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SANDSTONE MODAL ANALYSIS PROCEDURE

By

John Decker

Alaska Division of
Geological and Geophysical Surveys

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794 University Avenue, Basement
Fairbanks, Alaska 99701

STATE OF ALASKA

DEPARTMENT OF NATURAL RESOURCES

DIVISION OF GEOLOGICAL AND GEOPHYSICAL SURVEYS

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PROCEDURE FOR SANDSTONE MODAL ANALYSIS

1) Study a suite of thin sections.

2) Select thin sections to be point counted. A unimodal grain size of 0.5 mm is ideal.

3) Determine the grid spacing. The skip distance must be greater than 95 percent of the sand-size grains in the thin section.

4) Determine the tabulation convention.
   - Categories should be mutually exclusive.
   - Categories should be exhaustive.
   - Convention should allow rapid, unambiguous determinations.

5) Set-up the microscope (clean and center objectives, etc.) and mount the point counting stage.

6) Be sure that your microscope has a suite of objectives that will allow normal point counting at a magnification of between 200X and 400X. I use 312.5X as my main magnification, but I change objectives regularly to both higher and lower powers.

7) The thin sections are point counted using the cell concept; each thin section is subdivided into 4 imaginary cells, I use 4 skinny cells parallel to the long dimension of the thin section. One hundred detrital sand grains are counted from cell 1 on each of the selected thin sections, then the process is repeated 3 times, counting 100 grains from cell 2 on all the thin sections, then from cell 3, and finally from cell 4. This cell method allows for comparisons of calculated and predicted analytical error, and tends to average out operator bias developed during the course of the study.

7a) If you have thin sections that are half stained for either or both feldspars, and half unstained, the procedure is slightly modified: Subdivide the unstained half of each thin section into 4 cells and proceed as normal, counting 100 detrital sand grains from the first cell of each thin section and repeating until 400 detrital sand grains have been counted from all thin sections. Counts on the unstained half, however, lump all quartz and feldspar grain types into one category. Now, on the stained half, count the inverse population, lumping all non quartz and feldspar detrital sand grains, and subdivide quartz and feldspar into appropriate categories (depending on your tabulation convention). Count exactly the number of grains needed to make the total subdivided quartz and feldspar grains on the stained half equal the undifferentiated quartz and feldspar category on the unstained half. Count all necessary grains on the stained half of each thin section at one time (or use the cell method if you prefer, but it gets a little confusing because you are not necessarily counting 400 points on the stained half).

8) Compare the variation between the 4 100 point counts for each thin section, and compare the variation between the stained and

unstained totals. If actual calculated standard deviation regularly exceeds the predicted analytical error, a flag goes up that something is wrong. If calculated totals between stained and unstained halves of the same thin section vary more than 10 percent, another flag goes up.

9) Sum and recalculate the detrital mode data, and plot them on triangular classification and discriminant diagrams like those published by Dickinson and Suczek, 1979.

SUMMARY OF DIAGNOSTIC CRITERIA FOR SANDSTONE MODAL ANALYSIS

DETRITAL GRAINS

QUARTZ

monocrystalline--undulose:

Single crystal of quartz, grain boundary coincides with crystal boundary. Non-uniform extinction, undulosity greater than or equal to 3 degrees stage rotation. Undulosity is simply the angle between the 2 most divergent positions of the c-axis within a quartz crystal. Includes grains with variable or strongly undulose extinction, as long as no sharp breaks occur within the grain indicating that the grain is composed of multiple crystals.

<u>Procedure for determining undulosity:</u> In crossed nicols, put the grain in a position where the largest possible area of the grain is at extinction, more or less the middle of the undulosity range. (If the whole grain is at extinction, the undulosity is zero and the grain belongs to the straight extinction class.) Rotate the stage until one of the extreme areas of the crystal not in extinction in the central position becomes extinct, and record the stage reading. Rotate the stage in the opposite direction until the other extreme of the crystal becomes extinct, and record the stage reading. The undulosity is the absolute value of the difference in the two stage readings. If this value is less than 3 degrees, the grain belongs to the straight extinction class.

monocrystalline--straight:

Single crystal of quartz, grain boundary coincides with crystal boundary. Uniform extinction with less than 3 degrees of stage rotation.

polycrystalline--equigranular:

Multiple quartz crystals (2 or more) with mean grain size diameters between 0.02 mm and 0.0625 mm within a single grain. Individual crystals generally of equal dimension with no preferred orientation. Includes composite and semicomposite grains of Folk (1974). Boundaries between individual crystals are distinct, generally either sutured or polygonal, across which there is generally no optical continuity (as is typical of fractured monocrystalline quartz grains). Since a continuum exists between undulose monocrystalline quartz and polycrystalline quartz, polycrystalline quartz is operationally defined as having greater than or equal to one degree undulosity jumps across sharply defined boundaries. Polycrystalline quartz is distinguished from sandstone and siltstone grains by a completely annealed appearance and a lack of detrital grain characteristics of the internal crystals. Equigranular polycrystalline quartz with greater than 5 percent mica should be classified as unfoliated metaclastics.

polycrystalline--foliated:

Multiple quartz crystals (2 or more) with mean grain size diameters between 0.02 mm and 0.0625 mm. within a single grain. Individual crystals are elongate and have a preferred orientation. Presence of mica parallel to the foliation causes grain to be eliminated from this category and counted as a metamorphic rock fragment--quartz-mica schist/gneiss.

coarse polycrystalline quartz:

Multiple quartz crystals with modal grain size diameters greater than or equal to 0.0625 mm within a single grain. A distinction between foliated and equigranular fabrics is unnecessary due to the coarse internal crystal size relative to the grain size. Complete internal crystals are not common in this category, that is, part of the edges of internal crystals coincides with part of the edge of the grain. This category has no special genetic significance, it simply allows us to keep track of the grains that probably would be counted differently using the Gazzi-Dickinson method.

undifferentiated quartz:

Any monocrystalline or polycrystalline quartz grain with internal crystals having mean diameters greater than or equal to 0.02 mm, and having less than 5 percent impurities.

FELDSPAR

PLAGIOCLASE GRAIN DETERMINATION KEY

1) Is the plagioclase grain polycrystalline? = feldspar-feldspar aggregate or quartz-feldspar aggregate depending on the presence or absence of quartz.

2) Is the monocrystalline plagioclase grain so highly altered that zoning and twinning types cannot be determined? = altered feldspar.

3) Is the unaltered monocrystalline plagioclase grain zoned? = zoned plagioclase.

4) Is the unaltered unzoned monocrystalline plagioclase grain composed of both polysynthetic lamellar twins and a simple Carlsbad twin? = C-twin plagioclase.

5) Is the unaltered unzoned monocrystalline plagioclase grain composed only of polysynthetic lamellar twins? = A-twin plagioclase.

6) Is the unaltered unzoned monocrystalline plagioclase grain composed of a single twin which shows unequal illumination, or unequal interference colors (using the first order red accessory plate) in the 45 degree position? = C-twin plagioclase.

7) Is the unaltered unzoned monocrystalline plagioclase grain composed of a single twin which shows equal illumination and equal interference colors (using the first order red accessory plate) in the 45 degree position? = A-twin plagioclase.

45 DEGREE RULE: If the twinned plagioclase shows equal illumination and equal interference colors (using the first order red accessory plate) in the 45 degree position call it an A-twin.

NOTE: Both carlsbad, and combined carlsbad-albite grains may show equal illumination and equal interference colors in the 45 degree position depending on the orientation of the plagioclase crystal. If, and only if, you are uncertain as to whether a particular grain is an A-twin or a C-twin use the 45 degree rule. In other words, if a plagioclase grain contains an obvious C-twin, you are home free, forget the 45 degree rule.

DETERMINING PLAGIOCLASE COMPOSITIONS IN SANDSTONES USING EXTINCTION ANGLE

Since plagioclase crystals in sandstones may have been derived from several different sources, methods requiring multiple grains, like the Michel-Leve method, are not valid for accurate composition determinations. However, on any grain meeting the Michel-Leve orientation criteria, if the extinction angle is larger than 20 degrees (or any angle if cleavage to extinction relationships allow you to determine the sign of the extinction angle) the composition of the plagioclase is at least as calcic as the Michel-Leve chart indicates.

Accurate plagioclase determinations in sandstones using extinction angles can only be made on single grains using either the a-normal or combined carlsbad-albite method.

NOTE: The sign of the extinction angle requires knowledge about the position of the crystal faces that is not always available. In sections where (010) is perpendicular to the stage, the extinction angle between the fast ray, X', and (010) is positive when it bisects the acute angle formed by (001) and (010), and negative when it bisects the obtuse angle. Different sign conventions apply to different orientations, but the (010) normal orientation is the only one of value in determining composition from carlsbad and/or albite twin segments.

potassium feldspar--undifferentiated:

Single crystal of potassium feldspar; generally orthoclase or sanidine. Distinguished from quartz by lower refractive indicies, cloudy alteration, biaxial interference figure, and presence of cleavage. Takes a yellow potassium stain. Make special note of sanidine as probable indicator of volcanic origin.

plutonic feldspar:

Includes microcline-anorthoclase, perthite-antiperthite, and graphic-myrmekitic feldspar. Microcline and anorthoclase are triclinic and characterized by grid twinning. Perthite and antiperthite are characterized by wormy intergrowths of K-feldspar and plagioclase. Graphic and myrmekitic feldspar are characterized by fine wormy intergrowths of quartz and either K-feldspar or plagioclase, respecively.

unzoned plagioclase--A-twins:

Single plagioclase crystal with polysynthetic twinning (albite, pericline, or acline twin laws). Takes red Ca-stain but no yellow K-stain.

unzoned plagioclase--C-twins:

Single plagioclase crystal with simple twinning (Carlsbad, Manebach, or Baveno). Takes red Ca-stain but no yellow K-stain. An abundance of C-twins is suggestive of an igneous provenance.

unzoned plagioclase--untwinned:

Single plagioclase crystal with no apparent twinning or zoning. Takes red Ca-stain but no yellow K-stain. An abundance of untwinned plagioclase is suggestive of a metamorphic provenance.

zoned plagioclase:

Systematic or oscillatory zoning. In clastic grains, zoning often looks like undulatory extinction. Make special note of oscillatory zoning as a probable indicator of volcanic or hypabyssal origin.

undifferentiated plagioclase:

Any plagioclase grain. This category is generally used only for reconniassance point counts or for tabulating data from other sources.

undifferentiated feldspar:

Any feldspar grain. This category is generally used only for reconniassance point counts or for tabulating data from other sources.

altered feldspar:

Extensive alteration of single feldspar crystal Single crystal recognized by mass extinction of unaltered portion of the grain. Typical alteration includes sericitization, kaolinization, albitization, and vacuolization. Alteration may be either detrital or authigenic.

LITHIC GRAINS

SEDIMENTARY ROCK FRAGMENTS

microcrystalline chert:

Microcrystalline mosaic composed of individual quartz crystals less than 0.02 mm in diameter. Generally clear in plane light, with rare inclusions, no preferred orientation, and less than 5 percent argillaceous material. Distinguished from polycrystalline quartz on the basis of crystal size. Distinguished from microcrystalline felsic volcanic rock fragments by a lack of marked internal relief between individual crystals, lack of feldspar microphenocrysts, and absence of yellow K-stain in stained thin sections. Also suggestive of chert are the presence of criss-crossing veinlets. Cryptocrystalline and opaline silica are also included in this category; both are characterized by being nearly black in crossed nicols.

radiolarian chert:

Microcrystalline mosaic composed of individual quartz crystals less than 0.02 mm in diameter, and containing circular regions characterized by slight differences in texture and quartz purity. Such regions are generally interpreted as ghosts of radiolaria. Except for the circular regions, radiolarian chert looks like microcrystalline chert, and the same diagnostic properties apply.

foliated chert:

Microcrystalline mosaic composed of individual quartz crystals less than 0.02 mm in diameter which are elongate and have a preferred orientation. Except for the foliated fabric, foliated chert looks like microcrystalline chert, and the same diagnostic properties apply.

fibrous chert:

Fibrous chert and chalcedony in parallel, radial or concentric aggregates. Distinguished from foliated chert by a very high length to width ratio. Check the sign of elongation--chert can be either length-fast or length slow. Length slow chalcedony is thought (by Pittman and Folk, Nature Phys. Sci., 1971) to indicate an evaporite depositional environment.

probable chert grains:

Grains suspected of being chert but show no conclusive diagnostic properties.

cherty argillite:

Microcrystalline mosaic composed of quartz crystals and clay minerals less than 0.02 mm in diameter. Typical appearance is that of dirty chert. Argillaceous and carbonaceous material ranges from 5 to 70 percent.

argillite:

Unfoliated microcrystalline grains with greater than 70 percent argillaceous and carbonaceous material. Individual crystals are less than 0.02 mm in diameter. Grains commonly appear dark-gray to black in plane light. Although without apparent foliation, many grains have a crystallographic preferred orientation.

siltstone:

Multiple detrital clasts within a single grain. Internal clasts are greater than or equal to 0.02 mm but less than 0.0625 mm. Grains contain no preferred orientation and are not recrystallized.

sandstone:

Multiple detrital clasts within a single grain. Internal clasts are greater than or equal to 0.0625 mm. Grains generally contain no preferred orientation and are not recrystallized.

slate/shale:

Foliated quartzose microcrystalline grains with greater than or equal to 5 percent argillaceous, micaceous or carbonaceous material. Individual crystals are less than 0.02 mm in width. Grains commonly appear dark gray to black in plane light, and exhibit a mass exticntion effect in crossed nicols due to the parallel alignment of the microcrystalline platey minerals. Grains commonly are only slightly to moderately recrystallized. Slate/shale grains are distinguished from phyllite by a lack of complete recrystallization, and from argillite and cherty argillite by a foliated fabric.

carbonate:

Grains may be composed of single or multiple crystals of carbonate. Relatively large crystals are characterized by extreme relief, extreme birefringence, and intersecting cleavage and twin planes. Very fine-grained carbonate (micrite) is characterized by a dull gray color, high relief, and a failure to go extinct in cross nicols. Detrital carbonate is distinguished from authigenic carbonate by distinct, typically rounded, grain margins, and the appearance of occupying a detrital grain site.

coal/organic detritus:

Non-crystalline orange, red, brown, and black, translucent to opaque grains, commonly having branching twig structures and/or cellular texture.

probable sedimentary rock fragments:

Grains suspected of being sedimentary rock fragments but show no conclusive diagnostic properties.

other or undifferentiated sedimentary rock fragments:

Any rock fragments definately of sedimentary origin not specifically listed above.

VOLCANIC (AND HYPABYSSAL) ROCK FRAGMENTS

vitric/cryptocrystalline:

Grains composed of volcanic glass or slightly to moderately devitrified glass. Glass is transparent in plane light and black in crossed nicols. Devitrified glass is generally dark but not black in crossed nicols, and locally displays faint birefringence indicative of incipient crystallization.

microcrystalline felsic:

Microcrystalline mosaic of individual quartz and feldspar crystals less than Ø.Ø2 mm in diameter. Grains are typically misidentified as chert, and a cherty appearance is characteristic. However, microcrystalline felsic grains commonly display marked internal relief, may contain micro-phenocrysts of quartz or feldspar, and take a yellow K-stain in stained thin sections.

microgranular felsic:

Grains composed of individual crystals of quartz and feldspar having mean diameters between 0.02 mm and 0.0625 mm. Distinguished from microcrystalline felsic, quartz-feldspar aggregate, and feldspar-feldspar aggregate by internal crystal size, from polycrystalline equigranular quartz by the presence of feldspar, and from unfoliated metaclastic by a lack of apparent detrital texture and an overall intergrown holocrystalline igneous texture. These grains were probably derived from a hypabyssal source.

microlitic:

Microscopically bearly resolvable, subhedral, needle-like feldspar crystals within either a glassy (hyalopilitic) matrix, or a holocrystalline (pilotaxitic) matrix. Feldspar grains have either a parallel orientation (trachytic) or they are randomly oriented (felted). Microlites are arbitrarily defined for operational reasons as having widths less than 0.02 mm.

lathwork:

Grains contain subhedral to euhedral tabular plagioclase crystals with either an intergranular or intersertal texture. Laths commonly haveeither a parallel or random orientation. Laths are arbitrarily defined as having widths greater than or equal to 0.02 mm.

mafic volcanic:

Polycrystalline volcanic rock fragment containing, in large part, mafic minerals (typically pyroxene) and no quartz, with internal crystal having mean diameters between 0.02 mm and 0.0625 mm.

tuffaceous:

Clastic grains with a known or suspected volcanic origin. Clasts can be composed predominantly of crystals (crystal tuff), glass shards and pumice (vitric tuff), or volcanic rock fragments (lithic tuff). The matrix typically is composed of either vitric or micrcrystalline material, and generally is the key to distinguishing between tuffaceous grains and clastic grains of a sedimentary origin.

altered VRF:

Sericitized volcanic rock fragments look similar to sericitized feldspar but lacks the unit or mass extinction of the unaltered part of the grain.

probable volcanic rock fragments:

Grains suspected of being volcanic rock fragments but show no conclusive diagnostic properties.

other volcanic rock fragments:

Any rock fragment definately of volcanic origin not specifically listed above.

METAMORPHIC ROCK FRAGMENTS

unfoliated metaclastic:

Multiple detrital clasts within a single grain. Internal clasts have mean diameters between Ø.Ø2 mm and Ø.Ø625 mm. Grains contain no strong preferred orientation but internal clasts have been recrystallized. Internal grain boundaries commonly are sutured or polygonal; original detrital grain boundaries are indistinct at best. Similar appearing grains that are completely recrystallized are classified as hornfels. Grains with internal clasts greater than or equal to Ø.Ø625 mm are classified as sandstone if original clasts are recognizable, or as quartz-feldspar aggregate if the grain is completely recrystallized.

quartz-mica phyllite:

Foliated quartzose crystal aggregate with greater than or equal to 5 percent mica. Individual crystals are less than Ø.Ø625 mm in width. Grains commonly appear colorless in plane light because the rock has been completely recrystallized, typically to quartz and white mica. Internal quartz crystals generally are elongate with polygonal boundaries. Micas are well developed and commonly form continuous layers across the grain.

quartz-mica schist/gneiss:

Foliated quartzose grains with greater than or equal to 5 percent mica. Individual crystals are greater than or equal to Ø.Ø625 mm in width. Grains are completely recrystallized similar to quartz-mica phyllite, the main distinction between the two clast types is internal crystal size. Distinguished from coarse polycrystalline quartz based on the presence of mica.

greenstone:

Unfoliated polycrystalline aggregate composed in in large part of mafic minerals, commonly either pyroxene, amphibole, chlorite or epidote group minerals, having a mean internal crystal diameter between Ø.Ø2 mm and Ø.Ø625 mm. Clasts are moderately to completely recrystallized probably from a mafic igneous rock. Non-mafic minerals are mainly plagioclase and carbonate.

green phyllite:

Foliated polycrystalline aggregate composed in large part of mafic minerals, mainly amphibole, chlorite, and epidote group minerals, having a mean internal crystal diameter between 0.02 mm and 0.0625 mm. Clasts are completely recrystallized, generally from a mafic volcanic protolith.

greenschist/amphibolite:

Foliated polycrystalline aggregate composed in large part of mafic minerals, mainly amphibole, chlorite, pyroxene, and epidote group minerals, having a mean internal crystal diameter of greater than or equal to 0.0625 mm.

hornfels:

Unfoliated polycrystalline aggregate with a completely recrystallized equigranular metamorphic fabric. Granoblastic groundmass contains crystals with a mean diameter of less than 0.0625 mm. Micas if present are randomly oriented. Hornfels show no indication of a detrital clastic texture as do unfoliated metaclastic grains. Key porphyroblastic minerals, if present, include wollastonite, biotite, and andalusite.

probable MRF:

Grains suspected of being metamorphic rock fragments but show no conclusive diagnostic properties.

other metamorphic rock fragments:

Any rock fragment definately of metamorphic origin that is not specifically listed above.

PLUTONIC ROCK FRAGMENTS

quartz-feldspar aggregate:

Polycrystalline rock fragment composed of quartz and feldspar crystals with mean diameter greater than or equal to 0.0625 mm. Distinguished from polycrystalline quartz based on the presence of feldspar, and from microgranular volcanic rock fragments based on a coarser grain size.

feldspar-feldspar aggregate:

Polycrystalline rock fragment composed of feldspar crystals with mean diameter greater than or equal to 0.0625 mm. Distinguished from quartz-feldspar aggregate based on a lack of quartz, and from microgranular volcanic rock fragments based on a coarser grain size.

mafic plutonic rock fragment:

Unfoliated polycrystalline aggregate composed in larg part of mafic minerals with internal crystals having a mean diameter of greater than or equal to 0.0625 mm.

probable PRF:

Grains suspected of being plutonic rock fragments but show no conclusive diagnostic properties.

other or undifferentiated PRF:

Any rock fragment definately of plutonic origin not specifically listed above.

<u>DETRITAL MINERALS:</u>

Individual crystals other than quartz, feldspar, or carbonate.

biotite:

Brown, pleochroic, birdseye extinction, micaceous habit.

white mica:

Colorless, high birefringence, micaceous habit.

chlorite:

Light green or brown, pleochroic, very low commonly anomalous birefringence, fibrous habit.

clinopyroxene:

Colorless to shades or green and brown, moderately high relief, biaxial positive, right angle cleavage.

amphibole:

Colorless to shades of green and brown, generally pleochroic, moderate relief, biaxial negative, amphibole cleavage.

garnet:

Colorless to shades of green or pink, isotropic, very high relief.

zircon:

Colorless to pale brown, extreme relief, very high birefringence, uniaxial positive.

tourmaline:

Colorless to black and shades of pink, blue, green, and brown, pleochroic, moderate birefringence, parallel extinction, maximum absorption perpendicular to direction of eloangation.

rutile:

Red-brown, often very dark, extreme relief, extreme birefringence

other minerals:

Unknown monomineralic grain. Note any mineral that can be identified separately.

indeterminant grains:

Any grain that cannot be classified after lengthy analysis.

<u>MATRIX</u>

All detrital material smaller than sand-size.

silt:

Any monocrystalline or polycrystalline framework grain less than Ø.Ø625 mm in diameter.

argillaceous:

Detrital clay. Generally occurs as polycrystalline aggregates less than Ø.Ø625 mm in diameter, that are squashed between framework grains or into pore space. Protomatrix and orthomatrix of Dickinson, 197Ø.

pseudomatrix:

Maliable detrital aggregates greater than Ø.Ø625 mm in diameter that have been squashed between more competent framework grains. Detrital grains were probably originally argillite, cherty argillite, siltstone, slate/shale or phyllite grains but are now unrecognizable as such with certainty. Grains may still occupy a detrital sand grain site; but they have lost their original detrital grain shape, and their internal structure has been altered. Defined by Dickinson, 197Ø, who lists 3 criteria for recognition of pseudomatrix: 1) Flame-like wisps of crushed lithic fragments extend into narrowing orifices between undefromed ridid grains. 2) the pseudofluidal internal fabric of lithic fragments deformed by pseudoplasitc flow commonly conforms to the margins of confining rigid grains as concentric drape lines. 3) Large "matrix"-filled "gaps" in the framework suggest pseudomartix, and the suggestion is strengthened where each "gap"-filling is semi-homogeneous but texturally distinct from other "gaps".

other or undifferentiated:

Any detrital material less than 0.0625 mm in diameter. This category is generally used only for reconniassance point counts or for tabulating data from other sources.

CEMENT

Includes all "submetamorphic" authigenic material, generally filling open pores, but also includes in place replacement of detrital grains if the original grain is no longer recognizable. Cement does not include veins; vein material should not be included in the point count analysis (in fact, sandstones with veins should not be point counted).

silica:

Includes quartz, opal, chert, and chalcedony. Quartz typically occurs as relatively pure overgrowths in optical continuity with detrital quartz grains. Quartz overgrowths commonly have euhedral crystal faces, and may be separated from the host grain by a distinct dirty rim outlining the original detrital grain. Quartz also occurs as rim cement around detrital grains and lining pores. Quartz rim cement or drusy quartz is bladed to equant, euhedral to subhedral, and forms in radial aggregates lining voids. Opal most commonly occurs in tuffaceous sandstone as a pore filling cement. Opal is isotropic, colorless to various pale colors (commonly tan due to an abundance of water-filled inclusions), and has a very low refractive index (n = 1.435 to 1.460 depending on the water content). This low RI causes adjacent grains, even normally low relief quartz, to stand out in bold relief. Chert occurs as overgrowths in optical continuity on detrital chert, and as a devitrification product of opalline cement. Chert is distinguished from quartz on the basis of grain size, chert crystallites are less than 0.02 mm. Chalcedony classically occurs as radiating microfibrous aggregates, but all gradations occur between microfibrous and microgranular depending on orientation. Fibers can be either length fast or length slow, and both can occur in the same rock. Individual fibers may be twisted causing variations in extinction along the fiber; these are called "zebraic chalcedony" and are generally length slow. Zebraic chalcedony is thought (by Pittman and Folk, Nature Phys. Sci., 1971) to have formed by replacement of sulfate evaporite minerals. Chalcedony also forms in tuffaceous sandstone as a devitrification product of opalline silica.

carbonate:

Carbonate cements are common, abundant, and varied: they are best studied using thin sections specially stained for different carbonate cations. Calcite, aragonite, dolomite, siderite, and ankerite are the most common carbonate cements. All are colorless (when unaltered), and have extreme relief and birefringence. Calcite has perfect rhombohedral cleavage and lamellar twinning. Calcite cement can occur as optically continuous overgrowths on carbonate grains, or as a pore filling cement. Crystallographically continuous calcite may surround several grains producing a poikilotopic texture. Dolomite, siderite and ankerite may all resemble calcite, but more classically, occur as small euhedral to subhedral rhombs. Aragonite is biaxial, has parallel extinction, and elongate or fibrous grains are length fast. Most commonly occurs as densly packed radiating fibrous aggregates, but can also occur as elongate pseudohexagonal crystals. Calcite pseudomorphs after agagonite are common. If you really want to know what type of carbonate it is, use stains, x-ray, or probe.

hematite:

Hematite is opaque and appears black in plane light and with crossed nicols, when it is as thick as the thin section. However, hematite commonly forms very thin coatings on detrital grains, and has a translucent red or rusty orange color. Even large hematite zones appear red in reflected light (turn down, or off, the transmitted light source, and shine a high intensity light down on the thin section; hematite, if present, should stand out clearly.

clay minerals:

Authigenic clayey material grown in originally open pors space during diagenesis. Either clear and homogeneous (phylosilicate cement of Dickinson, 1970), or murky and polymineralic (epimatrix of Dickinson, 1970). Authigenic clay minerals are best recognized by their radial growth patterns into pore space and around detrital grains, and by the presence of medial sutures within the interstitial phyllosilicate which indicate the lines of juncture of pore filling crystals growing inward from surrounding framework grains.

glaucony:

A family of generally round green grains composed of one or more of the following minerals: chlorite, glauconite, skolite, celadonite, berthierine, chamosite, and smectite. Glaucony form by diagenetic replacement of generally porous detrital grains such as fecal pellets, biogenic carbonate debris, microfossils (internal molds), mineral grains, and rock fragments. Glaucony forms only in the marine environment. Grains are green to brown in plane light, and have a mottled appearance in crossed niccols that doesn't have a distinct extinction position.

sulfates:

The most common sulfate cementing minerals are anhydrite and gypsum. Anhydrite is biaxial, has moderate relief, high birefringence, and has 3 perfect cleavages. Gypsum has moderate to low negative relief, low biregringence, and 3 directions of cleavage. Both minerals generally form anhedral poikilotopic crystals surrounding several detrital grains.

other or undifferentiated cement:

Any submetamorphic authigenic material. This category is generally used only for reconniassance point counts or for tabulating data from other sources.

METAMORPHIC MINERALS

generally replacive minerals and alteration products.

zeolite:

Colorless, low relief, low to very low birefringence, blocky, bladed, acicular or fibrous habit, commonly with good cleavage.

albite:

Colorless, low relief, low birefringence, good cleavage, commonly twinned. Forms as anhedral pore filling, overgrowths on existing feldspar grains, or as the replacement of more Ca- or K-rich feldspar. Albite replacement of microcline may produce a twinned grain with a chessboard appearance.

chlorite:

Green, commonly pleochroic, very low, often anomalous birefringence ence, typically forms fibrous radial aggregates.

biotite:

Brown, pleochroic, birdseye extinction, micaceous habit.

white mica:

Colorless to very light green, moderate relief, high birefringence, micaceous habit. Includes paragonite (Na-rich), muscovite (K-rich), phengite (Al-poor), talc (Mg-rich), and sericite (undifferentiated very fine grained white mica).

epidote:

Colorless to pale yellow, yellow varieties are pleochroic, high relief, moderate birefringence (commonly with a stained glass window appearance). Elongation parallel to b = Y yields both length-fast and length-slow crystals in the same rock. Incipient epidote commonly forms medium gray cryptocrystalline mats with a myriad of tiny moderately birefringent points

clinozoisite:

Colorless, high relief, low birefringence (commonly anomalous), parallel extinction in elongate sections, elongation parallel to b = Y.

zoisite:

Colorless, high relief, moderatley low birefringence (commonly anomalous), parallel extinction.

prehnite:

Colorless, commonly murky, good cleavage, moderate birefringence (often anomalous), and parallel extinction. Forms anhedral crystals in veins but usually forms elongate crystals in sheaf-like aggregates (bow-tie structure).

pumpellyite:

Colorless to apple green or blue green pleochroism, moderately high relief, moderately low birefringence. Forms acicular, fibrous, or bladed crystals, generally in aggregates with various orientations. Typically elongates parallel to b = Y.

actinolite:

Colorless to pale green pleochroism, moderate relief, moderate birefringence, amphibole cleavage. Typically forms acicular or fibrous crystals.

glaucophane:

Colorless to shades of blue and purple pleochroism, moderate relief, moderatley low to moderate birefringence, amphibole cleavage.

lawsonite:

Colorless to light blue-green, moderate birefringence, parallel extinction, 2-D cleavage, 2 sets of lamellar twins, commonly euhedral prismatic, tabular or rhombic crystals.

jadite:

Colorless to very light green, moderate relief, moderately low birefringence (commonly anomalous), coarse granular or fibrous aggregates are most common and typically form porphyroblasts.

other metamorphic minerals:

Any metamorphic mineral not listed above. Tabualate the occurrence of each recognizable mineral separately.

OVERSIZE GRAINS (All grains greater than 2 mm diameter)

neovolcanic:

Neovolcanic grains are produced by volcanism contemporaneous with sedimentation, and can be either intrabasinal or extrabasinal. In most cases, it is difficult to distinguish neovolcanic grains from paloevolcanic grains eroded from pre-existing volcanic outcrop. Outsized volcanic clasts, especially when fresher and more angular than volcanic grains of the modal grain size is one clue to a neovolcanic origin. Oversize neovolcanic grains were probably introduced into the depositional basin by a different mode of transportation than the modal sand grains; for example air fall ash in a fluvial or marine depositional environment. Another clue to a neovolcanic origin is a high percentage of volcanic grains at certain stratigraphic horizons.

carbonate rip-ups:

Carbonate rip-ups are most common in the marine environment where shelf carbonate mud is ripped-up by stormes, landslides, or turbidity currents, and incorporated in a sandy deposit as oversized grains.

clastic rip-ups:

Shale chips ripped-up from overbank and levee areas by catastrophic flow are common in turbidity current deposits, but also occur in fluvial deposits.

shell fragments:

Shell fragments can be either intrabasinal or extrabasinal, however oversized shell material is generally intrabasinal.

detrital pebbles:

Detrital pebbles include any grains greater than or equal to 2.00 mm in diameter that doesn't belong to one of the above oversize catagories. They generally has similar rounding, composition, and alteration characteristics to their sand size counterpart.

other or undifferentiated oversize grains:

Includes any distinctive oversize clast type not specifically listed above. Tabulate the occurrence of each recognizable grain category separately.

POINT COUNT CATEGORIES WITH FORMULAS USED TO CALCULATE SUMMARY PERCENTAGES AND RATIOS

1 SAMPLE NUMBER
2 Map Number
3 Quadrangle
4 Latitude (deg min)
5 Longitude (deg min)
6 Collected by
7 Point Counted by
8 Rock Unit
9 QUARTZ
10 Quartz, monocrystalline, undulose
11 Quartz, monocrystalline, straight
12 Quartz, polycrystalline, equigranular
13 Quartz, polycrystalline, foliated
14 Quartz, polycrystalline, coarse
15 Quartz, undifferentiated
16 FELDSPAR
17 Potassium feldspar
18 Plutonic feldspar
19 Plagioclase, unzoned, A-twins
20 Plagioclase, unzoned, C-twins
21 Plagioclase, unzoned, untwinned
22 Plagioclase, zoned
23 Plagioclase, undifferentiated
24 Feldspar, undifferentiated
25 Altered feldspar
26 SEDIMENTARY ROCK FRAGMENTS
27 Microcrystalline quartz (chert)
28 Radiolarian chert
29 Foliated chert
30 Fibrous chert
31 Probable cherty grains
32 Cherty argillite
33 Argillite
34 Siltstone
35 Sandstone
36 Slate/shale
37 Carbonate
38 Coal/organic detritus
39 Probable sedimentary rock fragment
40 Other or undifferentiated SRF
41 VOLCANIC ROCK FRAGMENTS
42 Vitric/cryptocrystalline VRF
43 Microcrystalline felsic VRF
44 Microgranular felsic VRF
45 Microlitic VRF
46 Lathwork VRF
47 Mafic VRF
48 Tuffaceous VRF
49 Altered VRF
50 Probable volcanic rock fragment
51 Other or undifferentiated VRF
52 METAMORPHIC ROCK FRAGMENTS
53 Unfoliated metaclastic
54 Quartz-mica phyllite
55 Quartz-mica schist/gneiss
56 Greenstone.
57 Green phyllite
58 Greenschist/amphibolite
59 Hornfels
60 Probable MRF
61 Other or undifferentiated MRF
62 PLUTONIC ROCK FRAGMENTS
63 Quartz-feldspar aggregate
64 Feldspar-feldspar aggregate
65 Mafic PRF
66 Probable PRF
67 Other or undifferentiated PRF
68 DETRITAL MINERALS
69 Biotite
70 White mica
71 Chlorite
72 Clinopyroxene
73 Amphibole
74 Garnet
75 Zircon
76 Tourmaline
77 Rutile
78 Other minerals
79 Indeterminant grains
80 MATRIX
81 Matrix--silt
82 Matrix--argillaceous
83 Pseudomatrix
84 Matrix, other or undifferentiated
85 CEMENT
86 Cement--silica
87 Cement--carbonate
88 Cement--hematite
89 Cement--clay minerals
90 Cement--sulfates
91 Glaucony
92 Cement, other or undifferentiated
93 METAMORPHIC MINERALS
94 Zeolite
95 Albite
96 Chlorite
97 Biotite
98 White mica
99 Epidote
100 Clinozoisite
101 Zoisite
102 Prehnite
103 Pumpellyite
104 Actinolite
105 Glaucophane
106 Lawsonite
107 Jadite
108 Other metamorphic minerals
109 OVERSIZE GRAINS
110 Oversize--neovolcanic
111 Oversize--carbonate rip-up
112 Oversize--clastic rip-up
113 Oversize--shell fragment
114 Detrital pebble
115 Other oversize grain
116 MISCELLANEOUS
117 Porosity

118	TOTALS	FORMULAS
119	TOTAL DETRITAL SAND GRAINS	SUM(10 thru 79)
120	TOTAL MATRIX	SUM(81 thru 84)
121	TOTAL CEMENT	SUM(86 thru 92)
122	TOTAL METAMORPHIC MINERALS	SUM(94 thru 108)
123	TOTAL OVERSIZE GRAINS	SUM(110 thru 115)
124	TOTAL POINTS COUNTED	SUM(117 thru 123)
125	PERCENTAGES	
126	Detrital grains	(119)/(124)*100
127	Matrix	(120)/(124)*100
128	Cement	(121)/(124)*100
129	Metamorphic minerals	(122)/(124)*100
130	Oversize grains	(123)/(124)*100
131	Porosity	(117)/(124)*100
132	Qm	SUM(10 thru 11)/(119)*100
133	Qms (straight extinction)	(11)/(119)*100
134	Qmu (undulose extinction)	(10)/(119)*100
135	Qp	SUM(12 thru 14)/(119)*100
136	C (chert)	SUM(27 thru 31)/(119)*100
137	Qp* (Qp + C)	SUM(135 + 136)
138	Q (total quartz)	SUM(10 thru 15)/(119)*100
139	Q* (total quartz + chert)	SUM(136 + 138)
140	K (potassium feldspar)	(17)/(119)*100
141	K* (K + plutonic feldspar)	SUM(17 + 18)/(119)*100
142	P (plagioclase)	SUM(19 thru 23)/(119)*100
143	Pz (zoned plagioclase)	(22)/(119)*100
144	Puz (unzoned plagioclase)	SUM(19 thru 21)/(119)*100
145	F (total feldspar grains)	SUM(17 thru 25)/(119)*100
146	Ls- (SRF - C)	SUM(32 thru 40)/(119)*100
147	Ls+ (SRF + C)	SUM(27 thru 40)/(119)*100
148	Ls* (Ls- + Lms)	SUM(32 thru 40 + 53 thru 55)/(119)*100
149	Lvf (felsic VRF)	SUM(42 thru 44)/(119)*100
150	Lvm (mafic and intermediate VRF)	SUM(45 thru 48)/(119)*100
151	Lv (total volcanic rock fragments)	SUM(42 thru 51)/(119)*100
152	Lv* (Lv + Lmv)	SUM(42 thru 51 + 56 thru 58)/(119)*100
153	Lms (metasedimentary rock fragments)	SUM(53 thru 55)/(119)*100
154	Lmv (metavolcanic rock fragments)	SUM(56 thru 58)/(119)*100
155	Lm (total metamorphic rock fragments)	SUM(53 thru 61)/(119)*100
156	Lp (plutonic rock fragments)	SUM(63 thru 67)/(119)*100
157	Li (igneous; Lv + Lp)	SUM(151 + 156)
158	L (Ls+ + Lv + Lm + Lp)	SUM(147 + 157 + 155)
159	L- (Ls- + Lv + Lm + Lp)	SUM(146 + 157 + 155)
160	Lt (Qp* + Ls- + Lv + Lm + Lp)	SUM(137 + 146 + 157 + 155)

161	<u>RATIOS</u>	<u>FORMULAS</u>
162	Q (Q:F:L)	(138)/SUM(138 + 145 + 158)*100
163	F (Q:F:L)	(145)/SUM(138 + 145 + 158)*100
164	L (Q:F:L)	(158)/SUM(138 + 145 + 158)*100
165	Q* (Q*:F:L-)	(139)/SUM(139 + 145 + 159)*100
166	F (Q*:F:L-)	(145)/SUM(139 + 145 + 159)*100
167	L- (Q*:F:L-)	(159)/SUM(139 + 145 + 159)*100
168	Qm (Qm:F:Lt)	(132)/SUM(132 + 145 + 160)*100
169	F (Qm:F:Lt)	(145)/SUM(132 + 145 + 160)*100
170	Lt (Qm:F:Lt)	(160)/SUM(132 + 145 + 160)*100
171	Qp (Qp:Lv*:Ls*)	(137)/SUM(137 + 152 + 148)*100
172	Lv* (Qp:Lv*:Ls*)	(152)/SUM(137 + 152 + 148)*100
173	Ls* (Qp:Lv*:Ls*)	(148)/SUM(137 + 152 + 148)*100
174	Qms (Qms:Qmu:Qp)	(133)/SUM(133 + 134 + 135)*100
175	Qmu (Qms:Qmu:Qp)	(134)/SUM(133 + 134 + 135)*100
176	Qms (Qms:Qmu:Qp)	(135)/SUM(133 + 134 + 135)*100
177	Qm (Qm:P:K)	(132)/SUM(132 + 142 + 140)*100
178	P (Qm:P:K)	(142)/SUM(132 + 142 + 140)*100
179	K (Qm:P:K)	(140)/SUM(132 + 142 + 140)*100
180	Qm (Qm:P:K*)	(132)/SUM(132 + 142 + 141)*100
181	P (Qm:P:K*)	(142)/SUM(132 + 142 + 141)*100
182	K* (Qm:P:K*)	(141)/SUM(132 + 142 + 141)*100
183	K* (K*:Pz:Puz)	(141)/SUM(141 + 143 + 144)*100
184	Pz (K*:Pz:Puz)	(143)/SUM(141 + 143 + 144)*100
185	Puz (K*:Pz:Puz)	(144)/SUM(141 + 143 + 144)*100
186	Lv (Lv:Ls+:Lm)	(151)/SUM(151 + 147 + 155)*100
187	Ls+ (Lv:Ls+:Lm)	(147)/SUM(151 + 147 + 155)*100
188	Lm (Lv:Ls+:Lm)	(155)/SUM(151 + 147 + 155)*100
189	Lv (Lv:Ls-:Lm)	(151)/SUM(151 + 146 + 155)*100
190	Ls- (Lv:Ls-:Lm)	(146)/SUM(151 + 146 + 155)*100
191	Lm (Lv:Ls-:Lm)	(155)/SUM(151 + 146 + 155)*100
192	Ll (Ll:Ls+:Lm)	(157)/SUM(157 + 147 + 155)*100
193	Ls+ (Ll:Ls+:Lm)	(147)/SUM(157 + 147 + 155)*100
194	Lm (Ll:Ls+:Lm)	(155)/SUM(157 + 147 + 155)*100
195	Framework (Framework:Matrix:Cement)	(119)/SUM(119 + 120 + 121)*100
196	Matrix (Framework:Matrix:Cement)	(120)/SUM(119 + 120 + 121)*100
197	Cement (Framework:Matrix:Cement)	(121)/SUM(119 + 120 + 121)*100
198	C/Q*	(136)/(139)
199	Qp*/Q*	(137)/(139)
200	P/F	(142)/(145)
201	Lv/L	(151)/(158)
202	Lv/Lt	(151)/(160)
203	Alteration Index	SUM(25 + 49)/SUM(17 thru 25 + 42 thru 5
204	Gazzi-Dickinson Factor	SUM(14 + 35 + 55 + 58 + 63 thru 67)/119
205	C twins/Total Plagioclase	(20)/(SUM(19 thru 23)
206	Zoned/Total Plagioclase	(22)/(SUM(19 thru 23)
207	<u>SUMMARY</u>	
208	QUARTZ (Q)	138
209	FELDSPAR (F)	145
210	SEDIMENTARY ROCK FRAGMENTS (Ls+)	147
211	VOLCANIC ROCK FRAGMENTS (Lv)	151
212	METAMORPHIC ROCK FRAGMENTS (Lm)	155
213	PLUTONIC ROCK FRAGMENTS (Lp)	156
214	OTHER DETRITAL MINERALS	SUM(69 thru 79)/119*100
215	TOTAL	SUM(208 thru 214)

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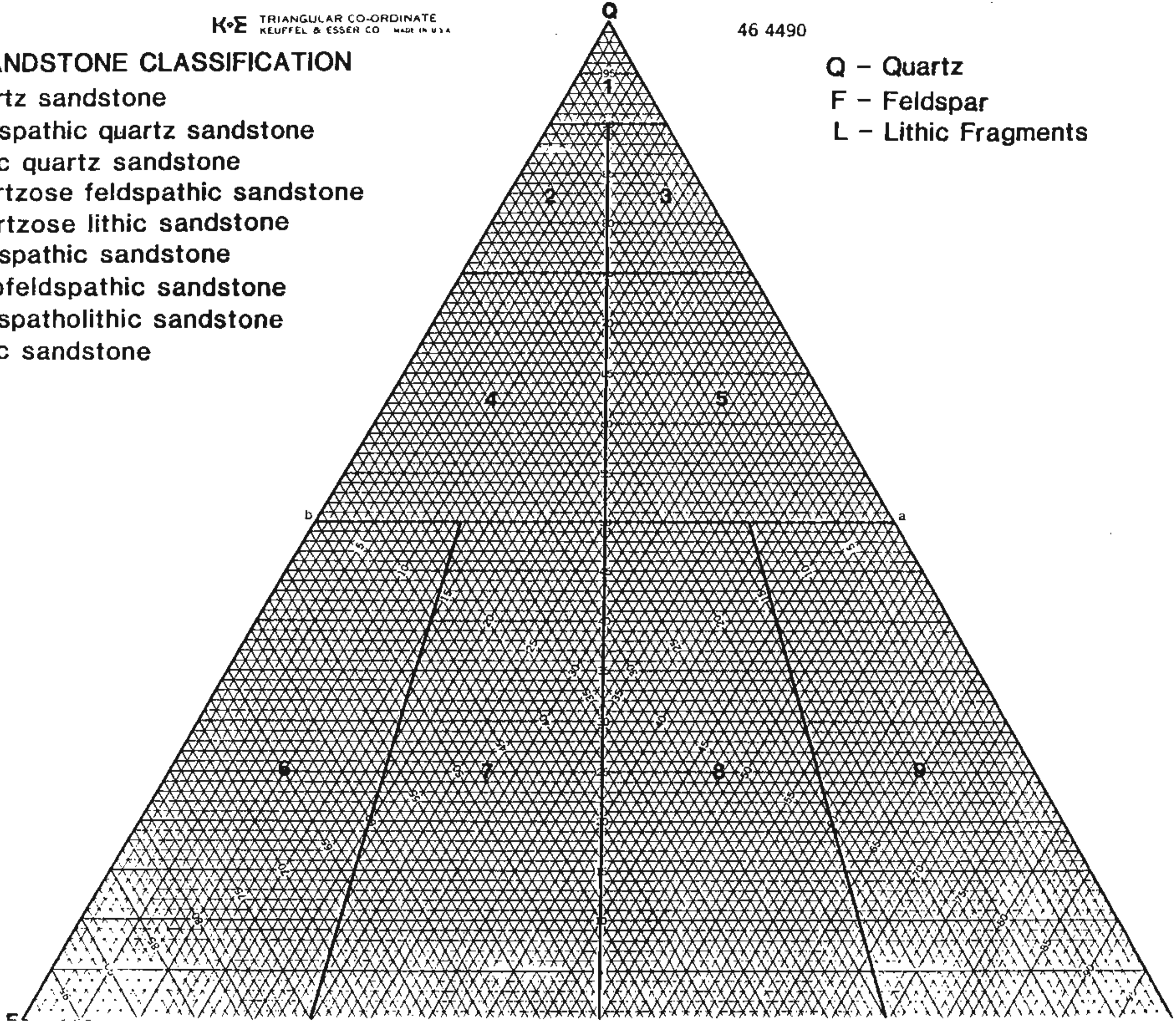
SANDSTONE CLASSIFICATION

1. quartz sandstone
2. feldspathic quartz sandstone
3. lithic quartz sandstone
4. quartzose feldspathic sandstone
5. quartzose lithic sandstone
6. feldspathic sandstone
7. lithofeldspathic sandstone
8. feldspatholithic sandstone
9. lithic sandstone

Q – Quartz
F – Feldspar
L – Lithic Fragments



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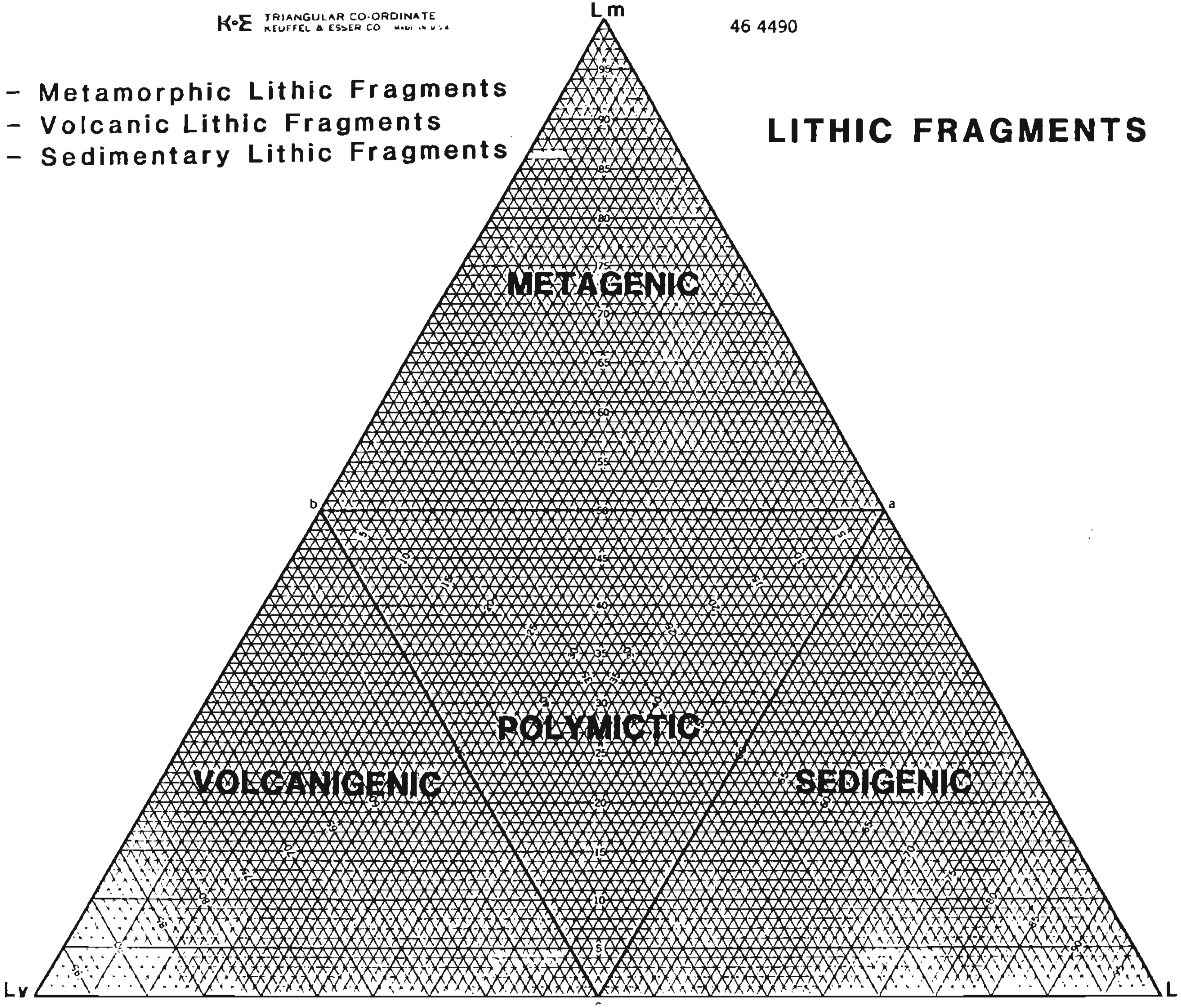
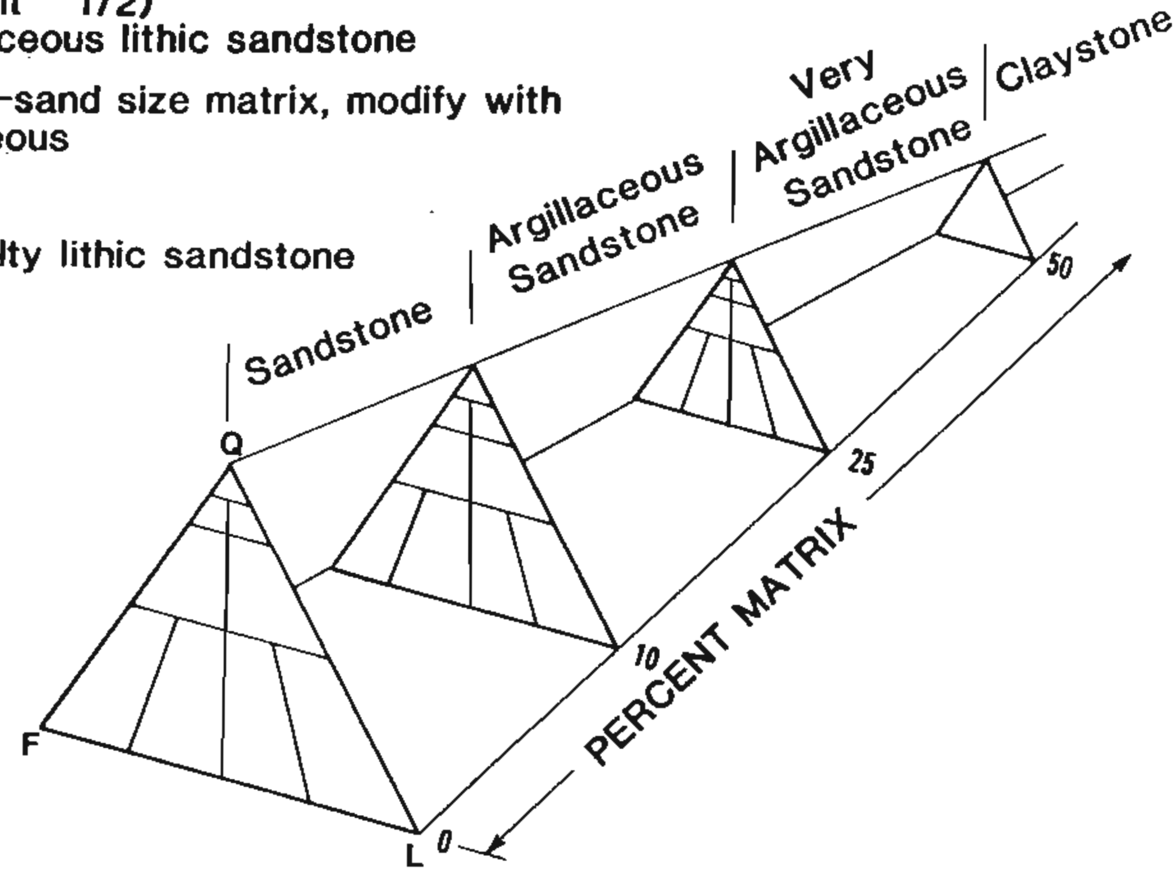


10% – 25% sub-sand size matrix, modify with
argillaceous (clay/silt 2/1)
muddy (clay/silt 2/1 and 1/2)
silty (clay/silt 1/2)
Ex: argillaceous lithic sandstone

25% – 50% sub-sand size matrix, modify with
very argillaceous
very muddy
very silty
Ex: very silty lithic sandstone



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