# Notes for Clastics and Coal Core-Logging Workshop

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## 1.0 The Importance of Core Logging Clastics and Coal Sedimentary Rocks

Clastic sedimentary rocks are composed of the detrital fragments of preexisting rocks and minerals and are one of three principle subdivisions of sedimentary rock classification (clastics, carbonates, and non carbonates [e.g., coal]). Hundreds of millions of dollars is expended each year for exploration core and rotary drilling in the search for commercial deposits of oil, gas, coal, and other industrial or precious minerals in the world, however, inaccurate or insufficient information is often recorded on the physical properties of the rock penetrated. Many focus their efforts on describing the target units or zones of commercial interest and record scant information on the majority of the down-hole section. Moreover, the economic zones of interest are not completely or consistently logged by individuals working for different companies in the same geographic areas. Time and money saving measures are no doubt important considerations of industry and consulting professionals, however, the practice of inconsistent levels of precision in logging and use of these logs is often regretted.

Although frequently looked on with disdain and at times relegated to new, inexperienced geologists, the task of core logging is in fact a highly specialized skill requiring careful observation, clear and accurate recording, and considerable personal discipline. Good drill logs are the primary record keeping document of the geologist and are used repeatedly by other individuals in varied technical disciplines. Logs must be clear, correct, and legible. The log contains the basic data used in geologic analysis, interpretation, and resource calculations and is the basis for economic evaluation and decision making (Erickson and Padgett, in Darling, ed.,2011).

A brief section on core logging of coal beds (and non-coal partings) is included in this report because of their economic importance. The importance of log detail in coal, parting, roof, and floor material is emphasized.

The purpose of the workshop is to instruct the user how to identify and describe (log) megascopic clastic cores in a sequential manner, with applications to hand samples, field exposures, and thin section petrography. The workshop will hopefully provide the user with needed information for better description or logging of clastics and coal and facilitate consistency in future logging.

## 2.0 Preparing for Core Logging

Before heading to the drill site or storage location to log core samples, a scope of work must first define the level of detail needed for the project, and several tools and logging aids will be required to measure and describe the core samples efficiently. These are described in the following subsections.

## 2.1 Level of Detail and Precision in Logging

The level of detail and precision in a core logging project is dependent upon the purpose of exploration and intended use of the log data. The level of detail should consider whether physical and or chemical tests will be subsequently performed on core samples of interest. The level of detail should also consider that the mesoscopic observations of the core samples can often be related to other mesoscopic observations of outcrops, road cuts, mine highwalls, as well as microscopic observations or analyses of samples in thin sections, electron microprobes, or X-ray fluorescence.

An academic sedimentologist, industry petroleum geologist, and geotechnical geologist or engineer would probably log the same core sample of a sandstone with differing terms and levels of detail and section interval thicknesses. The level of section detail should be predetermined by the core logger to adequately define the variation of the megascopic physical (and chemical) characteristics of the economic deposits or beds of interest. There is a tendency among industry professionals to list only the bare minimum of detail to save time and money. However, the core logger should consider that he will only have one opportunity to examine the core, and that there may be an added focus in the future on some other ore mineral, coal seam, or sandstone unit as a target; therefore, it is important to capture details for all sections of the core that may become important later.

It should not be forgotten that exploration core logging data is often the primary data source of geological and engineering based investigations. Core logging is used with other mesoscopic studies of outcrops, road cuts, mine highwalls, microscopic studies of petrographic thin sections, geophysical data of buried storage tanks and buried grabens, and remote sensing applications of light detection and ranging (LIDAR) and side looking airborne radar (SLAR) used for slope stability, seeps, and ore body trends. Moreover, core logging data is meant to be quantitative and therefore more useful in other mesoscopic and microscopic studies.

## 2.2 Core Logging Manuals

Core logging manuals are very useful for identifying rock types encountered in core samples. A logging manual is a small, flip-page, water repellant booklet with high-quality color photographs of typical rocks penetrated in regional sedimentary basins. Each core photograph has a basic description of the sample rock type, scale and an alpha-numeric code that facilitates data entry. Numerous published logging manuals are available for various regions or principal rock groups, such as Carboniferous coal bearing units in the Pocahontas Basin (Ferm and Melton, 1977), Southern Appalachian Coal Fields (Ferm and Weisenfluh, 1981) and within and adjacent to Devonian-Mississippian black shale sequences (Ettensohn and Hendricks, 2015).

### 2.3 Graphic Strip Logs

Core logging, data compilation, and interpretation are heavily dependent of visual presentation "as geologists think and communicate best in pictures" (Erikson and Padgett, in Darling, 2011). The graphical form of the geologist log is the strip log, and a simplified but scaled strip log should be produced from each core hole. Paper strip logs are typically three inches wide and divided incremental divisions of inches and tenths of inches that can be used to represent scales of tens to hundreds of feet (**see Figure 1**). There is no set format for constructing a strip log; the nature and length of the log will depend on the purpose of logging and the total depth. Essential information will generally include thickness, lithology, color, grain size and sedimentary structures.

The strip log should be sketched by the core logger during the down hole drilling operation to monitor the strata penetrated and correlate with other strip logs from nearby holes. This becomes very important if a project's core holes are drilled in different inclinations. The strip log is a quick and valuable reference for core loggers interpreting and predicting changes in target depths, coal core points, hole completion total depths, and therefore provides much needed assurance to the driller and office project manager.

### 2.4 Core Logging Tools

Essential core logging tools include log description and strip log templates, clip board, steel tape ruler (20 ft.) or a folding wood ruler (6 ft.) having tenths of feet increments, indelible felt pens for marking core boxes, wax crayons for marking core samples, rock hammer or sledge hammer, pocket knife for testing hardness, hand lense (10x magnification), hydrochloric acid (10% solution) for testing reaction to acid, digital camera or cell phone camera. Optional equipment includes core logging manuals, rock color charts, sample bags for rotary cuttings or augered unconsolidated sediments, and a hand-held Global Positioning Device (GPS) device for recording core hole location and surface elevation.

### 2.5 Location and Header Data

It is critical that the core logger collect locational and appropriate header data for all drilling assignments. This may appear obvious but it is often neglected in fast moving, multiple hole

**Figure 1.** Photograph showing examples of strip logs. The log on the left exhibits graphic representations of the lithologies and features in the lithology column; feature descriptions are written out to the right. The short log in the center shows the lithologies with color, with sedimentary features shown graphically to the right. A strip log template and a roll of logs are shown on the right.

campaigns. A hand-held GPS device is useful for determining latitude, longitude and surface elevation of drill holes, and these data may be needed before an engineering survey crew is able to visit the field to record the precise data at the staked locations. The project client, mine name or property owner, pit, bench, level, section, township, range, county, are vital information. The name of the drilling company, head driller, rig type, drill hole identification number, drill inclination, core diameter, dates of start and finish, etc. should always be recorded by the core driller for reference. The record should always include casing depth, sidewall or "perm plug" tests, plugging, and general hole conditions. Note taking should be brief and descriptive, employ standard abbreviations, and be quantified where possible (Erikson and Padgett, in Darling, 2011).

## 2.6 Determination and Listing of Core Loss

Core loss is a going concern in exploration core drilling and must be considered before core sample intervals are defined and described in the field or at the storage facility following the completion of the bore hole. The reasons for core loss are numerous and are not discussed here. Logging requires that the total core recovery (TCR) is measured to provide a record of the proportion of core recovered. The TCR is defined as the proportion of core recovered to the total length of the drilled run. The TCR includes both the solid core and the non-solid (or non-intact) core (Valentine and Norbury, 2011). The primary goal of the core logger, however, is to determine the relative position(s) of the core loss within or among the recovered samples of the core run.

Due to relative hardness and intactness, core loss tends to occur more frequently in claystones and coal seams than in other sedimentary rocks. The precision for logging coal seams and placement of in-seam core losses can be refined if the logging of the coal seams is done with the aid of an expanded scale geophysical log derived from the same bore hole after the drilling is completed. In most exploration core holes, however, the core hole is not geophysically logged.

The driller will typically measure and record the total length and bottom depth of the core placed in the core tray after each core run, and prior to placing the samples in the core box. His reason for doing so is to account for quality assurance/quality control (QA/QC) protocol related to drilling contract quotas for percentage of core recovery. As a time saving measure there is a tendency for some drillers (and core loggers) to assign and record the core loss at either the base or top of the recovered samples. However, it is the objective of the core logger, not the driller, to determine the most likely placement of the core loss within the core run. The core logger should first ask the driller for his opinion of where the core loss may have occurred within the core run. Based upon the driller's observed changes in water circulation, drill bit rotation, and drill speed during the core run, the driller will generally provide a reasonable answer. Nonetheless, the core logger should carefully examine the entirety of the recovered core and its relative intactness and observe the presence of abrupt or unusual changes in rock types, core intactness, jointing, fracturing, and weathering. There may also be erratic inclusions of wet clay, pebbles, or other surface cavings at a core loss point. Considering these criteria, the core logger should judiciously allocate the placement and length of core loss section(s) within a core run as deemed appropriate. An 80% TCR within a core run of predominately poorly intact claystone and coal beds might infer the placement of two to four separate intervals of core loss whereas an 80% TCR within a core run of moderately intact sandstone might infer the placement of one to three separate intervals of core loss. The core loss top and bottom depth and thickness intervals should be recorded on the log, and if reasonably deduced from the adjoining core samples, list an assumed rock type. The core loss intervals should also be clearly indicated within the core sample interval sleeves in the core box for reference and display in core photographs. This is accomplished by the placement of small wood blocks listing "Core Loss" and the associated depth intervals at the corresponding depth intervals.

Apparent core gains can occur where core is accidently dropped from the core barrel during the trip out of the hole but retrieved on the subsequent core run. This will yield a core recovery of less than 100% in the first core run but may result in a core run exceeding 100% in the subsequent run. Physical evidence for core gain includes markings of from the core catcher spring or a long single stick or core at the top of the subsequent run. Recoveries greater than 100% should be adjusted by deducting the presumed excess core at the top of the lower run and adding it to the lower part of the upper core run (Valentine and Norbury, 2011).

Core samples should be rinsed in a bucket of clean water to remove drilling muds and fluids by the driller or driller's assistant before placing in core boxes. This procedure will greatly enhance the results of core examination, logging, and photography.

### 2.7 Boxing of Core Samples

Boxing of core samples is usually performed by the driller or driller's assistant but should be carefully watched by the core logger. Errors in transferring the core from the sample tray and misorienting the core in the box, marking the top and bottom of core boxes, and replacing missing or dropped pieces of core in the box are a going concern. Coal industry-based drilling companies typically use wax based cardboard containers with a 10-foot core length capacity for NQ (core diameter = 1.88 in/47.6 mm) and BQ (core diameter = 2.5 in/63.5 mm) sized core samples, with intervening core box sleeves of 2 feet length. The top of the core should be placed at the top left corner of the core box, and the remaining core placed to the right of the preceeding sections. Coal cores and some oversized PQ (core diameter = 3.34 in/85 mm) sized "tight sand" and "tar sand" samples are occasionally boxed in customized wood containers for special handling and shipment.

The core logger should make sure the core segments properly fit together in the box, and that "Top" and "Bottom" are marked both on the inside and outside cover of the core box with an indelible ink or felt pen. The box cover should include the client name, core hole identification number, box number, and depth interval.

### 2.8 Marking of Core Samples

After the samples from a core run is examined for core loss, it is suggested that the core logger have an overview of the core, and to identify and mark the position of the sharp and gradational lithology contacts with a wax crayon. Marking fault contacts and bedding inclination or apparent dip is also recommended. This manner of marking samples is highly efficient for portraying these interpretations in color core photographs. Intervals that are to be sampled and removed for subsequent laboratory analysis, which may not be apparent at the time of the overview, should be marked as "SAMPLE" in a bold color scheme.

## 3.0 Principle Data Groups of Sedimentary Rocks

The principle data groups to identify and record during logging of clastic (and non clastic) sedimentary rocks are texture, structure, and composition. Texture is the size, shape, and arrangement (packing and fabric) of the components of a sedimentary rock. Some textures, porosity for example, are not simple properties but are complex and dependent upon the more fundamental grain characteristics, such as grain shape and sorting (Pettijohn, 1957). Textural properties are geometric and therefore useful for statistical analysis. The structures of sediments are those larger features that, in general, are observed or studied best in outcrop rather than hand specimen, core sample, or thin section. Structures are both inorganic and organic in origin. The inorganic structures are classified as either "primary" or "secondary." The primary structures are mainly dependent on current velocity and rate of sedimentation. Primary structures include "bedding" in the broadest sense, and all features included thereunder such as cross-bedding, graded bedding, ripple mark, and other bedding-plane phenomenon. The secondary structures are mainly the products of chemical action penecontemporaneous with sedimentation or shortly thereafter. Concretions, nodules, cone-in-cone, septaria, geodes, stylolites, and the like, are included as secondary structures (Pettijohn, 1957). The organic structures are the direct or indirect consequences of organic action. These include "fossils" in the broadest sense and include not only the petrifactions, but also trace fossils (ichnofossils) such as tracks, trails, borings, and so forth (Pettijohn, 1957).

## 4.0 Standard Descriptive Format

In describing clastics, or any rocks for that matter, a definite method and sequence of descriptive criteria should be used for consistency. For brevity, log descriptions are usually not listed in complete sentences, rather, they are listed in a specific sequence of descriptive criteria, known as "telegraphese," which uses single words or phrases separated by commas or semicolons. The log description for clastics should always begin with the principle rock type, followed by a comma, and in turn listed in the order of importance, by the properties of mineralogy (composition), color, weathering, grain size, grain shape, grain roundness, grain sorting, induration (hardness), cement or matrix, sedimentary structures, and fossils present. The typical sequence of descriptive criteria is as follows:

- **Lithology (rock type),**
  - **Mineralogy (composition),**
    - **Color,**
      - **Weathering,**
        - **Grain size,**
          - **Grain shape,**
            - **Grain roundness,**
              - **Sphericity,**
                - **Grain sorting,**
                  - **Induration (hardness),**
                    - **Cement or Matrix,**
                      - **Sedimentary structures (bedding, etc.),**
                        - **Fossils**

The above list is comprehensive and probably best suited for academic based research projects. A hand lense (10x magnification) should be used to better estimate grain shape, roundness, sphericity, and sorting, which are important for determining relative porosity and permeability. As a time saving measure, however, these criteria are often not logged but are quantified using a microscope or other laboratory methods.

### 4.1 Lithology (Rock type)

The most important criterion is the identification and listing of the lithology or rock type. For simplicity the basic siliciclastic rock types are defined on the relative percentages and proportions of component sand, silt, and clay sized grains and therefore includes sandstone, siltstone, and claystone (**see Figure 2**). "Shale" is a commonly used hybrid term containing varying proportions of sand, silt, and clay but universally accepted. "Conglomerate" is coarser than sand sized clastic rock and contains a predominance of rounded rock fragments, whereas "breccia" contains the same size class but a predominance of angular rock fragments.

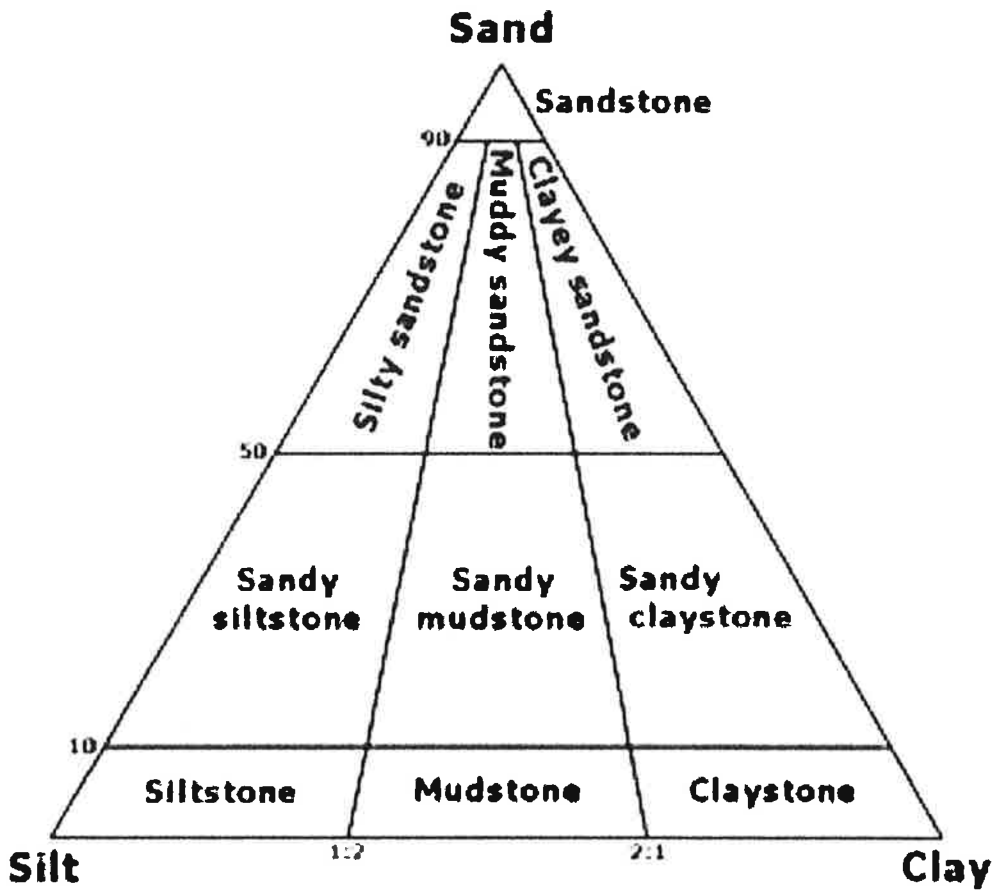


**Figure 2.** Ternary diagram of classification of siliciclastic rock types based upon the relative percentages (horizontal axes) and relative proportions (vertically inclined axes) of sand, silt, and clay sized grains (from Shepard, 1954).

### 4.2 Mineralogy (Composition)

The mineralogy (composition) of clastic rock is usually implied by the identity of the basic rock types, but it is a very significant aspect of rock characterization. Most sedimentary petrologists and core loggers consider exactness of mineralogic definition not worth the time involved. The level of mineral characterization is low in sedimentary studies compared to requirements in igneous and metamorphic petrology (Blatt et al., 1980). Many Carboniferous age sandstone and conglomerate units in the Eastern Interior (Illinois) Basin and Central Appalachian Basin have a very high percentage (>95%) of quartz ($SiO_2$) and so the mineral composition is often overlooked or not logged. Consideration must be taken, however, if the purpose for logging is for oil and gas reservoir studies or frac sand resource evaluations.

There have been over fifty classifications schemes proposed for sandstone. Most in current use involve a ternary QFL (quartz, feldspar, lithic/rock fragments) ternary diagram for framework grains and major divisions based on the relative amount of matrix. An example of a ternary diagram which shows the matrix component is that of Dott (1974); **see Figure 3**).

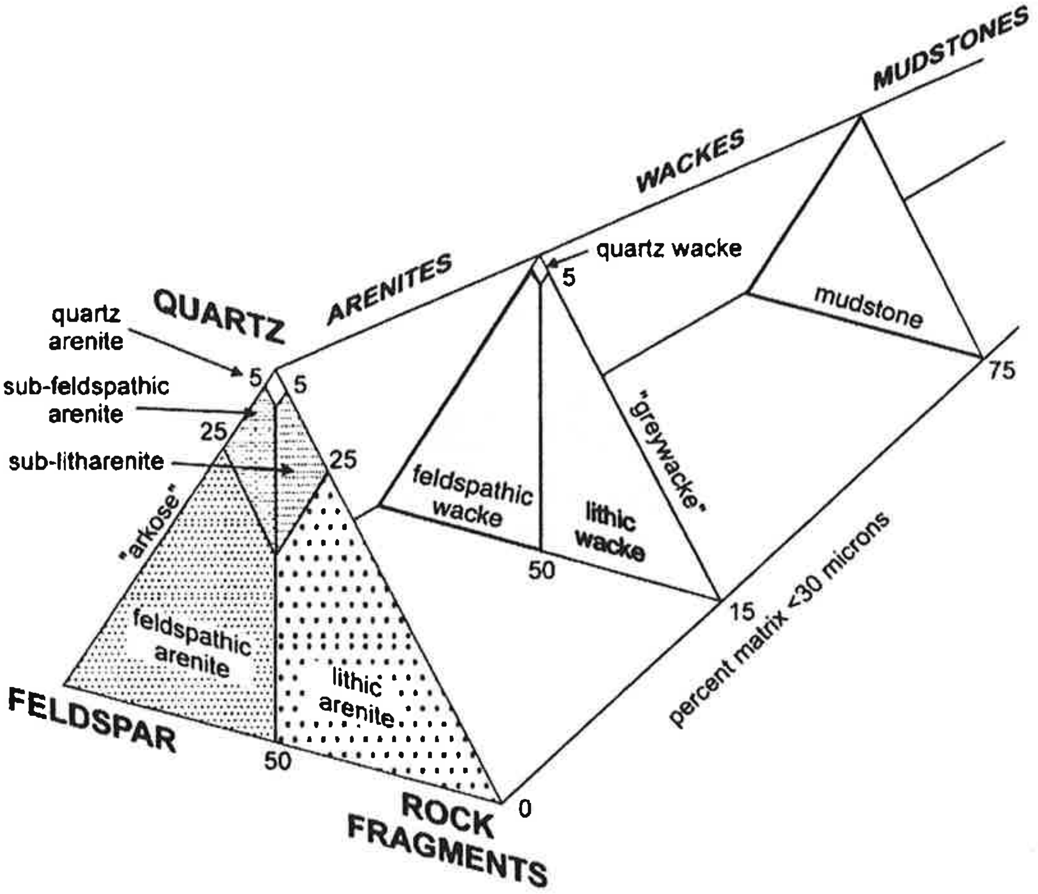


**Figure 3.** Ternary diagram of sandstone classification based upon percentage of mineral composition (quartz, feldspar, rock fragments) and percentage of rock matrix (from Dott, 1974).

### 4.3 Color

Color is one of the most obvious characteristics of a sedimentary rock and may convey information about composition, depositional setting, weathering, and oxidation state during deposition or after exposure. Color typically exemplifies some aspect of rock composition. A rock may exhibit a bulk color while also having components of different colors. The color may be derived from matrix, cement and various grains or impurities, including organic matter and clays.

Therefore, clastics may exhibit the entire spectrum of color from white to black, including green and red hues. Hence, color is often an important characteristic in describing clastics, but a problem In describing colors arises because humans see colors differently, which can contribute to issues of inconsistency. To alleviate such problems where colors truly matter, rock-color charts and notations are used for uniform descriptions. Most U.S. rock-color charts use the Munsell color system, a color solid that specifies colors based on three properties of color: hue (the color or shade of color), value (lightness or darkness) and chroma (color purity or intensity; **see Figure 4**).

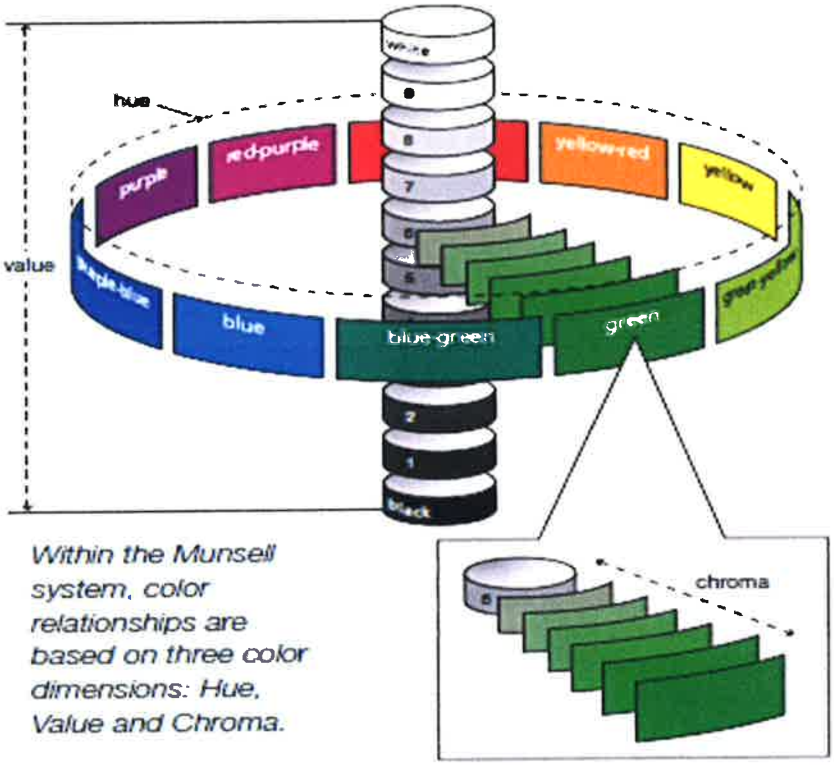


**Figure 4.** An illustration of a Munsell color solid (a sphere) that delineates color based on hue around the circumference (a particular gradation of color), value on the vertical axis (lightness or darkness), and chroma on the various radii (color intensity or saturation.) (http://artquill.blogspot.com/2012/11/the-munsell-color-classification-system.html)

For example, a typical rock color might be light-brown (5 YR 5/6), wherein the first designation "5YR" represents the hue, the second designation "5" represents the value, and the third designation "6" represents the chroma. The various Munsell colors are displayed as chips on a card with an associated color designation to which the rock color of the sample is compared (**see Figure 5**). The user can then select the closest color designation or interpolate between the chips to obtain a more accurate designation. If the logger does not have access to a rock color chart,

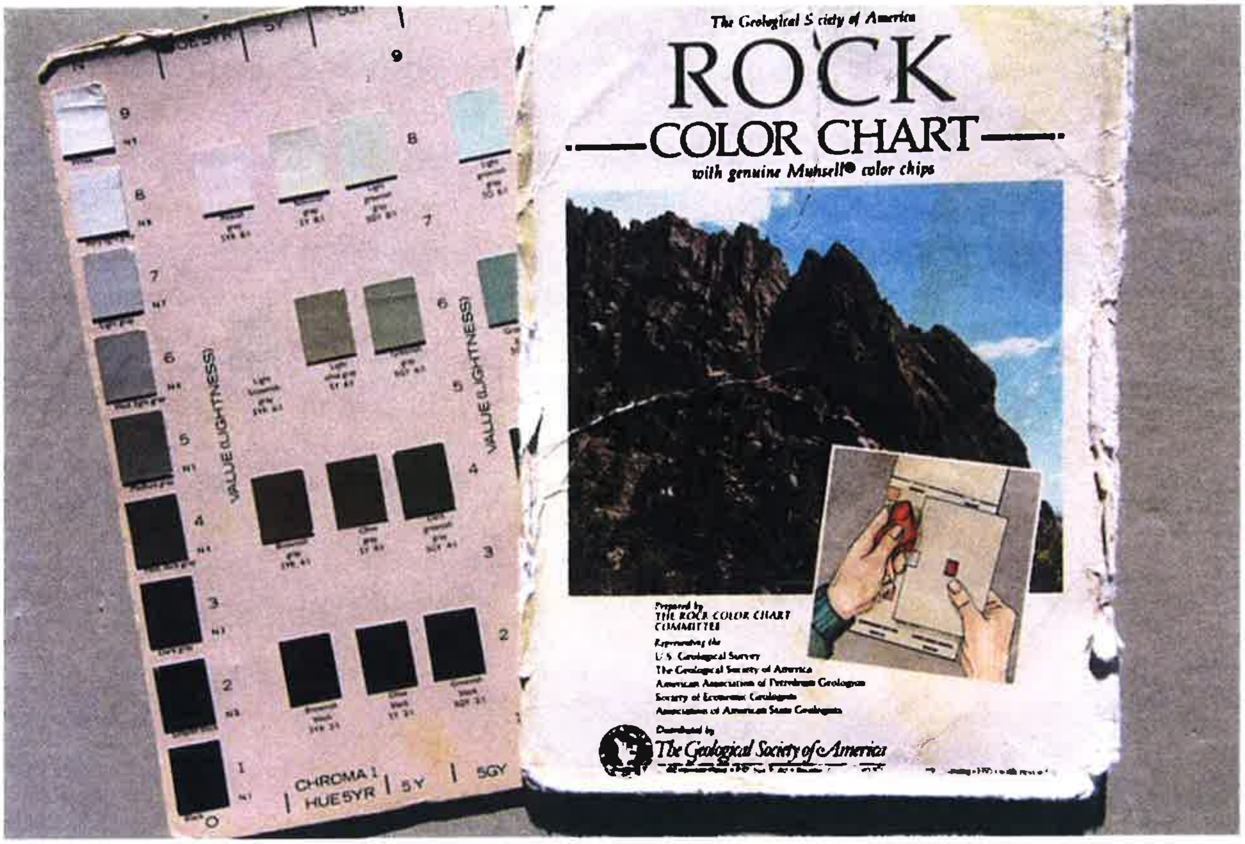


**Figure 5.** A photograph of an undated Geological Society of America Rock Color Chart, showing comparative color chips and Munsell designations one of the pages.

then the logger should make a consistent effort to distinguish shades of color by adding the appropriate suffix (e.g., very light, light, medium, dark, and very dark).

The core logger should record whether the core sample is dry or wet, as wet tends yield a darker value. There is no widely accepted choice of logging wet core samples, but wet core tends to be present in the very shallow subsurface and should be distinguished from otherwise dry core.

Finally, the core logger should note the presence and describe any secondary variable colors within a measured section of core. These occur in a characteristic geometric pattern and would be described as bands, streaks, blotches, mottling, speckling, and staining.

### 4.4 Weathering

The amount or extent of weathering follows the color description because weathering usually affects the color of the sample. Post depositional alteration of iron, manganese and other minor or trace elements from groundwater activity can impart darker or brilliant hues to the sample. The core logger can often observe various degrees of weathering within the first tens of feet of depth in the core sample due to proximity of joint surfaces or expansion fractures. The geotechnical geologist or engineer is usually interested in the physical strength of the rock, and the degree of weathering offers a relative indication of rock strength. The extent of weathering can be qualified as fresh or non-weathered, slightly weathered, moderately weathered, highly weathered, and completely weathered (**see Table 1**).

| Extent of Weathering | Surface Characteristics | Extent of Discoloration | Fracture Condition | Original Texture | Grain Boundary Condition |
|---|---|---|---|---|---|
| Fresh or Non weathered | Unchanged | None | Closed or discolored | Preserved | Tight |
| Slightly Weathered | Partial discoloration | 20% of fracture spacing on both sides of fracture | Discolored; may contain thin filling | Preserved | Tight |
| Moderately Weathered | Partial to complete discoloration; not friable | 20% of fracture spacing on both sides of fracture | Discolored; may contain thick filling | Preserved | Partial separation |
| Highly Weathered | Friable and possibly pitted | Throughout | | Mostly preserved | Partial separation |
| Completely Weathered | Resembles a soil | Throughout | | Partly preserved | Complete separation |

**Table 1.** Extent of weathering qualifications based upon surface characteristics, discoloration,and grain boundary conditions (from Core Logging Committee of the South Africa Section of the Association of Engineering Geologists, 1976, http://www.rockmass.net/files/core_logging_guide.pdf).

### 4.5 Grain Size

The grain size of a clastic rock is of considerable importance. The size of the fragments of which the rock is composed is in part the basis of subdivision into conglomerates, sandstones, siltstones, and shales (Pettijohn, 1957). A classification of sediment grain size diameters based was first proposed by Udden (1898) who introduced the term "grade" to refer to the sizes intermediate between two defined points on a size scale. The names proposed by Udden to describe the size grades were later modified by Wentworth (1922) and is the modified (Udden-Wentworth) grade scale that is widely used today. Krumbein (1934) introduced a logarithmic transformation of the Udden-Wentworth scale which included a phi (ø) scale, which was subsequently redefined by McManus (1963) as a dimensionless number:

$$\emptyset = -\log_2 \frac{d}{d_0}$$

Where $d_0$ is the standard grain diameter (i.e., 1 mm)

Use of the phi scale permits use of arithmetic rather than logarithmic graph paper and simplifies the calculation of both graphic and numerical descriptive statistics, such as mean, standard deviation, skewness, and kurtosis (Blatt et al., 1980). The Udden-Wentworth grain size class and associated phi scale designations are listed below (**see Table 2**).

| Millimeters (mm) | | Micrometers (μm) | Phi (ϕ) | Wentworth size class | | Rock type |
|---|---|---|---|---|---|---|
| | 4096 | | -12.0 | Boulder | Gravel | Conglomerate/ Breccia |
| | 256 | | -8.0 | Cobble | | |
| | 64 | | -6.0 | Pebble | | |
| | 4 | | -2.0 | Granule | | |
| | 2.00 | | -1.0 | Very coarse sand | Sand | Sandstone |
| | 1.00 | | 0.0 | Coarse sand | | |
| 1/2 | 0.50 | 500 | 1.0 | Medium sand | | |
| 1/4 | 0.25 | 250 | 2.0 | Fine sand | | |
| 1/8 | 0.125 | 125 | 3.0 | Very fine sand | | |
| 1/16 | 0.0625 | 63 | 4.0 | Coarse silt | Silt | Siltstone |
| 1/32 | 0.031 | 31 | 5.0 | Medium silt | | |
| 1/64 | 0.0156 | 15.6 | 6.0 | Fine silt | | |
| 1/128 | 0.0078 | 7.8 | 7.0 | Very fine silt | | |
| 1/256 | 0.0039 | 3.9 | 8.0 | Clay | Mud | Claystone |
| | 0.00006 | 0.06 | 14.0 | | | |

**Table 2.** Udden-Wentworth grain size class and phi scale designations (from Wentworth, 1922).

It is time consuming to measure sediment grain size during logging. A graphic sediment grain size scale should be used. An example is shown below (**see Figure 6**).

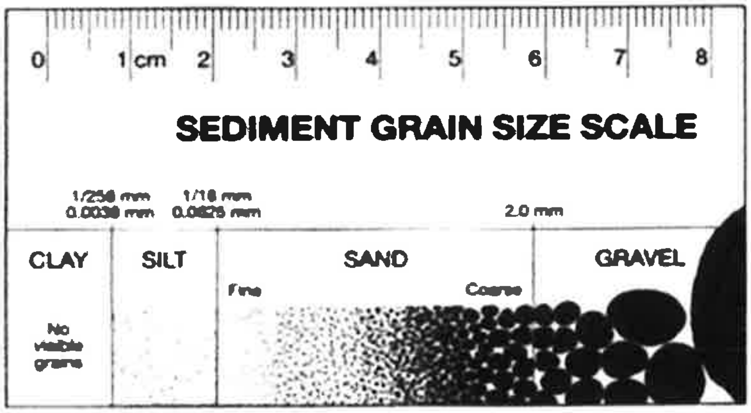


**Figure 6.** Illustration of a graphic sediment grain size scale (from http://faculty.chemeketa.edu/afrank1/rocks/sedimentary/sedtexture.htm)

### 4.6 Grain Shape

The shape and roundness of pebbles and sand grains have long been used to decipher the geologic history of a deposit and distance from a source or provenance. Grain shape should not be confused with grain roundness. Most sand sized grains approach the shape of a sphere and can simply be called spherical. A perfect sphere has internal axes of equal length. Pebble sized grains are more difficult to classify. Zingg (1935) classified pebble shapes on the basis of diameter ratios of grain axes, where a is the length (long axis), b is the breadth (intermediate axis), and c is the thickness (short axis; **see Figure 7** and **Table 3**).

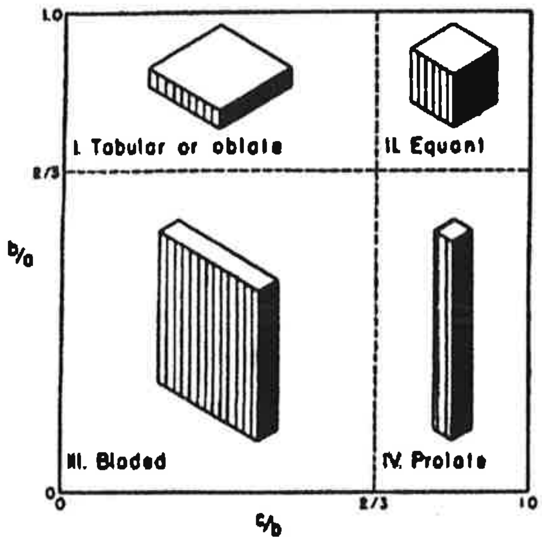


**Figure 7.** Illustration of pebble shape classes. Note that the representative solids shown have the same roundness (0) but they have different shapes (from Zingg, 1935).

| Class No. | b/a | c/b | Pebble Shape |
|---|---|---|---|
| I | > 2/3 | < 2/3 | Oblate (Disc-shaped or tabular) |
| II | > 2/3 | > 2/3 | Equant (Spherical) |
| III | < 2/3 | < 2/3 | Bladed (Triaxial) |
| IV | < 2/3 | > 2/3 | Prolate (Rod-like) |

**Table 3.** Geometric relations of pebble shape classes, where a is the length (long axis), b is the breadth (intermediate axis), and c is the thickness (short axis; from Zingg, 1935).

### 4.7 Grain Roundness

Grain roundness concerns the sharpness of the edges and corners of a clastic fragment. It is independent of shape. Wadell (1932) quantitatively defined roundness as the ratio of the average radius of curvature of the corners of the grain image divided by the radius of the largest inscribed circle. This is expressed as:

$P$ (rho) = $\sum (r_i/R)/N$
Where $r_i$ = individual radii of the corners
N = number of corners
R = radius of the maximum inscribed circle

By such definition, a sphere has a roundness of 1.0 as well as a sphericity of 1.0. Roundness is difficult to measure and very time consuming, and the results are often not repeatable by different persons or the same operator. Russell and Taylor (1937) defined five roundness classes or grades (**see Table 4**):

| Grade Terms | Class Limits | Description |
|---|---|---|
| Angular | 0 to 0.15 | Showing very little or no evidence of wear; edges and corners sharp. Secondary corners numerous (15-30) and sharp. |
| Subangular | 0.15 to 0.30 | Showing definte effects of wear. The faces are virtually untouched; edges and corners have been rounded off to some extent. Secondary corners numerous (10-20) though less so than in angular class. |
| Subrounded | 0.30 to 0.50 | Showing considerable wear. The edges and corners are rounded off to smooth curves. The area of the orginial faces is considerably reduced. Secondary corners much rounded and reduced in number (5-10). |
| Rounded | 0.50 to 0.70 | Original faces nearly absent, but some comparatively flat surfaces may be present. All original edges and corners have been smoothed off to broad curves. Secondary corners greatly subdued and few (0-5). |
| Well Rounded | 0.70 to 1.00 | No original faces, edges, or corners remain. The entire surface consists of broad curves; flat areas absent. |

**Table 4.** Grain roundness classes and geometric limits (from Russell and Taylor, 1937) and their associated descriptions (from Pettijohn, 1957).

The most commonly used method of estimating roundness is visual comparison of grains with standard images of known roundness (Powers, 1953; **see Figure 8**).

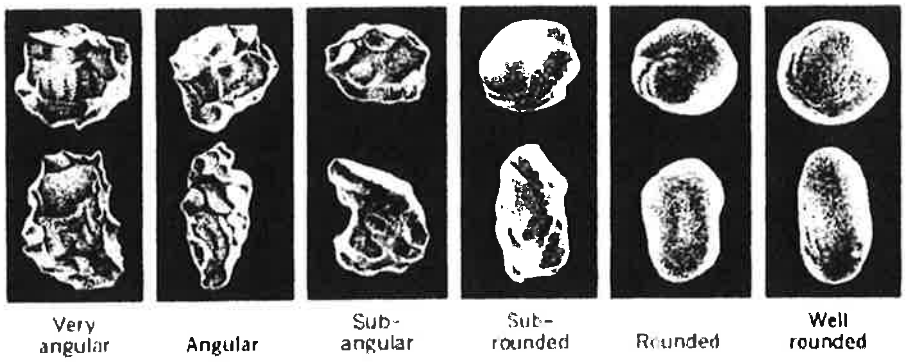


**Figure 8.** Images of grains for the determination of roundness. Images on the upper row represent grains of high sphericity, and images on the lower row represent grains of low sphericity (from Powers, 1953).

### 4.8 Sphericity

Grain sphericity is usually not considered in core log descriptions because of the time and detail required to collect these microscopic data. However, it is one of several important criteria for determining and testing the type and quality of deposits of frac sand used as a proppant in horizontal drilling operations for oil and gas. A proppant chart based on a geometric scale of grain sphericity and grain roundness produced by Krumbein and Sloss (1963; **see Figure 9**) is the primary reference, and a value of $\geq$0.6 for each is the industry standard (Benson and Wilson, 2015). Although the measurement of grain sphericity is not possible during core logging, the core logger can nonetheless observe and record whether the sample merits further testing and precision analysis.

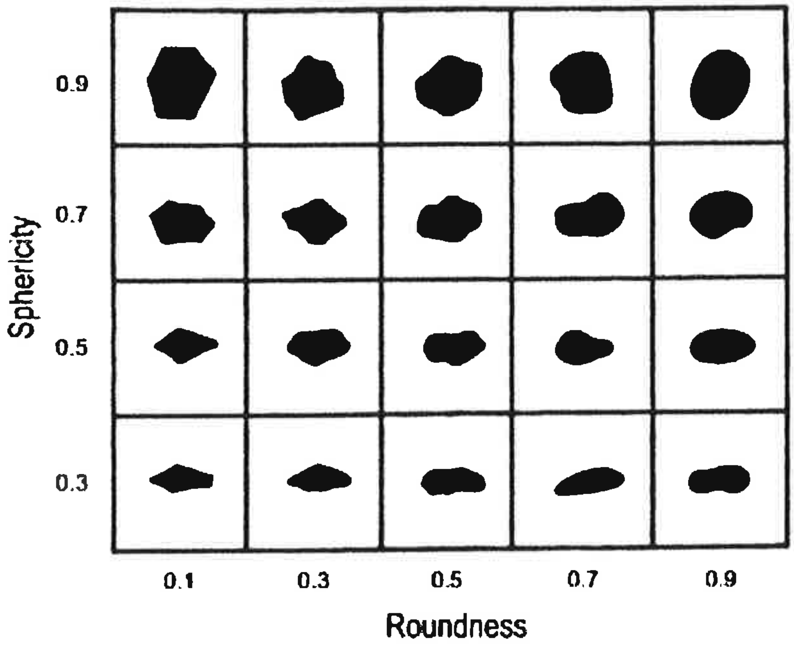


**Figure 9.** Chart of geometric grain sphericity and grain roundness for determining the quality of frac sand deposits used as a proppant in horizontal drilling (from Krumbein and Sloss, 1963).

### 4.9 Grain Sorting

Grain sorting originally referred to the number of size grades within a clastic rock (Udden, 1914), but more simply as the degree of uniformity of grain size. Sorting is an important aspect of grain frequency distribution curves and calculations, and useful for assessing oil and gas permeability. An example of a grain sorting diagram is provided on the following page (**see Figure 10**).

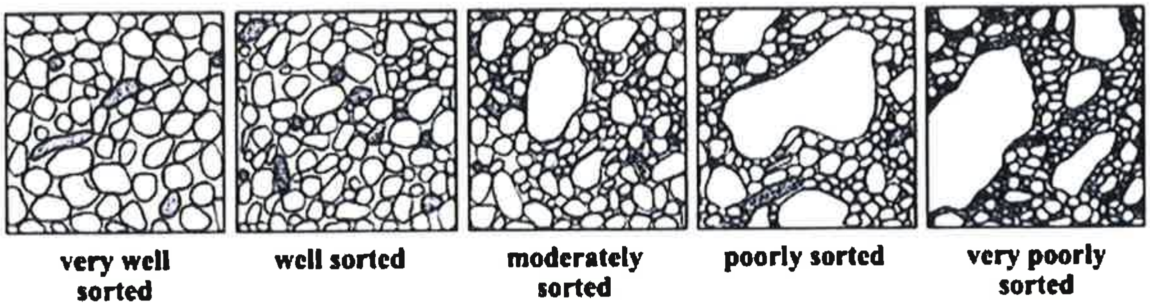


**Figure 10.** Illustration of classes of grain sorting in clastic rocks (from http://faculty.chemeketa.edu/afrank1/rocks/sedimentary/sedtexture.htm)

### 4.10 Induration (Hardness)

Induration or hardness can be related to intact rock strength as a qualitative indication of density and or resistance to breaking or crushing. Hardness and strength is a function of the individual rock type but may be modified by weathering or chemical alteration (Engineering Geology Field Manual, U.S. Department of the Interior, Bureau of Reclamation, 1998 ; https://www.usbr.gov/tsc/techreferences/mands/geologyfieldmanual-vol1/chap04.pdf).

Hardness and strength are difficult characteristics to assess with field tests. Two field tests can be used; one is a measure of the ability to scratch the surface of the sample with a knife, and the other is resistance to fracturing with a hammer blow (Ibid, p. 82). A means of qualifying hardness on a relative scale for core samples or other field exposures is provided on the following page **(see Table 5)**:

| Alpha-Numeric Descriptor | Descriptor | Criteria |
|---|---|---|
| H1 | Extremely hard | Sample cannot be scratched with knife or sharp pick. Can only be chipped with repeated heavy hammer blows. |
| H2 | Very hard | Sample cannot be scratched with knife or sharp pick. Breaks with repeated heavy hammer blows. |
| H3 | Hard | Sample can be scratched with knife or sharp pick with difficulty (heavy pressure). Heavy hammer blow required to break sample. |
| H4 | Moderately hard | Sample can be scratched with knife or sharp pick with light or moderate pressure. Sample breaks with light hammer blow. |
| H5 | Moderately soft | Sample can be grooved 1/16 in (2 mm) deep by knife or sharp pick with moderate or heavy pressure. Sample breaks with light hammer blow or heavy manual pressure. |
| H6 | Soft | Sample can be grooved or gouged easily by knife or sharp pick with light pressure and can be scratched with fingernail. Breaks with light to moderate manual pressure. |
| H7 | Very soft | Sample can be readily indented, grooved or gouged with fingernail and carved with a knife. Breaks with light manual pressure. |

**Table 5.** Descriptors and relative scale for rock hardness based upon results of field testing criteria (Engineering Geology Field Manual, U.S. Department of the Interior, Bureau of Reclamation, 1998 ; https://www.usbr.gov/tsc/techreferences/mands/geologyfieldmanual-vol1/chap04.pdf).

The diameter of the core or fragment size will influence the estimation of hardness and should be considered when testing. A 5 to 8-inch (130 to 200 mm) length of NQ-size (or larger diameter) core should be used for hardness determinations. Standards (heavy, moderate, and light hammer blow) should be calibrated with others mapping or logging core for a work project.

### 4.11 Cement or Matrix

One of the obvious effects produced by cementation is the change from a loose sand to a sandstone that has strength (lithification). Cementation is a post-depositional process but a very important criterion in the preliminary gauging of physical strength of crushed stone, dimension stone, and roof strata in underground coal mines. Diagenetic silica is present in sandstones in many morphologic and crystalline forms, but the core logger need only be concerned with the basic cement types that can be identified megascopically or with a hand lense. Quartz ($SiO_2$) and chert (microcrystalline quartz) are common in quartz arenites, but siderite ($FeCO_3$), hematite ($Fe_2O_3$) and low-magnesium calcite ($CaMgCO_3$ where $MgCO_3$ <4 mol%) are present in many sandstones (Blatt et al., 1980). Clay minerals and potassium feldspar are common in siltstones and claystones. A list of cements and associated rock types is presented below (**see Table 6**).

| Cement | Associated rock type |
|---|---|
| Silica | All siliciclastic rocks |
| Calcium carbonate | All siliciclastic rocks |
| Siderite | Sandstone |
| Hematite | Sandstone |
| Potassium feldspar | siltstone, claystone |
| Clay minerals | siltstone, claystone |

**Table 6.** List of cements and associated rock types.

### 4.12 Sedimentary Structures

There are many types of sedimentary structures that can be observed in core samples, and brief overview and classification is included herein (**see Table 7**). Stratification or bedding is by far the most common sedimentary structure (Blatt et al., 1980), and should be given special attention.

| **I. Stratification** | |
|---|---|
| A. Bedding and lamination | |
| B. Cross-stratification | |
| C. Irregular stratification includes: | soft sediment folding (slumping)<br>convolute lamination<br>load structures<br>fluid escape structures<br>sedimentary sills and dikes<br>mud cracks<br>bioturbation (burrows, roots, etc.) |
| **II. Bedding Plane Structures** | |
| A. Tool marks includes: | striations<br>grooves<br>brush, bounce, and roll marks |
| B. Scour marks includes: | flutes<br>large scours ("cut and fill", channels)<br>rill marks, crescentic marks |
| C. Bed forms includes: | ripples, dunes, antidunes<br>grain lineation, burrow marks<br>swash marks and other wave marks |
| D. Biogenic marks | |

**Table 7.** Classification of sedimentary structure types (from Blatt et al., 1980).

### 4.12.1 Bedding

Bedding (stratification) is by far the most common sedimentary structure. A bed refers to a layer of sedimentary rock that is clearly distinguishable from the layers above or below by virtue of some discontinuity in rock type, internal structure, or texture (Blatt et al., 1980). The terms "band" and "lens" are useful for subdivision of a layer on the basis of color, composition, texture, or cementation; a band is laterally continuous on an outcrop scale, whereas a lens is not (Blatt et al., 1980).

Ingram (1954) classified bedding thickness on a geometric scale (**see Table 8**). Beds are commonly defined as layers greater than 1 cm in thickness, and layers less than 1 cm (0.39 in) in thickness are called "laminae."

| Bedding Classification | Bed Thickness |
|---|---|
| Very thickly bedded ("Massive") | >100 cm (> 39.37 in) |
| Thickly bedded | 30-100 cm (11.81-39.37 in) |
| Medium bedded | 10-30 cm (3.94-39.37 in) |
| Thinly bedded | 3-10 cm (1.18-3.94 in) |
| Very thinly bedded | 1-3 cm (0.39-1.18 in) |
| Thickly laminated | 0.3-1.0 cm (0.12-0.39 in) |
| Thinly laminated | < 0.3 cm (< 0.12 in) |

**Table 8**. Classification of bedding thickness (from Ingram, 1954).

### 4.12.2 Bedding contact

Beds are frequently but not necessarily separated from each other by bedding plane joints. The upper and lower boundaries of a bed may be sharp or gradational. The lower boundary of a bed is also called the "sole," and it may display sedimentary structures called sole marks, casts, or molds (Blatt et al., 1980). The type of upper and lower contact should be recorded, and for gradational contacts, some physical basis for defining the position of the arbitrary contact should be apparent and listed (e.g., slight color difference, change in grain size, etc.).

### 4.13 Fossils

As a product of erosion, transportation, and particle size degradation, and deposition, and often repeated cycles of the same processes, most sandstones and coarser grained clastic rocks lack fossils. Siltstones and shales contain various marine and transitional invertebrates, as well as trace fossils (ichnofossils) and plant fossils. Scholarly books on the classification and identification of trace fossils (Frey, 1975; Seilacher, 2007; Bromley, 2012) and plant fossils (Smith) are available for detailed study and description, but simplified identifications for logs may suffice.

It is not possible to identify most fossils beyond the phylum level because of the reworking of the sediments. However, it is useful to identify the presence of fossil "hash" or storm deposits for thin formations or zones of stratigraphic economic interest for possible correlation of units as marker beds.

## 5.0 Rock Quality Designation (RQD)

Rock quality designation (RQD) is a modified core recovery percentage which is used for determining the relative strength of rock types and depth intervals of interest based upon the of intactness of core samples. RQD is useful for geotechnical projects and for gauging or estimating underground coal mine roof support conditions. RQD is measured by summing the intactness of core sample pieces over 100 mm (3 in) in length and divided by the length of the core run.

Core breaks caused by the drilling process are usually determined by the presence of irregular, rough, or fresh surfaces. Core samples broken by drilling should be fitted together and counted as a single piece of intact core.

The measurement of RQD is defined as:

$$\text{RQD} = \frac{\text{Length of intact pieces} > 100 \text{ mm (3.94 in).}}{\text{Total core run length}}$$

The calculated values of RQD and associated descriptions are provided (**see Table 9**).

| RQD Value | Description of Rock Quality |
|---|---|
| 0-25% | Very poor |
| 25-50% | Poor |
| 50-75% | Fair |
| 75-90% | Good |
| 90-100% | Excellent |

**Table 9.** Rock quality designation (RQD) values and associated descriptions (from Deere, et al., 1967).

## 6.0 Photographing Core Samples

Photographing core samples is normally performed after the core has been marked, logged, and placed in core boxes, and after the sampling intervals for laboratory testing have been marked but before the samples have been removed for shipping. In oil and gas exploration, core samples that are "slabbed" (cut in half) for analytical testing are often photographed on the open cut face.

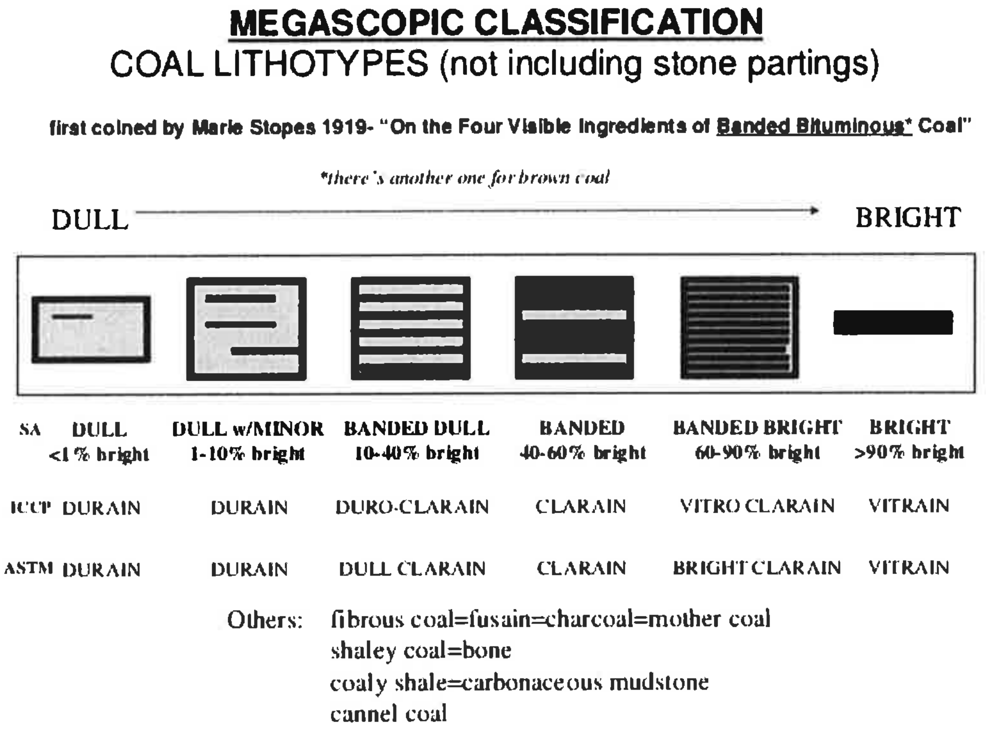
A digital camera or a cell phone camera is suitable for most needs. A low cost ($100) digital camera using a memory card can be mounted on an overhead photo stand to record consistent image distance and minimize framing issues. A vertical image distance of five feet would enable three core boxes to be photographed in one image. A dry erase white board or a 5" x 7" file card should be used to denote the core hole identification, core box number, and depth interval, and this placard should be legible and placed at the top center of the photograph.

It is important that the core samples are photographed in full natural day light, and not under fluorescent light, to obtain the best image. Photographs recorded at dawn and dusk produce unwanted shadows of the photographer or other nearby features. It is preferable that the core samples be photographed as "wet" by applying a light, freshwater spray to reveal the surface detail of the core. However, because of time constraints, most core at the drill site is photographed as "dry" or in a drying condition from the drilling and rinsing process. It is critical to review and check the quality of digital images before leaving the drill site or storage building.

## 7.0 Logging of Coal in Core Samples

Coal is not a homogeneous substance but consists of various organic and inorganic constituents. In the same way as inorganic rocks are composed of minerals, coals consist of macerals. However, there is a difference. A mineral is characterized by a fairly well-defined chemical composition, by the uniformity of its substance, and by the fact that they are crystalline, whereas a maceral of coal varies widely in its chemical composition and physical properties and is not crystalline. Furthermore, the three maceral groups, vitrinite, exinite (or liptinite), and inertinite, can only be identified using oil immersion microscope objectives with 25 to 50x magnification (Stach et al., 1982). Therefore, coal macerals cannot be identified megascopically or in the process of core logging.

The term lithotype designates the different macroscopically recognizable bands of coal seams. As defined by Stopes, these humic (banded) lithotypes include in decreasing levels of brightness, vitrain, clarain, durain, and fusain. A graphic scale of brightness and the associated lithotype are provided on the following page (**see Figure 11**).



**MEGASCOPIC CLASSIFICATION**

COAL LITHOTYPES (not including stone partings)

first coined by Marie Stopes 1919- "On the Four Visible Ingredients of Banded Bituminous* Coal"

*there's another one for brown coal

DULL → BRIGHT

| | | | | | | |
|---|---|---|---|---|---|---|
| SA | DULL<br><1 % bright | DULL w/MINOR<br>1-10% bright | BANDED DULL<br>10-40% bright | BANDED<br>40-60% bright | BANDED BRIGHT<br>60-90% bright | BRIGHT<br>>90% bright |
| ICCP | DURAIN | DURAIN | DURO-CLARAIN | CLARAIN | VITRO CLARAIN | VITRAIN |
| ASTM | DURAIN | DURAIN | DULL CLARAIN | CLARAIN | BRIGHT CLARAIN | VITRAIN |

Others: fibrous coal=fusain=charcoal=mother coal
shaley coal=bone
coaly shale=carbonaceous mudstone
cannel coal

**Figure 11.** Graphic scale of coal brightness and associated coal lithotypes (from https://www.slideshare.net/adhlino_bono/coal-mine).

Coal drill core surfaces are generally unsuitable for logging because of the poor intactness and difficulty of determining relative concentrations of banding and coal lithotypes. Attention in the field should be directed toward obtaining accurate depth and thickness measurements and the logging of non-coal partings (Goscinski et al., in Dutcher, ed., 1978). If the core samples have suitably large fragments, a megascopic petrographic analysis can be attempted as part of a preliminary effort to determine the petrographic character of the coal (Friedman, in Dutcher, ed., 1978). In the laboratory, a more complete and precise description of the coal core can be made (Goscinski et al., in Dutcher, ed., 1978). Qualitative descriptions of lithotype or inorganic band thickness and relative concentrations of detrital or inorganic materials should be logged if there is insufficient time to measure in the field (**see Table 10**).

| Band Thickness | Range (mm) | Range (in.) |
|---|---|---|
| Thin bands | 0.5 to 2.0 | 0.02 to 0.08 |
| Medium bands | 2.0 to 5.0 | 0.08 to 0.20 |
| Thick bands | 5.0 to 50 | 0.20 to 2.00 |
| Very thick bands | >50 | >2.00 |

| Concentration | Percent of Layer |
|---|---|
| Sparse | <15 |
| Moderate | 15 to 30 |
| Abundant | 30 to 60 |
| Dominant | >60 |

**Table 9.** Qualitative descriptions of coal, inorganic band thickness and relative concentration (from Dutcher, 1978).

Rock partings within coal beds affect coal quality, mineability, and mining practices, and are very important to identify and log. Logging and sampling must to obtain samples that represent, as nearly as possible, the coal that is produced commercially for the mine (Holmes, 1911). Judgement must be applied toward obtaining samples that will be most representative of the coal bed (Swanson and Huffman, 1976). A coal bed that is mined or anticipated to be mined underground will be conveyed, washed and beneficiated at the surface preparation plant along with its non-coal partings, so careful attention must be made to describe the partings. A coal bed that is mined or anticipated to be mined at the surface will be described in the same manner but usually any and all rock partings greater than 0.2 feet thick will be "scalped" or removed from prior to the washing and processing. Also, subordinate coal benches that are above or below the principle target seam that are less than 0.5 feet thick and separated by more than 0.5 feet of non-coal partings are usually not economically recoverable.

Visual descriptions of coal core samples are difficult to make unless the core is broken or split open. Ash is the inorganic residue that remains after complete incineration of coal, and is a by-product of clay minerals, silica (quartz), pyrite, siderite, calcium carbonate, gypsum, and various other minerals. High-ash coal (>25 weight percent ash) or mineral rich partings generally are visually distinct in a coal bed. Non coal partings include carbonaceous shale (>50 weight percent ash), impure coal (25 to 50 weight percent ash) which is also known as "bone" coal, pyrite, clay, and shale (Stanton, 1976).

## 8.0 Logging of Black Shale in Core Samples

Black shales have always been important as source rocks for conventional hydrocarbons, but in the last decade, they have become increasingly important as major sources of unconventional oil and gas, for which they act as source, reservoir, and seal. However, in black-shale core samples, one black shale sample typically looks very much like any other. Therefore, despite some characteristic differences in composition and radioactivity, characteristics that cannot be visually discerned, black shales are difficult to log wholly on visual characteristics. However, in place of black shale lithologic characteristics, other characteristics like lithologic associations where they occur, stratigraphic or biostratigraphic marker horizons, and radioactivity can be successfully used to log black-shale cores.

Lithologic Associations—Many black shales are commonly associated with other lithologies, including gray or greenish-gray shales, siltstones, dolostones, and limestones, and the occurrences are often specific to certain stratigraphic horizons, making them very useful for correlation. One prominent example is the Upper Devonian Three Lick Bed of Provo et al. (1978), which is represented by three, closely spaced, gray-shale beds in upper parts of the Ohio Shale (see Figure 12) and its equivalents in eastern Ohio, eastern Kentucky, and north-central Tennessee. It forms an excellent horizon for correlation in parts of a black-shale sequence that are otherwise homogeneous. Similar important lithologic associations with black shales are represented by the limestones and shales of the Cherry Valley Member of the Marcellus Shale (e.g., Lash and Engelder, 2011) and by the sandstones and siltstones of the middle member of the Bakken Formation (Pitman et al., 2001).

Stratigraphic Marker Horizons—Although units like the Three Lick Bed are also prominent stratigraphic marker horizons, most marker horizons, though widespread, are much thinner. Common horizons in black shales include cone-in-cone limestone horizons (see Figure 12), bentonites, zones of carbonate or phosphorite concretions (see Figure 12), and bones beds or lag horizons. Zones of cone-in-cone limestones and concretions are diagenetic features that are typically unit-specific in black shales but are commonly dispersed randomly throughout that unit. While these features do have some correlative value, understanding where they occur in a black-shale sequence may be more important, as they can be impediments to horizontal drilling (Blood et al., 2019). Bone beds or lag horizons are very thin concentrations of sand-size debris that may contain resistant bone fragments, conodonts, lithic fragments or pyritic clasts that accumulate during flooding events and hiatuses in sedimentation. They typically occur at the bases of black-shale units, and along with bentonites or altered volcanic-ash beds, are widespread and have great correlative value (e.g., Conkin and Conkin, 1984).

Biostratigraphic Marker Horizons—Biostratigraphy provides yet another way of determining chronostratigraphic position in a relatively homogeneous black-shale sequence. Conodonts and palynology are very important tools in determining correlative zonation in Paleozoic black shales (e.g., Ettensohn et al., 1989, 2009), but the time and expertise needed to process and interpret these microfossils is prohibitive for their use in expedient core description. However, in some black shales, a few megascopic fossil occurrences do provide important biostratigraphic information. In the Devonian black shales of east-central United States, the occurrence of Protosalvinia (Foerstia) is an example (Hasenmueller et al., 1983). Protosalvinia was a planktic alga that was widespread in Late Devonian seas across eastern and central parts of North America. With close examination, the alga can be identified in most black-shale cores from the area; examples are usually present between the lower and middle Huron Shale Member of the Ohio Shale and its equivalents in the Chattanooga and New Albany shales (see Figure 12).

Radioactivity—Provo et al. (1978) divided the Upper Devonian black shales of Ohio and eastern Kentucky into a series of radioactive units based on the examination of many gamma-ray logs across the area. Ettensohn et al. (1979) demonstrated that these same units could be recognized in artificial gamma-ray logs (radioactivity profile) made from outcrops and cores using a hand-held scintillometer (see Figure 12); and hence, it became possible to correlate from the subsurface into outcrops and into cores that lacked gamma-ray logs. These kinds of correlations using gamma-ray units became the basis for many cross sections showing the nature of black-shale radioactive units across the Appalachian Basin and into the Illinois Basin (e.g., Kepferle et al., 1978). Therefore, if the black shales in any basin have been divided into easily recognizable gamma-ray units, artificial gamma-ray logs of cores are an expedient way of correlating units in that core back into the basin.

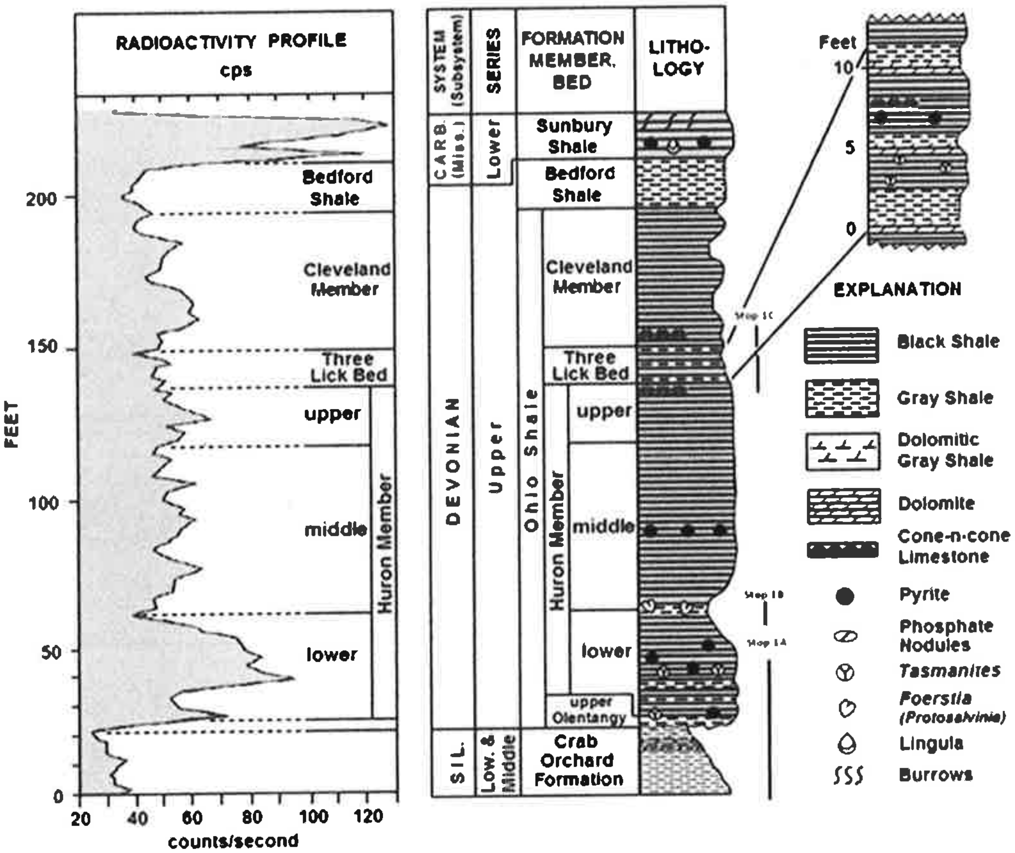


**Figure 12.** Artificial gamma-ray log (radioactivity profile) and lithologic log from an outcrop on the eastbound lane of Interstate 64 in Rowan County, Kentucky, showing the characteristic radioactive units in the Upper Devonian Ohio, Bedford, and Sunbury shales of eastern Kentucky.

Core-Logging Manuals—If it becomes necessary to log large numbers of cores in a particular black shale, or in any lithologic unit, it may be useful to develop a core-logging manual with representative photos of commonly occurring lithologies and an accompanying alpha-numeric designation for each lithology or feature. Rather than writing many descriptions of commonly occurring lithologies, lithologies can be recorded quickly using a previously determined alpha-numeric descriptor, and these descriptors can subsequently be computerized to generate a stratigraphic column for each core. First used in the coal measures (e.g., Ferm and Weisenfluh, 1981), a core-logging manual for the Devonian black shales in Kentucky was recently developed by Ettensohn and Hendricks (2015).

## 9.0 List of Core Samples Reviewed in Course Workshop

**Coal Core**
KGS Hole ID: PRVDNC0077
DDH No: Gil-31
KGS Call No. 372
Providence Quad., Webster Co., KY
No. 6 (Pride) Coal
266.88'-276.88' Depth

**Coal Roof and Floor Sequences**
KGS Hole ID: UNNTWN0020
DDH No. WKUG-9
KGS Call No. 545
Uniontown Quad., Union Co., KY
No. 13 (Baker) Coal, No. 11 (Herrin) Coal, No. 9 (Springfield) Coal roof and floor
460.0'-529.4'; 629.0'-654.0' depth

**Conglomeratic Sandstone - USGS Stratigraphic Test**
KGS Hole ID: RUSH0007
USGS No. R-7
KGS Call No. C-328
Rush Quad., Carter Co., KY
Lee Formation - Conglomerate (Pennsylvanian)
466.5'-506.5' Depth

**Tar Sand Commercial Test**
Mega West Energy Corporation
No. 104 Moonshine
KGS Call No. T-6578
KGS Rec. No. 133678
Riverside Quad., Warren Co., KY
Big Clifty Sandstone (Chesterian-Mississippian)
503.0'-517.5' depth

**"Tight Sand"- Unconventional Gas Test**
Ashland Exploration Company
No. 1 Hattie Neal
KGS Call No. T-5691
KGS Rec. No. 11647
Webbville Quad., Lawrence Co., KY
Berea Sandstone (Devonian)
1484.0'-1517.5' depth

**"Tight Sand"- Unconventional Gas Test**
Terra Nova Exploration
No. 2 Western Pocahontas Properties
KGS Call No. (?)
KGS Rec No. (?)
Elliott Co., KY
Berea Sandstone (Devonian)
1202.0'-1264.4' depth

**Black Shale – Source Rock/Reservoir Rock**
Somerset Gas Service Company
No. 1 Morelandbell, Inc.
KGS Call No. T-6588
KGS Rec No. (?)
Leslie Co., KY
Cleveland Member and Huron Member of Ohio Shale (Devonian)
2735.0'-2775.0'; 2787.0'-2967.0' depth

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