Terrigenous Deep-Sea Sediments

1. Introduction to Marine Sediments in General
   a. We will consider marine sediments from bathyal, abyssal or hadal depths. I will refer to them as open ocean marine sediments. We will focus on deep sea sediments, but include some mention of neritic sediments, which form in estuaries, open coastlines, the continental shelf, banks, platforms, plateaus, islands and other shallow water environments. However, we have already covered neritic sediments in lab as well as in preceding lectures.
   b. Open ocean marine sediments consist of particles and precipitates of a wide variety of origins. These particles and precipitates reach the deep sea floor by a variety of transportation mechanisms, and some of the particles are formed on the sea floor itself.
   c. We classify sediments by either descriptive or genetic terms.
      i. A descriptive system is used to classify sediments when the sediments are being viewed for the very first time. At this point, no data has been collected and we know virtually nothing about the sediment, so it is prudent to defer interpretation for later. Initially, the goal is to describe precisely what you see and can measure on the spot, and interpret later the origin of the sediment when you have more data. This is what you did when you described the cores in lab.
      ii. By contrast, a genetic system classifies sediment based on its genesis, which implies that you already know how it formed and you already know quite a bit about it!

2. Genetic Classification of Marine Sediments
   a. Genetic classification used in Kennett (1982) is useful in interpreting the greater significance of marine sediments, so we will use this type of classification for most class discussions. The genetic system used in the text is described below.
   b. Terrigenous (=lithogenous, derived from rocks from the oceanic or continental crust)
      i. Terrigenous sediments are composed of mineral grains that include minerals such as
         (1) quartz
         (2) feldspar (especially K-spar)
         (3) clay minerals [illite, kaolinite, montmorillonite (= smectite), chlorite]
         (4) mica
         (5) hornblende
         (6) pyroxene
         (7) amphibole
         (8) olivine
      ii. Volcaniclastic sediment - Sediments dominated by grains from volcanic origins are often put in their own class separate from terrigenous sediment.
         (1) mostly glass with some crystals or composite grains of glass and crystals
         (2) the crystals are feldspar (Na or Ca-spars), pyroxene, amphibole, olivine, hornblende, mica, and others
      iii. Sometimes terrigenous sediments are grouped by their mechanism of transport
c. Biogenous (produced by organisms)
   i. Calcareous (calcite or aragonite)
      (1) planktonic foraminifers
      (2) calcareous nannofossils
      (3) other minor constituents
         (a) pteropods
         (b) ostracodes
         (c) echinoids (spines), holothurians (spicules), sponges (spicules)
         (d) algal products - usually limited to neritic environments
         (e) calcareous bentonic foraminifers
   ii. Siliceous (opal = amorphous SiO$_2$.nH$_2$O)
      (1) Diatoms
      (2) Radiolarians
      (3) minor constituents: silicoflagellates, sponges (spicules), other
   d. Authigenic (derived from seawater = hydrogenous)
      i. Ferromanganese oxides (manganese nodules and crusts)
      ii. Smectite clays
      iii. Zeolites
      iv. Hydrothermal sulfides

3. Classification of Marine Sediments Based on Physical Description
   a. Below is an example of a descriptive sediment classification scheme. Deep sea sediments
      can be classified on the basis of the composition, shape, size, and arrangement of the
      constituents. The text describes the scheme developed by the Deep Sea Drilling Project
      (DSDP), then modified by the Ocean Drilling Program (ODP). [Just for your information,
      the program has changed hands from the U.S. to Japan, who has renamed it the
      International Ocean Drilling Program (IODP).] The sediment classification scheme I use
      below is described in a publication by Mazzullo and Graham (1987) and was used by ODP.
      This classification system is essentially a descriptive system, which can be subsequently re-
      interpreted genetically if desirable (i.e., dominance of radiolarian skeletons suggests a
      biogenic ooze). Descriptive classification systems are preferable to genetic systems when
      used in the field or during initial curation. This prevents apriori mistakes in interpretation
      and so avoids bias in gathering of primary information.
   b. Granular Sediment
i. Pelagic sediments
   (1) principal names describe composition and consolidation
      (a) ooze, unconsolidated calcareous and/or siliceous pelagic sediment (>60% pelagic and neritic grains)
      (b) chalk, firm pelagic sediment composed predominantly of calcareous pelagic grains.
      (c) limestone, hard pelagic sediment composed predominantly of calcareous pelagic grains.
      (d) radiolarite, diatomite, and spiculite: firm pelagic sediment composed predominantly of siliceous radiolarians, diatoms, and sponge spicules respectively.
      (e) chert (sometimes a chemical sediment if its origin is in question)

ii. Neritic sediments (not a deep-sea sediment)
   (1) Classified based on texture and fabric
   (2) (see p. 48, Mazzullo and Graham, 1987 for details)

iii. Siliciclastic sediments
   (1) Classification is based on consolidation and texture using Udden-Wentworth grain-size scale

<table>
<thead>
<tr>
<th>Subdivision</th>
<th>Phi units (φ)</th>
<th>Diameter (Fm)</th>
</tr>
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<tbody>
<tr>
<td>Granule</td>
<td>-1</td>
<td>2000 -</td>
</tr>
<tr>
<td>Very Coarse Sand</td>
<td>0</td>
<td>1000 -2000</td>
</tr>
<tr>
<td>Coarse Sand</td>
<td>1</td>
<td>500 -1000</td>
</tr>
<tr>
<td>Medium Sand</td>
<td>2</td>
<td>250 -500</td>
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<tr>
<td>Fine Sand</td>
<td>3</td>
<td>125 -250</td>
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<tr>
<td>Very Fine Sand</td>
<td>4</td>
<td>62 -125</td>
</tr>
<tr>
<td>Silt</td>
<td>8</td>
<td>4– 62</td>
</tr>
<tr>
<td>Clay</td>
<td>&lt;8</td>
<td>&lt;4</td>
</tr>
</tbody>
</table>

Fm = micrometer (10^–6 m)  
Phi = φ = -log₂ d, where d is the diameter of a grain.

(2) examples of sediment names: sand, silt, and silty clay for unconsolidated siliciclastic sediments and claystone, sandstone, etc. for lithified sediment.

iv. Volcaniclastic sediments: classification based on texture, meaning size of the particles
   (1) Sizes from large to small are breccia (has bombs >64 mm in diameter), lapilli (2-64 mm), ash (<2 mm).
   (2) and consolidation
      (a) called a tuff when consolidated
(b) called by its dominant particle (a breccia, lapilli or ash) when unconsolidated.

v. Major and minor modifiers used in classification of granular sediments

(1) describe proportions of grains by composition, texture and sometimes grain fabric, grain shape, and sediment color. Major descriptor precede the principal name whereas minor modifiers follow the principal name. This follows ODP procedure.

(2) proportions

(a) Trace amount (<10%), not included in the formal name
(b) Minor amount: principal name with ____ (10-25%)
(c) Major amount: major descriptor (>25%) principal name

(3) See Mazzullo et al. (1988) for additional information.

c. Chemical Sediment

i. Chemical sediment classes

(1) carbonaceous sediments (principally plant and algal remains, like peat or sapropels)
(2) evaporites (salt, gypsum, and anhydrite are typical evaporite minerals)
(3) silicate/carbonates (ones that are not granular and non-biogenic in appearance and they are described by their crystalline appearance like cryptocrystalline chert, massive calcite or dolomite.
(4) metalliferous sediments (nonbiogenic, non-granular sediments include pyrite, glauconite and are classified by their mineralogy.)

d. Application of Naming Scheme

i. Major constituents precede the principal name, minor constituents follow the principal name. Trace constituents are not included in the name.

ii. Example 1

(1) 65% forams
(2) 26% nannos
(3) 9% radiolarians
(4) unconsolidated
(5) = nannofossil foraminifer ooze with radiolarians

iii. Example 2

(1) 46% diatoms
(2) 31% radiolarians
(3) 14% silt
(4) 7% clay
(5) 2% ash
(6) = silty radiolarian diatom ooze with clay

4. More on Marine Facies
a. The factors influencing the formation of a particular type of sediment deposit are many, but the key factors are:
   i. provenance: proximity and nature of source
   ii. deposition, including transport to sea floor (pathway and mechanism), mechanics of settling onto and incorporation into the sediment.
   iii. post-depositional history, including bioturbation and early diagenesis (comparatively low temperature and low pressure compared to sediment deep below the sediment surface)

b. Brief introduction to the major marine facies:
   i. "Red Clay" (also called brown clay, pelagic mud, or deep-sea mud)
      (1) primarily made of authigenic and lithogenous material.
      (2) very fine-grained (texturally either silty clay or clayey silt)
      (3) consists of
         a) clay minerals, some of which are authigenic,
         b) eolian quartz1 and eolian feldspar (both are typically silt size)
         c) zeolites (authigenic)
         d) volcanic ash (eolian delivery)
         e) Mn nodules and micro-nodules
         f) biogenic phosphate (fish bone fragments, teeth, fish and mammal ear bones)
         g) magnetite (bacterially produced in situ)
         h) cosmic spherules (meteor debris)
      (4) found in deepest parts of ocean, far from continents, distant from sites of productivity, and below the CCD.
   ii. Volcanic muds
      (1) primarily volcanic constituents include
         a) ash, zeolites altered from ash, smectite clays altered from ash;
         b) grains larger than ash, like lapilli,
         c) and crystals;
         d) but often mixed with calcareous and siliceous shells in shallow water (<4,000 m), and siliceous tests in deep water beneath high productivity zones and terrigenous grains near continental sources.
      (2) found near hot spots above mantle plumes and spreading centers where volcanism is quiet. Also found near and down wind from island arcs where volcanism is explosive.
      (3) Average grain size decreases away from volcanic source
   iii. Glacio-marine sediments
      (1) primarily lithogenous

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1Some silt-size quartz may be authigenically precipitated from siliceous fossils rather than eroded and transported from land. See Schieber et al. (2000; Nature, 406:981-985 and 951).
(2) particles of wide size range, from clay to gravel, poorly sorted
(3) consist of clay, silt, sand, and rock fragments of diverse origin (glacier can erode a
very large area)
(4) transported onto continental shelf and even passed the shelf edge by
  glaciers/iceberg
    (a) from Antarctica from the Oligocene to Recent
    (b) Late Miocene, Late Pliocene through Quaternary in the North Atlantic and
        Pacific Oceans.
(5) Glaciomarine sediments can include dropstones, which are carried by ice bergs and
    are dropped when the ice bergs melt, which can be hundreds to thousands of miles
    from the glacier of origin depending on the currents.
iv. Calcareous Ooze
(1) primarily biogenous
(2) consists of foraminifers which are sand-size (smaller if broken), calcareous
    nannofossils, which are mostly fine silt and clay-size with minor amounts of other
    planktonic fossils like pteropods and ostracodes and minor amounts of benthic
    foraminifers.
(3) typically found at depths above calcium carbonate compensation depth (CCD) -
    think of white capped seamounts covered with carbonate ooze instead of snow.
    (a) CCD= 5000 m deep in Atlantic; 4,000-3500 m in S. Pacific, shallower in the N.
        Pacific (2400 m).
    (b) calcite becomes more soluble with
        (i) high pressure and low temperature, which makes calcite unstable below 5500
            m water depth in the modern oceans. This is a thermodynamic effect.
        (ii) increasing concentration of CO₂, which increases as follows.
            1) CO₂ is more soluble in cold water, which is what forms bottom water in the
               modern oceans. It gets its high charge of CO₂ from the atmosphere at the
               surface at high latitudes, where it is cold.
            2) increasing age of bottom water due to increasing concentration of CO₂ from
               respiration added during the Grand Tour from the North Atlantic basin to the
               North Pacific basin.
    (c) calcareous sediments are common from transitional to equatorial climates and
        rare in polar and subpolar climates due to dissolution and the shallow CCD.
        Calcareous sediments are common on bathymetric highs of the ocean sea floor.
v. Siliceous Ooze
(1) primarily biogenous
(2) consists primarily of two groups: diatoms, which are mostly silt-size but range
    from clay to sand-size; and radiolarians, which are mostly sand-size.
(3) found mostly beneath high-productivity zones of the ocean. In the modern ocean
    (a) radiolarians most common in sediments at low latitudes,
    (b) diatoms in sediments of high latitudes
vi. **Hemipelagites**
   1. primarily lithogenous, with significant biogenous admixture
   2. A range of particle sizes generally from coarse sands to clay, depends upon type of sediment delivered and mechanism of transport in the ocean
   3. Consists mostly of detrital silicate grains deposited by settling from sea water or by downslope transport like slumping and turbidity currents.
   4. Found on continental shelves, slopes, rises, and abyssal plains along dispersal pathways from the land to the deep sea.

5. **Terrigenous Sediment:** The remainder of these notes deals with terrigenous sediments, those derived from other rocks: later notes get to details of authigenic and biogenic sediments.
   a. First, look at how sediments get to where they are deposited. There are several methods:
      i. if biogenic and planktonic, then they fall (settle) from the surface to the seafloor.
      ii. if not biogenic, then must either be formed in place or formed elsewhere and transported in.
   b. **Input**
      i. Riverine input: mostly settles out near shore at the present high stand, but during low sea level, much river input will be transported across a narrow shelf to spill over the shelf break onto the slope. At the lowest stands of sea level of the Quaternary, rivers build deltas at the shelf break and empty sediment directly onto the upper slope.
      ii. Eolian input: blown off the world deserts
      iii. Glacial input: from rivers draining inland glaciers and glaciers that calve icebergs at the coast and ice shelves that calve icebergs.
      iv. There are other input mechanisms of lesser importance, but we don’t have time to explore them, alas. This list is incomplete, but accounts for most of the terrigenous sediment carried into the deep sea.
   c. **Dispersal upon reaching the sea**
      i. Settling: through the water column, the fate of eolian material, shells of planktonic organisms, ...
      ii. Currents and waves (occur in deep sea too. For example, western boundary undercurrent, internal waves that move along thermoclines)
      iii. Gravity transport: slumps, slides, debris flows, turbidity currents, creep, etc.
      iv. Other (i.e., advection along pycnoclines where they impinge on the slope)
   d. **Gravity flows:**
      i. **slumps and slides**: large blocks of sediment slide downslope along a slip plane. The blocks rotate so that the sliding edge moves down relative to the free edge. Beds that were originally horizontal dip into the slope. The blocks remain internally intact.
      ii. **debris flow**: large grains are supported by buoyancy in a slurry of small grains and water. The mixture flows under the pull of gravity on a slope because the slurry has relatively low viscosity. Self-lubricating
      iii. **grain flows**: grains provide mutual support. Move because they bounce against
one another while driven down hill by gravity.

iv. **fluidized sediment flow**: pore water percolates up and fluidizes (supports) the sediment while it flows under the pull of gravity. Needs very little slope. This is what wrecked Moss Landing Marine Lab in California during the 1989 earthquake. Quicksand operates under the same principle.

v. **turbidity currents**: turbulent motion of water within the flow keeps the sediment grains in suspension.

(1) *These are extremely important* and very common in the deep marine sediments, especially near continental margins and island margins.

(2) They can carry sediment 1000's of km downslope from their source

(3) Sandy, massive turbidites on steep slopes can move at terrific rates, 40-55 km/hr and with considerable erosive power and momentum. For example, turbidites resulting from a debris flow caused phone cables to break during the Grand Banks earthquake of 1929. The slide, debris flow, and turbidites were initiated by the earthquake.

(4) In contrast, dilute, fine-grain turbidites may travel very slowly and may not cause much erosion during their passage.

(5) Turbidity currents lay down characteristic deposits called turbidites.

vi. **Turbidites**


(2) Turbidites are typically graded from coarse, dense particles on the bottom to small light particles at the top. Some units are well sorted. The Bouma sequence describes small turbidites (see your text book) and the classification system of Mutti and Ricci Lucchi describe the full spectrum of turbidite deposits found in the ocean, the Bouma sequence being the finer grained types (see Mutti, E. and F. Ricci Lucchi, 1978, Turbidites of the Northern Apennines: Introduction to facies analysis, International Geology Review, 20(2): 125-166.

(3) The lithogenous type that originates from a lithogenous provenance consists mostly of silicate detritus deposited by settling from turbidity currents. This type is found on continental margins and abyssal plains, which are themselves built mostly from turbidites. It is porobably obvious that in areas with extensive carbonate reefs, the source material is shell carbonate, so the turbidites are made of shells. The sorting here is also by density, but some large shells are less dense than some smaller compact shells, so size does not correlate as well with density as it does in lithogenous material. So the grading may not be visually obvious, though it is graded.

(4) Bouma sequence, described from bottom to top.

(a) Massive, medium to coarse sand, poor or no grading, sharp scour base - unit A
(i) Rapid deposition from a high concentration suspension where size sorting is inhibited.
(ii) The unit is deposited during passage of the turbidite head.

(b) Parallel laminated and graded, medium sand - unit B
   (i) transition between hydraulic conditions of A an C
   (ii) passage of the turbidite neck

(c) Cross bedded, graded, medium sand - unit C
   (i) near bottom traction and saltation load
   (ii) passage of the upper turbidite tail

(d) Parallel laminated silts and mud, graded - unit D
   (i) turbulent flow alternates with laminar flow
   (ii) passage of the middle turbidite tail

(e) Mud unit also called unit E
   (i) flocs of clay and silt settle out
   (ii) deposited during passage of the last of the turbidite tail

**Terrigenous Sediments - Part 2**

6. Depositional environment of Continental Margins: Slope
   a. Sedimentologic importance (numbers from Kennett, 1982)
      i. Slopes contain 41% of all marine sediments (200 million km$^3$)
      ii. Aerially covers about 9% of the sea floor (28 million km$^2$).
      iii. Thickness of about 12 km on passive margins.

b. Technology
   i. The widespread use of side-scan sonar of various swath widths from high resolution narrow swaths only a few kilometers wide to GLORIA, which has a swath of 40 km;
   ii. SEABEAM, a high resolution bottom profiling system;
   iii. Submersibles have dramatically changed our image of the sea floor and points toward activity of un-imagined processes.

c. Morphology
   i. Shelf break
      (1) lies near 130 m on average
      (2) the depth coincides approximately with the maximum fall in sea level during the last 1-million years of glacial maximums.
      (3) the shelf break is a profound environmental boundary subject to an unusual group of processes (breaking internal waves, shelf-edge front, etc.)

   ii. Slope
      (1) upper slope
         (a) slope steeper than lower slope, 15°, maximum gradient below shelf break
         (b) exceptions to typical morphology
            (i) can be different on fault controlled slopes and slopes made of accretionary
prisms.
(ii) usually different near deltas where sediment supply is large
(iii) different morphology on carbonate platforms

(2) lower slope
(a) lower limit 4-5 thousand meters in Kennett, 1982; but the lower limit is more typically cited at 2,000 meters. This limit varies with the author and the region, so beware. The slopes of the east coast margin bottoms at 2000 m whereas the slopes of the west coast margin (fault controlled) bottoms at ~4000 m.
(b) the bottom of the slope is defined where the incline lessens to less than 1 in 40 or about 3° to 6°
(c) a continental rise or deep sea fan forms at the base of the slope.

iii. Features on the slope
(1) canyons
(a) morphology
(i) Straight type of canyon
1) Head on slope
2) Broad valley floor, shallow
3) Scarps suggest headward erosion
(ii) Meandering type of canyon
1) Notch the shelf and at low stand of the sea may or may not have connected to an onshore-river canyon.
2) Narrow, floor bracketed by tall wall.
3) Meandering path.
4) "Point bars" and undercut canyon walls in meanders suggest active process.
5) What is the cause of canyon meanders? It remains incomplete answered.
(iii) Both canyon types have gullies that dissect the intercanyon divides.
1) gullies form by mass wasting.
2) gullies introduce fine-grain sediment onto the canyon floor.
(iv) Both types of canyons have sand-rich sediments on their floor relative to intercanyon regions, which are thick deposits of hemipelagites.
(v) Pattern of canyons and gullies incised on slope:
1) dentritic,
2) canyons of the slope merge on the lower slope and upper rise and a few channel ultimately empty onto abyssal plains.
(vi) Erosion processes
1) turbidity currents, which are infrequent in Holocene but common in Pleistocene, incise and downcut canyons
2) creep and mass wasting moves sediments down canyon floors and gullies
3) bioerosion of canyon and gully walls
4) tidal currents also move sediment on canyon floors

(2) Intercanyon regions
   (i) built up by
      1) spillover of sediment from the shelf, advection along and settling from
         pycnoclines that impinge on the shelf and slope, turbidity currents, net
         tidal movement downslope.
      2) slumps and slides can modify the form of canyon and intercanyon areas
         a) (Normark, 1990) Ranger Submarine Slide, Baja California
         b) Big Sur slide
         c) South Wilmington Canyon slump blocks
   (ii) the shape of the lower slope is modified by
      1) contour current transport (Segall et al., 1989)
      2) erosion by gullies and canyons

(3) Subsurface structure of the slope (definitions discussed in Kelling and Stanley,
    1976 and references therein)
   (a) passive margins
      (i) wide shelves
      (ii) prograding slopes of moderate gradient
      (iii) laterally extensive continental rise built of wedges of sediment
      (iv) can be modified by local faulting (Blake Plateau) and deltas
      (v) subside at slow rates, 10cm/1000yr, in contrast to active margins. New
         Zealand, for example, subsides at 300cm/1000yr!
   (b) active margins typically have these features, which differ from those of
      passive margins.
      (i) Active margins with transforms faults,
      (ii) narrow shelves,
      (iii) steep, fault-defined slopes often with step and platform morphology like
         the California Borderland and the Mediterranean Sea
   (c) Active margins with subduction zones
      (i) flanked by deep trenches
      (ii) narrow shelves,
      (iii) accretionary wedges from offscraping of sediments from subducting
         plates
   (d) Active margins at backarc basins - buttressed margins
      (i) marginal sea type behind island arcs
      (ii) very wide and shallow shelves like South China Sea
      (iii) can be narrow like Taiwan
      (iv) morphology depends on stage of development of the marginal basin

(4) Effect of climate change - Lower sea-level (Piper and Normark, 1989)
   (a) Sediment delivery increased dramatically due to increased continental erosion
      since the onset of Pleistocene-style glaciation 2.5 million years ago.
(b) Sediment delivery to the deep sea is greater by about an order of magnitude during glacial lowstands compared to high stands of the sea. The effect is due to increased continental erosion by rivers and glaciers and delivery of sediment directly to the shelf break in contrast to storage in coastal estuaries as happens today. Eolian transport is also greater during glaciations due to increased extent of deserts and/or faster atmospheric winds.

(c) Relict topography in canyons suggests periods of rapid down cutting (Pantin and Stubblefield, unpub.), apparently during glacial low stands. Evidence for such downcutting includes hanging gullies, meanders stranded 100 meters above floor of canyon, and the fact that no process active at present, or at least at present scales, seem capable of incising meandering canyons suggests that the canyons were cut during some past climatic regime.

(d) Canyons form during low sea level, and are filled during high stands, given enough time!

iv. Deep sea fans
   (1) formed by turbidites that deposit at the exit from deep sea canyons at the base of the slope.
   (2) morphology of the fan is controlled by the direction of local sea level change (falling or rising) and the rate of sediment input
   (3) a “cone” in JPK is a large fan. The name “cone” is not widely used today.

v. Abyssal plains
   (1) remarkably flat and smooth
   (2) formed by turbidity currents that pond in an enclosed basin.
   (3) can include coarse grain turbidites on fans nearest continental sources (like the Hatteras Abyssal Plain), but most are made of turbidites that are very fine grained (like the Madeira Abyssal Plain)
   (4) The turbidites cover over the basaltic abyssal hills of the basement that are formed by crustal faulting of the flanks of oceanic ridges.
   (5) Plains typically contain alternating layers of pelagic sediment deposited during high sea level, and turbidites, deposited during low sea level.
   (6) Most abyssal plains in the Atlantic began to form in the Oligocene Epoch, when glaciation commenced on Antarctica.

7. Clays
   a. Mineral clays (as opposed to clay-size particles) are layered aluminosilicates with varying amounts of hydration and specific mineral structures. They are present in almost all sediments and dominate the constituents of some. For example, "red clay" or pelagic clay is such a sediment. Mineral clays generally are also clay-size.
   b. Formation of clays:
      i. some form through metamorphic processes on continental rocks
      ii. others through chemical weathering of igneous rock
iii. others through submarine alteration of other clays, minerals, or volcanic glass by ion exchange
iv. Others form by mechanical weathering of igneous or metamorphic rock.

c. We do know something about the processes which form some of the more common clays, and especially that they reflect the type of soil in the source region which in turn reflects a response to climate: Four clays, which are very important because of what they can tell us of their source region, are illite, chlorite, kaolinite and montmorillonite (=smectite).

d. Chlorite:
   i. Chemically UNSTABLE a pressure and temperatures of the surface earth.
   ii. found only where erosion is dominated by mechanical processes and chemical weathering is unimportant (e.g., high latitudes).
   iii. Chlorite is a metamorphic mineral that mechanically erodes out of metamorphic rock and is dispersed to the sea.

e. Illite (general term for the mica group)
   i. most common clay mineral
   ii. produced by mechanical weathering of continental rock
   iii. stable on Earth’s surface; found in all climates
   iv. reflects input patterns of rivers and winds

f. Kaolinite
   i. Produced by chemical weathering of rocks
   ii. More abundant where chemical weathering is most aggressive (e.g., in the tropics).
   iii. Varies inversely with chlorite.

g. Montmorillonite (Smectite)
   i. Alteration product of volcanic material
   ii. This volcanic material can be from land or sea
   iii. Takes 20 m.y. to change, a slow process. This statement is highly arguable, but it is beyond the scope of the course to get into the details. Be aware that marine geochemists are coming forward with remarkable new data formation of clays in the marine environment.

h. Characteristic patterns
   i. chlorite dominant clays in cold and temperate zones
   ii. kaolinite dominate clays in tropical regions
   iii. We can use this information to interpret various things including --
      (1) paleo-positions of climate zones on continents nearby our deposition site
      (2) intensity of weathering (more or less clay produced during a period of time)

8. Windblown (Eolian inputs)
   a. mostly in arid regions, like the Sahara and deserts of Mongolia
   b. follow wind patterns
      i. surface winds (e.g., trade winds)
ii. high altitude winds like the jet stream

c. Components:
   i. whatever was eroded, generally lithogenous
   ii. quartz is common and often a major component. Can include small rock pieces, feldspar
      and of course, clays.
   iii. other debris
      (1) freshwater diatoms
      (2) phytoliths (siliceous plant parts)

d. useful for paleo-interpretations of weather patterns
   i. winds
   ii. distribution of arid climates

9. Volcanic sediments: clastic debris resulting from volcanic activity. So almost everything
   except lava, which is a rock rather than sediment!
   a. pyroclastics- clastics resulting from the explosion
   b. epiclastic - reworked volcanic rocks
   c. Ash is important in deep marine environments.
      i. Volcanic glass and crystals like feldspar, pyroxene, etc, which are those formed as part
         of magma differentiation.
      ii. Grains are < 2 mm in diameter
      iii. ash falls may be LOCAL, TROPOSPHERIC, or GLOBAL
      iv. big particles settle fastest, therefore, if you look at particle size distribution across
         an ash horizon, you can look at the strength, direction of wind plus estimate the
         source of the material
      v. Global ashfalls are extremely fine; may take years to settle

10. Glacial sediments: (or ice covered, now or then)
   a. Arctic and Antarctic differ
      i. Arctic: mostly sea ice
         (1) this accumulates sediment during the winter, when it restricts normal settling
         (2) releases its load during the summer
         (3) Greenland and its surrounding are the exception. Here there is a big glacier with
             tremendous glacial erosion, gouging of the shelf, etc.
      ii. Antarctic: glacial ice
         (1) sea ice is less important due to ring of glaciers (dominant ice on the continent
             rather than covering the sea)
         (2) glacial ice and icebergs are more important in Antarctica
         (3) Scrape up sediment, can carry big boulders
         (4) Distribute coarse material nearest continent, but much less sorting and grading by
             size than gravity driven processes.
         (5) Large stones can be ice-rafted great distances from land - Dropstones
         (6) Sediment delivery to the sea may be episodic or seasonal
11. Extraterrestrial Sources
   a. microtektites
      i. = small hundred (s) of microns
      ii. Formed from ejecta of a large impact event (asteroid of comet)
      iii. quantity may indicate occurrence of a catastrophe. In fact, layers coincide with major climatic changes; extinctions
   b. Cosmic debris
      i. Spherules from stony and metalliferous meteorites
      ii. Very minor constituents of marine sediment, but very interesting.

REFERENCES ON THE SLOPE ENVIRONMENT
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