the microscope; methods for studying the finer fractions of shales are highly imperfect.

3.2 Kinds of Fine-Grained Deposits

3.2.1 Basically there are two kinds of fine detrital deposits:

residual mud: Deeply weathered parent rock is transformed to largely clay-mineral and clay-size material, still in place. It's essentially a soil. Sometimes you can still see relict textures, structures, and mineralogy of the parent rock. This stuff grades downward into fresher parent rock. By its very nature, there's not much of it in the geologic record (it forms a ***paleosol***, *an ancient soil preserved in the sedimentary record*), but when seen, it's very important for interpretation. When it's rich in aluminum hydroxide minerals, it's called ***bauxite***, and is *the main ore of aluminum*.

transported mud: Fine detritus is eroded from source areas and transported, mainly by water but also by wind and ice, to sites of deposition, mainly in the oceans but also in lakes and rivers. This is by far the more abundant kind.

3.3 Terminology

3.3.1 Terminology for fine-grained detrital deposits and rocks is not well standardized. Here are several terms you should be aware of:

clay: A tricky word. It's used in *three senses*: *size*, *composition*, and *material*. In the *size* sense, it's used for *all sedimentary material finer than 1/256 mm*. In the *compositional* sense, it's used for *clay minerals*, a large and varied group of minerals, mostly sheet silicates, that are found in abundance in fine sediments. In the *material* sense, it's used for *the sticky gooey material potters use*.

silt: sedimentary material 1/256 - 1/16 mm

mud: silt plus clay in approximately equal proportions, or in unspecified proportions.

shale: this common term has been used in two different ways:

- θ for *all detrital rocks finer than sandstones* (so that it's as broad a term as sandstone, conglomerate, or limestone), and θ for *fine-grained detrital rocks that show prominent fissility and/or cleavage*.

I'm partial to the first usage myself, and I think it's the majority usage.

Mudstone (mudrock): this term has had three usages:

θ for *all fine-grained detrital rocks*, as a synonym of shale in the first sense above;

θ for *all fine detrital rocks whose proportions of silt-size material and clay-size material is not known or cannot be known*; and

θ *for an indurated mud that is like shale (in the second sense above) but lacks fissility*.

I suppose I practice the second usage. I'm not sure what the majority opinion is.

siltstone: a mudstone or shale (same messiness as above) in which silt-size material predominates over clay-size material.

claystone: a mudstone or shale (same messiness as above) in which clay-size material predominates over silt-size material.

argillite: a fine-grained detrital rock more indurated than mudstone or shale by incipient metamorphism and less fissile than most mudstone and shale.

slate: a fine-grained low-grade metamorphic rock with prominent cleavage; usually derived from shale.

3.3.2 For the latest in detailed descriptive classification of shales, and a review of earlier classifications, see the book by Potter, Maynard, and Pryor.

3.4 Grain Size of Muds and Shales

3.4.1 What can we say about the grain size of fine detrital sediments and sedimentary rocks? *Not very much.* This is one of the most troublesome problems of sedimentary petrology.

muds: The usual method of size analysis is *settling*. Problems: (1) shape and density of particles is much different from quartz spheres; (2) aggregation is common (even dominant) in original deposition, so when you disaggregate the sample for size analysis (that's the standard thing to do), *your size analysis usually has little relevance to the original nature of the deposited particles*.

shales: *diagenesis has an important effect on size distribution*. To the extent that you can see mineral grains under the microscope, you can estimate their size, but how do you know the extent of recrystallization (even aside from the problem of aggregation noted under muds above)?

3.5 Typical Constituents of Shales

clay minerals: dominant except in the coarser siltstones. About 60% on average, maybe even more. Range from 40% to almost 100% typically.

quartz: 25% on average, mainly in the silt fraction. (Most shales, even seemingly very fine, have a substantial silt fraction.)

feldspar: also mainly in the silt sizes; more liable to be affected by diagenesis; 5-10% typically.

carbonates: about 5% on average; mainly calcite, but also dolomite and siderite (the last being authigenic). Calcite can come from biogenic material or chemically precipitated fine material in the depositional environment; you can't tell unless you see fossil fragments.

iron oxides: up to 5%, usually hematite; iron is in the form of oxides only when the environment is oxidizing; more later.

iron sulfides: pyrite is often abundant, if the environment was reducing.

various other minerals: lots of them, seldom very abundant.

volcanic glass: variable, minor.

amorphous silica: variable, usually minor, but abundant in the transition through siliceous shale to argillaceous chert.

organic material: ubiquitous; averages 1-2%, but sometimes up to 10-15%. (Important: *most of the organic material in the world is in shales!*)

3.6 Kinds of Shales

3.6.1 Here's a *very unofficial* tabulation of "kinds" of shales you're likely to run into. (I don't feel bad about presenting this to you, because there's no generally accepted classification of shales anyway.)

"common" shales: clay minerals plus quartz, plus some other minerals, about 1% organic matter; Fe is in reduced state, not abundant (about 1-2%). Usually some shade of gray, more or less fissile.

red shales: dominant fine-grained part of red-bed sequences. Notably unfossiliferous. Most likely nonmarine: occur usually in what seem to be fluvial depositional systems (more later). Red color is caused by very fine particles of hematite. But not much richer in Fe than common shales: up to 4-5%.

black (carbonaceous) shales: notably very fissile (often "papery"); very rich in carbon (10-15%); also in FeS_2, usually pyrite in fine-grained disseminated form (modern carbonaceous muds have several forms of FeS_2 usually lumped under the term hydrotroilite). Often also high concentrations of trace elements: V, U, Ni, Cu, etc. Deposited under anaerobic conditions. How produced is usually unclear: deep marine silled basins, restricted circulation of bottom waters; possibility of shallow closed lagoons etc. also; Black Sea muds are of this kind.

siliceous shales: grade over into bedded cherts; high percentage of amorphous silica. Very hard, durable, not easily weathered, not likely to be very fissile. Silica could be from volcanic ash falls or biogenic opaline silica.

calcareous shales: most shales have a very low percentage of $CaCO_3$, but some grade toward limestone (intermediate kinds are called calcareous shale through argillaceous limestone); rock gets less fissile, lighter weathering, fizzes, typically more fossiliferous.

3.7 Practical Things About Structures

3.7.1 I'll say some things about structures in shales here, because more than in most other rocks they're on a scale small enough to be seen and studied in hand specimen.

3.7.2 Many shales are *thinly laminated*, on scales of the order of a millimeter or less. The laminae tend to be *even and regular*. Some likely causes:

grain size
organic-matter content
carbonate content

Each of these, especially the last two, result in alternating lighter and darker laminae upon weathering.

3.7.3 Variations in grain size might result from *slight variations in supply from settling in a quiet-water environment*, or from *episodic influx of slightly coarser material due to storms*. *Seasonal differences in supply* might also be invoked. Seldom can you really pin anything down.

3.7.4 ***Fissility*** is *the tendency for shale (or any other sedimentary rock, for that matter) to split or part along bedding planes*. This is usually thought to result from greater or lesser concentrations of micaceous mineral grains lying parallel on bedding planes. But *many shales show neither lamination nor fissility*, bioturbation being a possible reason. (***Bioturbation*** is *the process of disruption of the original depositional nature of a sediment by the life activities of the epifauna and infauna*.) Then again, *many nonfissile shales are well laminated*.

3.7.5 ***Slaty cleavage*** (or rock cleavage, or just plain cleavage) is *a different kind of splitting tendency, developed during either diagenesis or incipient metamorphism*. This is generally thought to come about by reorganization and realignment of micaceous mineral grains in a stress/deformation field. Often, but not always, the cleavage is parallel to the axial planes of folds.

3.8 Clay Mineralogy

3.8.1 General

3.8.1.1 The ***clay minerals*** are *a varied group of silicate minerals, mostly phyllosilicates* (sheet silicates), that tend to be found as very fine particles, of the order of microns to small fractions of a micron, in fine sediments. There are several important varieties, none of which is dominant. Their proportions vary depending upon source-rock composition, weathering environment, and diagenesis.

3.8.1.2 As you can imagine, *clay minerals are not easy to study*: even in the coarser size range it's difficult to see them microscopically. Standard techniques for study include electron microscopy, which allows you to see the particle shapes beautifully, and x-ray diffraction, which allows you to identify their mineralogy, after a fashion. Probe techniques have been developed more recently. A complicating factor is isomorphous substitution among iron, magnesium, silicon, and aluminum in various ion sites in most of the clay minerals, leading to a great range of compositions.

3.8.1.3 Clay mineralogy is worth a whole course in itself. What I'll do here is just give you a cursory account of the most important clay minerals and their occurrence.

3.8.2 Structure

3.8.2.1 Two structural units are involved in clay-mineral structures:

octahedral sheets: two planes of closely packed oxygens and hydroxyls with a plane of Al, Fe, and/or Mg between. The Al, Fe, and/or Mg are in octahedral coordination with the O and OH; that is, each of the former is equidistant from six of the latter, which are arranged as an octahedron around the former. Figure 4-8 shows a rough sketch of the arrangement. Figure 4-9 is a more detailed view of the geometry, perpendicular to the sheet. The oxygen-to-oxygen distance is 2.94 Å, and the thickness of the sheet is 5.05 Å. If Al is in the octahedral positions, only two-thirds of the positions are filled; if Mg and/or Fe are in the octahedral positions, all of the positions are filled.

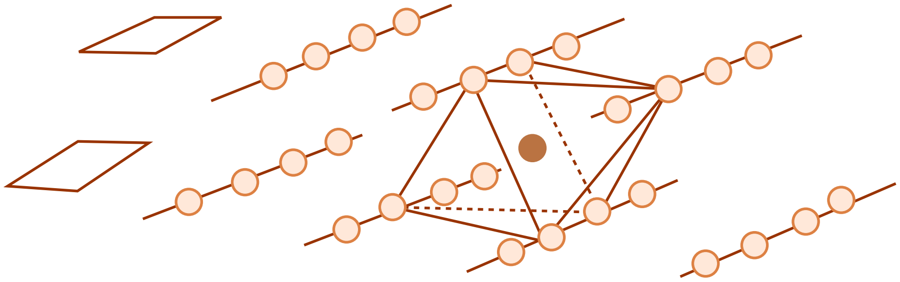


Figure 4-8: Sketch of the arrangement of atoms in the octahedral sheet of clay-mineral structures

Figure by MIT OCW.

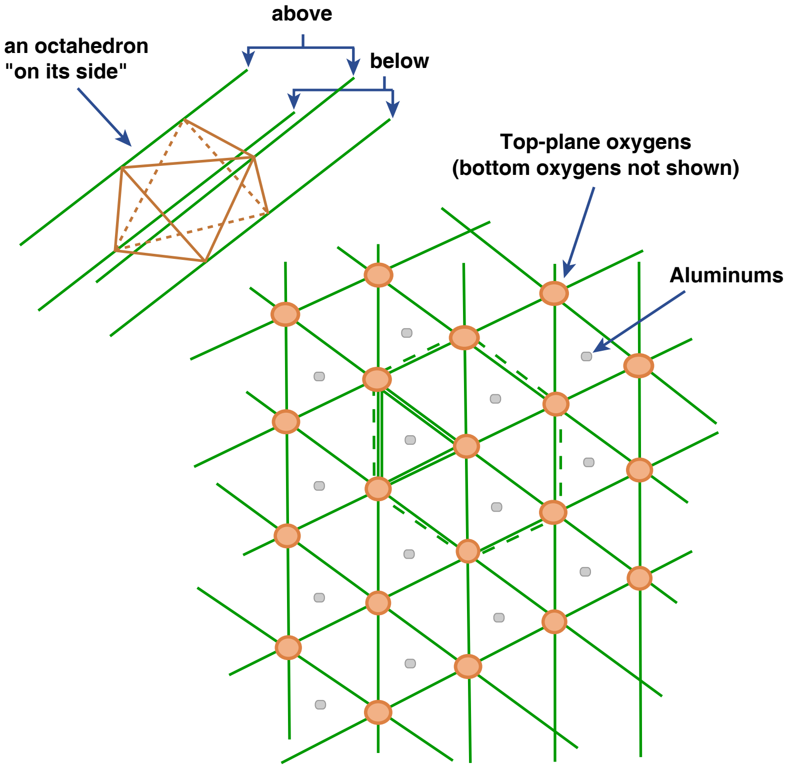


Figure by MIT OCW.

Figure 4-9: More detailed view of the geometry of the octahedral sheet of clay-mineral structures

tetrahedral sheets, in which silica (SiO_4) tetrahedra are polymerized by sharing of three of the four oxygens to form a sheet structure with hexagonal symmetry. Figure 4-10 shows two diagrammatic representations. The oxygen-to-oxygen distance is 2.55 Å, and the thickness of the sheet is 4.65 Å.

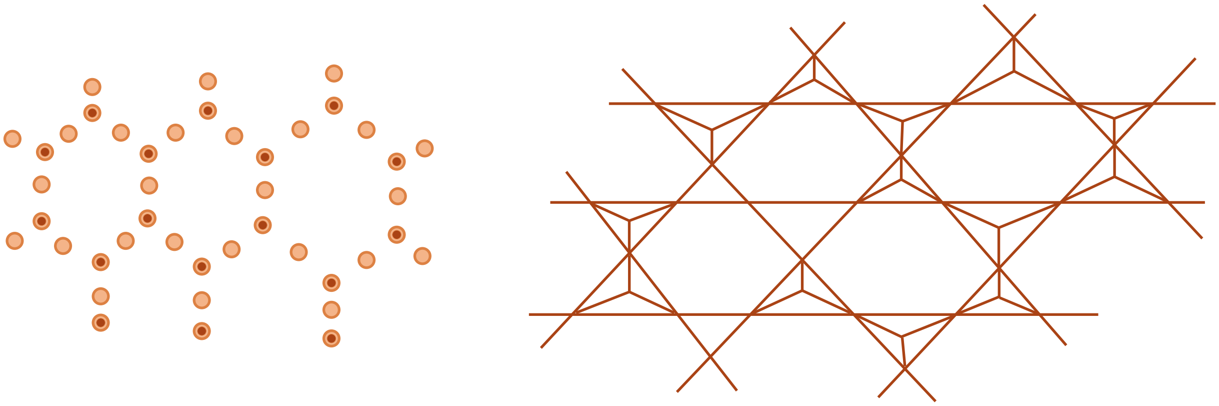


Figure 4-10: Diagrammatic representations of the arrangement of silica tetrahedra in the tetrahedral sheet of clay-mineral structures

Figure by MIT OCW.

3.8.2.2 *These two layers, or sheetlike arrangements, fit together, one on top of the other, in such a way that the vertices of the tetrahedra in the tetrahedral sheet point toward the octahedral sheet.* The unshared oxygens of the tetrahedral sheet and the oxygens of the octahedral sheet are the same; they are shared for double duty. The hydroxyls that form part of the octahedral arrangement fit into the hexagonal holes of the tetrahedral sheet.

3.8.2.3 The dimensions of the two sheets are almost but not quite right for this shared arrangement. There has to be some strain in the lattices to make them go together to share oxygens. This seems to be accommodated by alternate cocking of the tetrahedra, to contract the tetrahedral sheet a little, and stretching and thinning of the octahedral sheet to make it a little bigger. I'll schematize this two-layer structure as shown in Figure 4-11.

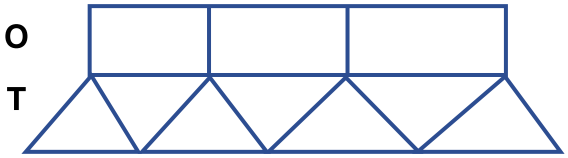


Figure 4-11: Sketch of the combination of octahedral and tetrahedral sheets in two-layer day-mineral structures

Figure by MIT OCW.

3.8.2.4 It's also possible to construct a three-layer arrangement in which a tetrahedral layer is sandwiched between two tetrahedral layers. Figure 4-12 shows the highly schematic way I'll represent this three-layer structure.

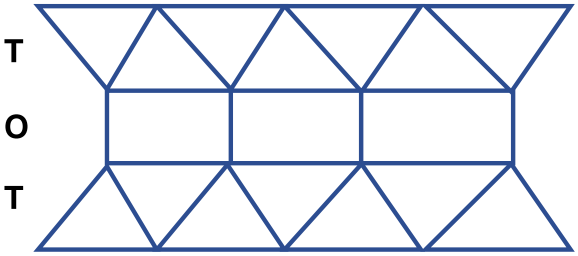


Figure 4-12: Sketch of the combination of octahedral in three-layer clay-mineral structures and tetrahedral sheets

Figure by MIT OCW.

3.8.3 Classification

3.8.3.1 The structural classification of sheet-silicate clay minerals is based on the octahedral-tetrahedral layer structure outlined above.

Kaolinite

Kaolinite is the main two-layer mineral. It's *fairly simple chemically*: $Al_4(Si_4O_{10})(OH)_8$, with no isomorphous substitutions; it's *the purest of the clay minerals*.

Only two-thirds of the octahedral positions are filled, by aluminum; minerals like that are called ***dioctahedral***. A consequence of this partial emptiness is that there can be *geometrically different stacking arrangements of the layers*, leading to polymorphism. There are two such stacking polymorphs, ***dickite*** and ***nacrite***, neither of which is nearly as common as kaolinite. The whole group of like minerals, kaolinite plus its two stacking polymorphs, is sometimes called the ***kandite group***.

There's *no net charge on the tetrahedral-octahedral layers*; the layers are held together only by van der Waals bonds. The repeat distance normal to the layers is 7.2 Å, so this group of minerals is sometimes called ***seven-Ångstrom clays***.

The crystals can get fairly large, up to tens of microns, because there's very little stress in the structure; *kaolinite is the coarsest of the clay minerals*.

There's also a hydrated form of kaolinite, called ***halloysite***, with a single layer of water molecules between the layers; this disorders the stacking and increases the interlayer spacing to about 10 Å.

Kaolinite is formed mainly by weathering of feldspars; production of kaolinite is favored by acidic and warm environments.

Illite

Illite is a *hydrous muscovite-like clay mineral*. It has the same three-layer structure as muscovite, but less than the one-in-four replacement of Si by Al that's characteristic of muscovite (the figure is between one-in-five and one-in-six). So there isn't the same charge deficiency as in muscovite, and not as many K^+ ions in the interlayer positions. H_3O^+ ions are also present in the interlayer positions. Also, substitutions in the octahedral layer are greater and more random; there's lots of variability.

Illite is *never found well crystallized, only as clay-size particles*. The particle size is typically less than one micron. This is because there's considerable stress in the layers.

As with the other micas, there are *polymorphs resulting from different stacking symmetry of the TOT layers*: 1M (one-repeat-layer monoclinic), 2M (two-repeat-layer monoclinic), 3T (three-repeat-layer tetragonal), etc. But usually these are hard to identify in illites.

Illite-sericite-muscovite are all similar, and called ***white mica***; there's progressively less Al substitution and therefore less interlayer K^+ and more interlayer water. There are no well defined boundaries, but the term ***muscovite*** is used for *metamorphic stuff*, the term ***sericite*** is customarily used for *diagenetic or incipiently metamorphic stuff*, and the term ***illite*** is used for *clay minerals in sediments and also in sedimentary rocks*. There's considerable overlap in usage, however.

Illite is formed mainly by *weathering of Kspar in temperate weathering environments*. With increasing intensity of weathering, kaolinite is formed instead.

Montmorillonite

Technically montmorillonite is one important mineral in what's called the ***smectite group***. Montmorillonite is a clay mineral which like illite has the basic muscovite arrangement but which is *able to expand by taking up a lot of water (or other polar molecules) in the interlayer positions*. The reason is that the bonds between the TOT units are weaker, because of details of stacking of the layers, and also because the charge imbalance is located mainly in the interior octahedral layer rather than in the outer tetrahedral layers. When the mineral is collapsed the layer spacing is 9.6 Å, but when fully expanded it's almost 20 Å.

Montmorillonite has variable percentages of large cations, Ca^{++} and Na^+, in the interlayer positions. There's substitution of Al for Si in the tetrahedral layer, and variable proportions of Fe^{++}, Mg^{++}, and Al^{3+} in the octahedral layer.

Montmorillonite is *formed by the weathering of plagioclase, ferromagnesian aluminosilicates, and volcanic glass*; its development is favored by alkaline environments.

Chlorite

Chlorite is *the most important regular mixed-layer clay mineral*. Its structure is an alternation of trioctahedral TOT layers, with Mg^{++} and Fe^{++} in the octahedral positions, and brucite layers, with the composition $(Mg^{++}, Fe^{++})_3(OH)_6$, giving a repeat spacing of about 14 Å. There's a great range and diversity of ionic substitutions in each of the three ion sites, as well as stacking polymorphs.

So chlorites are very complicated. Bonding between layers is by van der Waals bonds. Chlorite is produced in abundance only in relatively mild weathering environments, where it survives from the source rocks, although in the form of finer particles. So it's characteristically a high-latitude product.

Random mixed-layer minerals

Several combinations of clay minerals will interlayer randomly, because of generally similar basic atomic structure of all the sheet-silicate clay minerals. These minerals can be almost as stable as the single-layer minerals; they're abundant in both modern sediments and ancient rocks, although there's a tendency for regularization as diagenesis becomes stronger. Important kinds:

illite-kaolinite
chlorite-kaolinite
chlorite-vermiculite

Amorphous clay minerals

These are clay minerals with *little or no x-ray diffraction effects*, although apparently more ordered than just glass. Si is in tetrahedral coordination with oxygen, and Al, Fe, and Mg are in octahedral coordination with oxygen, but there's no regular longer-range structure.

There has been considerable difference of opinion about how important such minerals are. One reason is that they are very difficult to identify, especially when mixed with better-ordered clay minerals. In any case, they readily become better organized upon burial.

3.8.3.2 Figure 4-13 shows crude sketches of structural organization of the clay minerals.

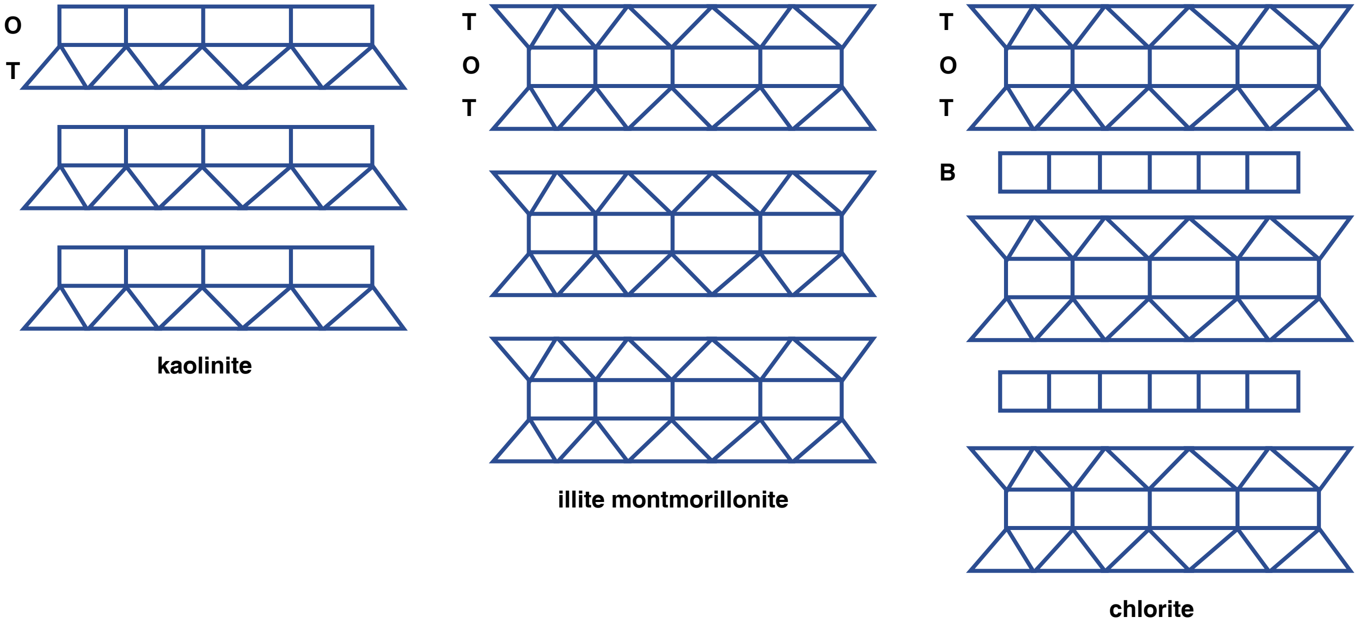


Figure 4-13: Sketches of the structural organization of clay minerals

Figure by MIT OCW.

4. VOLCANICLASTIC ROCKS

4.1 Introduction

4.1.1 Particulate volcanic material, once out of the ground, is in fact sedimentary material, so *all pyroclastic rocks could be treated as sedimentary rocks*. (I'm not recommending that you do this, however.) And commonly they're interbedded with strictly sedimentary rocks. Also, pyroclastic volcanic rocks grade over—both case by case and also in a given area—into sedimentary rocks sensu stricto composed largely or entirely of pyroclastic material.

4.2 Where are Volcanoes?

4.2.1 Mainly in the following kinds of places:

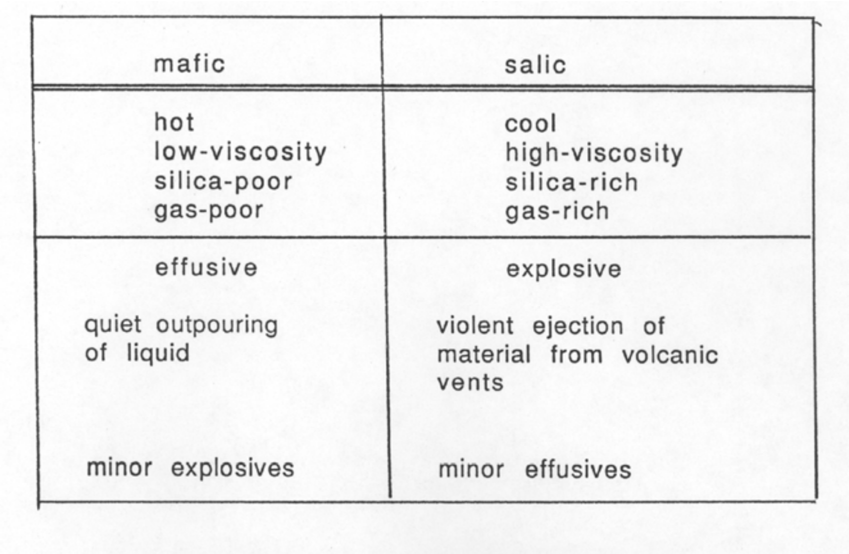
mid-ocean ridges, basalt; sedimentologically unimportant

subduction zones ("mobile belts" or "geosynclines" in the ancient); andesites, felsites; at continental margins; sedimentologically very important.

cratons, basalts etc.; sedimentologically not very important

4.3 What Comes Out of Volcanoes?

4.3.1 Table 4-2 shows an idealized spectrum of volcanoes. From Table 4-2 you should expect that the sedimentologically important volcanic material is *felsic pyroclastics*.



mafic	salic
hot low-viscosity silica-poor gas-poor	cool high-viscosity silica-rich gas-rich
effusive	explosive
quiet outpouring of liquid	violent ejection of material from volcanic vents
minor explosives	minor effusives

Table 4-2 Idealized spectrum of volcanoes

4.3.2 Particulate components that come out of volcanoes (all of which is called ***tephra***):

volcanic glass: shards (curved spicule-like forms, bubble-wall fragments), pumice (porous gas-filled solidified froth)

crystals: mostly phenocrysts separated out of the magma; quartz (euhedral, often embayed); plagioclase (often zoned); Kspar; lots of biotite flakes; hornblende, augite, etc.

volcanic rock fragments: cognate (lava broken up by later events); accidental (wall-rock blocks, mainly aphanitic felsic rocks).

4.3.3 Two important terms:

volcaniclastic: used for all fragmental volcanic rocks, any mechanism of origin, any depositional environment, any admixture of nonvolcanic components, but usually only if the volcanic component is dominant.

pyroclastic: used for rocks produced by explosive ejection of volcanic material from a volcanic vent.

4.4 Classification of Pyroclastic Material

4.4.1 The generic term for *solid particulate material that comes out of volcanic vents* is ***tephra***. Here's a breakdown of tephra by particle size:

blocks: >32 mm fragments, broken from previously consolidated lava; tends to be angular

bombs: >32 mm objects formed by solidification of lava in flight; rounded, often with "bread-crust" surface; a deposit of bombs is called an ***agglomerate***.

lapilli: 4-32 mm volcanic materials; deposit is ***lapilli tuff***

ash: <4 mm volcanic particulate materials; deposit is called *tuff*

4.4.2 The term ***tuff*** is used for *lithified deposits of tephra*; it's usually used just for ash-size deposits. Tuff can also be classified the basis of nature of particles: *vitric tuff*, *crystal tuff*, *lithic tuff*.

4.5 Kinds of Volcaniclastic Rocks

pyroclastic deposits: sediment deposited directly from volcanic emanations, in various ways. These are *commonly interbedded with "normal" sedimentary rocks*.

reworked pyroclastic deposits: newly deposited pyroclastic material reworked by water (in rivers or in shallow-marine environments); the material is pyroclastic, but the structure is epiclastic (produced by surficial processes); also included are debris-flow deposits. These *grade continuously into "normal" sedimentary rocks*.

erosional volcaniclastic deposits: sediments deposited in normal ways by erosion of volcanic source rocks. These *grade continuously into "normal" sedimentary rocks*, and differ from them only in that most of the material is volcanic.

4.6 Modes of Deposition of Pyroclastics

Ash falls: pyroclastic material is *ejected "loose" into the atmosphere and settles back to earth particle by particle*. The material is dispersed in an oblong fan downwind; grain size and thickness vary regularly. The deposit becomes fairly well sorted by fractionation by settling velocity. The deposit can cover hundreds to thousands of square kilometers, and forms key beds that lap across different geological provinces. The material can fall either onto land or into water bodies, resulting in *air-fall* and *water-laid* deposits. How do you tell these apart? If the water-laid material experiences no currents greater than threshold, it would be difficult.

Ash flows (also called ***nueés ardentes***): Basically *a subaerial density current*. The eruption produces a cloud of glowing particles and gas, at temperatures of 500-1000° C, which acts as a heavy fluid and flows down slopes at speeds of tens of meters per second. Such flows travel tens of kilometers or even more. The deposit often becomes welded after deposition (hence the term ***welded tuff***), because heat doesn't escape immediately, resulting in a welded tuff. Many rhyolites turn out to be welded tuffs when their texture is examined closely. Such deposits can also be submarine. These deposits are also called ***ignimbrites***.

Base-surge deposits: high-velocity, steam-laden, horizontally moving eruptive clouds, basically *an explosion phenomenon*; they're seen also in large artificial explosions like nuclear blasts. They can leave antidune cross-stratification! (And good overall stratification.) Sometimes the deposit contains airfall blocks analogous to dropstones in a glaciomarine deposit.

Tuffs weather readily. They have high porosity, large surface area, and chemically reactive volcanic composition. Feldspar weathers to kaolinite as soft earthy masses; glass weathers to silica in solution, zeolites, clay minerals; femags weather to dissolved silica, ions, and clay minerals. The ash readily loses its distinctive character. When completely altered, many ash beds are converted to ***bentonite*** (*a material usually consisting almost entirely of the clay mineral montmorillonite*).

4.7 Erosional Volcaniclastics

4.7.1 These are the rocks you're most likely to deal with in a sedimentary context. The nature of the rocks and the range of characteristics are the same as for nonvolcaniclastic sediments, but the composition of the particles is distinctive.

4.7.2 Typical constituents:

volcanically derived crystals: quartz, feldspar, etc. (even olivine)

glassy material, but readily weathered

rock fragments: gravel size, sand size

4.7.3 This stuff is weathered, eroded, transported by "ordinary" mechanisms, and then deposited in rivers, coastal environments, and marine environments.

4.7.4 One very characteristic kind of volcaniclastic deposit is ***debris flows***: These are unusually important in volcanic areas because of removal of vegetation cover then rapid erosion by heavy rains, and development of a high-concentration slurry. The term ***lahar*** is used for *large debris flows generated by heavy rain in an ash-covered landscape*. Lahar deposits show no stratification or sorting, with clasts of all sizes in a tuffaceous matrix. How would you tell lahar deposits from ash flows? No welding; pumice not collapsed; possibly more nonvolcanic stuff.

4.7.5 Other kinds of volcaniclastic deposits (not especially exciting):

- fluvial deposits
- beach deposits
- offshore sands
- turbidites

4.7.6 Deposits commonly found interbedded in a volcanic area:

- lava flows
- ash flows
- lahar deposits
- erosional volcaniclastics
- other sedimentary rocks
- soil horizons

4.7.7 Away from the immediate area of volcanism, one tends to find ash beds representing ash falls (constituting a very minor proportion of the section) interbedded with "normal" sedimentary rocks.