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PART I : Original Photographs of Our Lab

Photomicrographs of Detrital Grains

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**Rock fragments (XPL)**
SS : very fine-grained sandstone fragment,
A : argillite,
QM : quartz-mica aggregate.

Manhang Formation
Danyang coalfield

Photo courtesy of C. Lim

---

**Rock fragments (XPL)**
S : siltstone rock fragment,
A : argillite.

Manhang Formation
Danyang coalfield

Photo courtesy of C. Lim

---

**Chert grain (XPL)**

Manhang Formation
Danyang coalfield

Photo courtesy of C. Lim
**Limestone rock fragment** (XPL)
Manhang Formation
Mungyeong coalfield
Photo courtesy of C. Lim

**Slate fragment** (OPL)
Manhang Formation
Danyang coalfield
Photo courtesy of C. Lim

**Quartz-mica aggregate fragment** consisting of quartz and muscovite (XPL)
Manhang Formation
Cheongseon coalfield
Photo courtesy of C. Lim

**Quartz-mica tectonite fragment** deformed between competent grains by shear stress (XPL)
Manhang Formation
Danyang coalfield
Photo courtesy of C. Lim
Spike-shaped overgrowth of tourmaline. Host tourmaline is subrounded (XPL)
Manhang Formation
Cheongseon coalfield
Photo courtesy of C. Lim

Rounded tourmaline (OPL)
Manhang Formation
Mungyeong coalfield
Photo courtesy of C. Lim

Plagioclase replaced by quartz (XPL)
Manhang Formation
Gangreung coalfield
Photo courtesy of C. Lim
Photomicrographs of Quartz

(*) Atlas of sedimentary rocks under the microscope
(A. E. Adams, W. S. MacKenzie, and C. Guilford)
(**) A color Illustrated Guide to Constituents, Texture, Cements, and Porosities of Sandstones and Associated Rocks
(Peter A. Scholle)

This shows subrounded quartz grains which are single crystals, taken with crossed ploars(XPL). The matrix between the sand grains contains opaque iron oxide and some calcite. The latter shows high-order pink and green interference colors. (*)

The three rounded grains in the center are made up of a number of quartz crystals in different orientations and are thus composite or polycrystalline quartz. The composite nature of the grains is clear only in the view taken with polars crossed. Note that the boundaries between the crystals are sutured. This is the characteristics of quartz from a metamorphic source. The much finer sediment surrounding the composite quartz grains contains monocrystalline quartz and brownish clasts of fine-grained material which are probably shale or slate fragments. (*)

This shows a composite quartz grain viewed under crossed polars, in which not only are the crystal boundaries within the grain sutured, but also the crystals are elongated in a preferred direction. Such grains are called sheared quartz or stretched metamorphic quartz. In this type of quartz, individual crystals normally show undulose extinction as a result of stain. (*)
The quartz grain in the center of the field of view is made up of parts of two crystals. One, comprising the upper left portion of the grain is showing a mid-grey interference color, whereas the rest of the grain comprises a crystal with areas showing a slightly different interference colors. The left- and right-hand sides are in extinction and interference colors become progressively paler towards the center of the grain. Such a grain would show **sweeping extinction (undulose extinction)** when rotated.(**)

Detail of **volcanic quartz** crystal. This grain has straight extinction, a euhedral outline, and a large *negative crystal* or vacuole. The vacuole has the same crystallographic orientation as the complete quartz grain, hence the term *negative crystal*. This feature is common but not ubiquitous in quartz of volcanic origin(Pleistocene Yellow Group(tuff), Wyoming).(**)

A **volcanic quartz** grain with euhedral, bipyramidal outline. Euhedral shape, embayments, straight extinction, and scarcity of inclusions are all indicative of an extrusive igneous source, but none, by itself, is conclusive evidence(Pleistocene Yellow Group(tuff), Wyoming).(**)

A **nondetrital quartz** grain (in a nonsedimentary *source* rock) showing rounded outline and embayment. Thus, not all original grains are angular, and embayment is not restricted to volcanic quartz. Quartz crystal(photo center) is surrounded by plagioclase feldspar (Pleistocene Yellowstone Group(tuff), Wyoming).(**
Large grain in center is a single-crystal, slightly undulose quartz grain ('end phase' or 'igneous' quartz of Krynine, 1940 and 1946). Grain extinguishes completely with between 1 and 5 degrees of stage rotation. Such extinction behavior is best studied using a universal stage but can be done with less accuracy on a flat stage. Slightly undulose quartz can be derived from most types of source terrains (Upper Cambrian Gateburg Fm., Pennsylvania). (**)

A semicomposite quartz grain with slightly undulose extinction. Grain consists of a number of separate quartz crystals with very closely aligned optic c-axes. Such grains are common in hydrothermal veins but also occur in many metamorphic and plutonic rock types (Upper Triassic New Haven Arkose, Connecticut). (**)

Quartz grains with abundant needle-shaped mineral inclusions. The inclusions in this case are sillimanite, but actinolite, tremolite, rutile, and other minerals can also be found as needle-like inclusions in quartz. Detrital quartz grains with sillimanite inclusions are excellent evidence for a metamorphic source area (Paleozoic andalusite schist, New Hampshire). (**
### Photomicrographs of Carbonate Rocks

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<tr>
<td><img src="image1.jpg" alt="Echinoderm grains" /></td>
<td>Echinoderm grains showing cloudy appearance due to the presence of abundant inclusions. Minute inclusions are also observed in syntaxial overgrowth, but abundance is less than host grain. Micritic envelopes are well developed Ordovician Yeongheung Fm. Photo courtesy of Dr. CM Yoo</td>
</tr>
<tr>
<td><img src="image2.jpg" alt="Gastropod" /></td>
<td>Gastropod showing no internal microstructure due to complete dissolution of aragonite and subsequent filling by calcite. Scale bar is 300 micrometers. Ordovician Yeongheung Fm. Photo courtesy of Dr. CM Yoo</td>
</tr>
<tr>
<td><img src="image3.jpg" alt="Stylolite" /></td>
<td>Stylolite cross-cut the replacement dolomite crystals. Ordovician Yeongheung Fm. Photo courtesy of Dr. CM Yoo</td>
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</table>
Photomicrograph of brachiopod showing excellent preservation of their original laminar foliated layer. **Pseudopunctate** is well developed.

Ordovician Yeongheung Fm.

Photo courtesy of Dr. CM Yoo

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**Saddle dolomite cements** are developed in the cavity after evaporite nodule dissolution. The dolomites were dissolved partially as evidenced by the corroded cement margin and subsequently filled by very coarse sparry calcite shown in the lower half of the photomicrograph.

Ordovician Yeongheung Fm.

Photo courtesy of Dr. CM Yoo

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**Deformed peloids.** Relatively competent ooids (oval shape) are remained in less deformed state. White wavy and anastomosing bands are sparry calcite cements formed earlier than compaction.

Ordovician Yeongheung Fm.

Photo courtesy of Dr. CM Yoo
<table>
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<tr>
<th>Fossiliferous grainstone. Bioclasts are cemented by blocky sparry cements. Micritic envelopes are well developed in fossil fragments.</th>
<th>Ordovician Yeongheung Fm.</th>
<th>Photo courtesy of Dr. CM Yoo</th>
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<tr>
<th>Fossiliferous packstone. Bioclasts are randomly distributed in lime mud matrix. Well developed micritic envelope is observed in crinoid fragment. The inside pores of some gastropods are filled with dolomite rhomb. Trilobite fragments and disarticulated ostracods are visible also.</th>
<th>Ordovician Yeongheung Fm.</th>
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<tr>
<th>Crinoid fragment with micrite envelopes.</th>
<th>Ordovician Mungog Fm.</th>
<th>Photo courtesy of Dr. JI Lee</th>
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Gastropod.
Ordovician Mungog Fm.
Photo courtesy of Dr. JI Lee

Radial ooids. The original radial textures are well preserved and this means the original mineral of these ooids was probably calcite.
Ordovician Mungog Fm.
Photo courtesy of Dr. JI Lee
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<td><strong>Diagenetic albitization (Ab)</strong> of plagioclase (P) along cleavage planes. Note dissolution along cleavage planes (arrows).</td>
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<td>Cretaceous Haman Fm.</td>
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<td>Photo courtesy of Dr. JI Lee</td>
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| **Albite (dark gray) and calcite (light gray) replacement of K-feldspar (medium gray).** You can see small remnant original plagioclase in right center of this sand-size grain in mudrock. |
| Cretaceous Jeomgog Fm. |
| Photo courtesy of Dr. JI Lee |
Plagioclase albitization along grain margin. Faint oscillatory compositional zoning is observed. Within this plagioclase grain is observed calcite (light).

Cretaceous Haman Fm.

Plagioclase (P) albitization along microfractures. Albite overgrowth (Ab) and calcite cement (Cc) are also observed.

Cretaceous Haman Fm.

Albitization along microfracture (arrows) in plagioclase (P1). Albite overgrowth (Ab) and calcite cement and replacement are also observed.

Cretaceous Haman Fm.

Photo courtesy of Dr. JI Lee
Euheadral K-feldspar (K) and calcite (Cc) filling in fracture of mudrock

Cretaceous Jeomgog Fm.

Photo courtesy of Dr. JI Lee

Early micrite (light gray)-cemented sandstone. Note the brightness contrast between quartz (dark gray) and plagioclase (medium gray). The unaltered nature of plagioclase grains indicates that plagioclase albitization occurred during diagenesis, not in source area.

Cretaceous Jinju Fm.

Photo courtesy of Dr. JI Lee
### Photomicrographs of Quartz

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<td><img src="image1.png" alt="Quartz grains containing tiny mineral or fluid inclusions" /></td>
<td>Quartz grains containing tiny mineral or fluid inclusions (arrowheads). Quartz grains are generally subangular to subrounded (XPL). Manhang Formation Gangreung coalfield. Photo courtesy of C. Lim.</td>
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<tr>
<td><img src="image2.png" alt="Deformation lamellae of quartz formed by dislocation along specific crystallographic plane" /></td>
<td>Deformation lamellae of quartz formed by dislocation along specific crystallographic plane. Such lamellae are probably of pre-depositional because of intraparticle deformation (XPL). Manhang Formation Danyang coalfield. Photo courtesy of C. Lim.</td>
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<tr>
<td><img src="image3.png" alt="Quartz replaced by calcite" /></td>
<td>Quartz replaced by calcite (left) (XPL). Manhang Formation Cheongseon coalfield. Photo courtesy of C. Lim.</td>
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Semi-composite quartz (XPL)
Manhang Formation
Cheongseon coalfield
Photo courtesy of C. Lim

Polycrystalline quartz grain with sutured crystal-crystal boundaries. Such quartz is classified as a "unstable" grain. This quartz is sourced from low-grade metamorphic rocks (Young, 1976). (XPL)
Manhang Formation
Danyang coalfield
Photo courtesy of C. Lim

Quartz grain showing crystal units with polyhedral outlines, smooth intercrystal boundaries, and triple junctions of the boundaries meeting 120°. This quartz is classified as a "stable" grain, which means it was ultimately derived from medium- to high-grade metamorphic rocks (Young, 1976). (XPL)
Manhang Formation
Gangreung coalfield
Photo courtesy of C. Lim

Quartz grains with secondary overgrowth. Quartz grains are generally subangular to subrounded. (XPL)
Manhang Formation
Danyang coalfield
Photo courtesy of C. Lim
<table>
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| ![Various types of quartz grains (XPL)](image1) | Various types of quartz grains (XPL)  
Jangseong Formation  
Samcheog coalfield  
Photo courtesy of C. Lim |
| ![Quartz grains containing abundant vacuoles (XPL)](image2) | Quartz grains containing abundant vacuoles (XPL)  
Hambaegsan Formation  
Samcheog coalfield  
Photo courtesy of C. Lim |
| ![Various types of quartzs (XPL)](image3) | Various types of quartzs (XPL)  
Gohan Formation  
Samcheog coalfield  
Photo courtesy of C. Lim |
Photomicrographs of Feldspar

(*) Atlas of sedimentary rocks under the microscope
(A. E. Adams, W. S. MacKenzie, and C. Guilford)

(**)A color Illustrated Guide to Constituents, Texture, Cements, and Porosities of Sandstones and Associated Rocks
(Peter A. Scholle)

This photo shows a large plagioclase grain which is easily identified by the twinning in the photograph with polars crossed. The grain shows a combination of two types of twins which are probably Carlsbad (simple twin) and albite (multiple twinning). The cloudiness seen in PPL is caused by patchy alteration of the feldspar. The highly birefringent, fine-grained alteration product is probably sericite, a mica. (*)

This photo shows a pebble-sized fragment composed almost entirely of microcline. Microcline can be identified easily by the cross-hatched twinning which it invariably shows. Although the microcline shows little alteration, feldspar grains in the upper left, including multiple-twinned plagioclase, are brownish colored as a result of alteration. In contrast, the quartz in the upper right is relatively clear and unaltered. (*)

Grains showing perthitic intergrowths, comprising blebs or lamellae of sodium-rich feldspar in potassium-rich feldspar, are not uncommon in sediments. This photo shows a very coarse sand-sized fragment of perthite. Most of the other sediment grains are quartz and the matrix contains highly birefringent mineral grains too small to identify at the magnification shown. (*)
Complex twinning in a plagioclase feldspar grain. Exact types of twinning are best determined on a universal stage, but albite, carlsbad, and pericline twins are probably present here. Twin types can sometimes indicate source area. Pink tint grains resulted from staining for plagioclase (Ordovician Newtown Gneiss, Connecticut). (**)

Plagioclase feldspars (unstained) in a volcanic sandstone. Note euhedral crystal outlines, well-defined crystal zoning (growth-composition lines) and the albite twinning. All these features, taken together, are indicative of volcanic plagioclase (Tertiary Horse Spring Fm., Nevada). (**)

Microcline feldspar with typical microcline grid twinning. Although such twinning is characteristic of most triclinic alkali feldspars, it is most commonly shown by microcline. Some small inclusions of plagioclase with albite twinning are present here (Ordovician Newtown Gneiss, Connecticut). (**).
Yellow grain in center is a microcline feldspar with spindle twinning—the irregular lamellar twins can often be used to distinguish microcline. Yellow color is a stain for K-spar. The brown, elongate grain directly to the left of the microcline is biotite (Precambrian Hitchcock Lake Mbr. of Waterbury gneiss, Connecticut). (**)

A plagioclase feldspar largely replaced by calcite. To accurately determine composition of sandstones it is often necessary to recognize feldspars in very advanced stages of destruction. Calcite replacement is one very common form of diagenetic alteration (Pennsylvanian-Permian Sangre de Cristo Fm., New Mexico). (**
Photomicrographs of Rock Fragments

(*) Atlas of sedimentary rocks under the microscope (A. E. Adams, W. S. MacKenzie, and C. Guilford)
(**) A color Illustrated Guide to Constituents, Texture, Cements, and Porosities of Sandstones and Associated Rocks (Peter A. Scholle)

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<th>This photograph shows a sediment with many rock fragments. The two fragments in the center of the photograph above the large quartz grain are made up of fine-grained material which cannot be resolved at this magnification. They are fragments of shale or slate, and the characteristic platy shape is a result of derivation from a cleaved source rock containing abundant platy minerals. The sediment is very poorly sorted, containing many small rock fragments, quartz grains and at least one twinned feldspar (in the center, near the top), as well as the large quartz grain, part of which is seen at the base of the photograph. (*)</th>
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<td>This photograph shows a fragment of muscovite-bearing quartz-rich rock. The mica flakes show a preferential alignment resulting in a schistose texture. Such fragments are sometimes classified as schistose quartz rather than metamorphic rock fragments. (*)</td>
</tr>
<tr>
<td>This photograph shows two different igneous rock fragments. To the left and above the center of the field of view is a fine-grained, probably volcanic, basic rock. It consists of microphenocrysts of plagioclase feldspar set in a groundmass of feldspar, very small pyroxene crystals and opaques. Pale green chlorite occurs, possibly filling original vesicles. The lower part of the field of view is mostly occupied by a coarse-grained plutonic rock fragment consisting mainly of plagioclase feldspar and pyroxene. (*)</td>
</tr>
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Sedimentary rock fragment-chert. Note the very uniform microcrystalline quartz with no visible relict texture. Grain is surrounded by carbonate matrix and cement. Chert derived from sedimentary sources can be mistaken for very finely crystalline volcanic rock fragments or clay clasts if not carefully examined (Cretaceous Travis Peak Cgl., Texas). (**)

A detrital dolomite fragment (SRF). Note the rhombic shape of constituent crystals as well as their pronounced zoning with cloudy centers and clear rims. These are good criteria for the recognition of dolomite although many dolomites do not show either characteristic. Staining is the most reliable technique for identification of detrital or authigenic dolomite (Cretaceous Rieselberger Sandstone, Germany). (*)

A large grain of definite metamorphic origin. Consists of numerous, elongate, crenulate quartz crystals welded together. Most probably this is a fragment of a sheared metaquartzite (Oligocene Tongriano Fm., Alaska). (**)

This photograph shows a schistose texture commonly seen in high-rank metamorphic rock fragments. Elongate quartz grains are separated by thin mica plates. Detrital fragments of such rock types are normally quite soft and rarely survive extensive transport; however, when such fragments are found, they are excellent indicators of a metamorphic source (Paleozoic andalusite schist, New Hampshire). (**

(*) The multiple asterisks indicate that the sample is marked as having an asterisk, while the single asterisk indicates that the sample is marked as having no asterisk.
Vocanic rock fragments (FRF's). The large grain in upper center shows laths of plagioclase set in a very finely crystalline matrix. The other dark grains are also VRF's but are much more difficult to identify because of the lack of phenocrysts. Such VRF's must be carefully distinguished from detrital chert or clay clasts. The cement in this example is calcite (Cretaceous Ildefonso Fm., Puerto Rico). (**)

Abundant volcanic glass shards composed of opalline silica. Fragments of shard-filled sediment can be found and also are excellent indicators of a volcanic source area (primarily acidic volcanism) (Tertiary Horse Springs Fm., Nevada). (**)

A volcanic feldspar grain. This grain would not be classified as a VRF, but it would be useful in confirming a volcanic source or in deciding whether associated fine-grained rock fragments are of volcanic origin. This example shows a plagioclase with well developed twinning, euhedral outline, and faint (but very diagnostic) compositional zoning set in a glassy groundmass (Tertiary Needles Range Fm., Nevada). (**)

(*) = Note: These are not common components of volcaniclastic sediments.

### Photomicrographs of Other Detrital Grains

**Source**: A color Illustrated Guide to Constituents, Texture, Cements, and Porosities of Sandstones and Associated Rocks (Peter A. Scholle)

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<tr>
<td><img src="image1" alt="Hematite ooids" /></td>
<td><strong>Hematite ooids</strong> illuminated with very strong transmitted light ( conoscopic condenser lens inserted). Note the reddish-yellow color indicative of hematite which may be partially altered to goethite-limonite. Oolitic iron minerals include hematite, chamosite, limonite, and siderite. Jurassc Eisenoolith, Germany</td>
</tr>
<tr>
<td><img src="image2" alt="Hematite" /></td>
<td><strong>Hematite</strong>, here as oolitic coatings on carbonate skeletal fragments. The hematite in this sample is opaque, but in very thin sections, with stronger transmitted light, or in reflected light, one can commonly distinguish a dark red to brown color characteristic of this mineral. Hematitic ooids are normally indicative of oxidizing marine environments, as well as paleosols and weathering horizons. Silurian Clinton Fm., Pennsylvania</td>
</tr>
<tr>
<td><img src="image3" alt="Detrital micas" /></td>
<td><strong>Detrital micas</strong> (muscovite). The grains with the bright blue (second order) birefringence are muscovite flakes. They are nearly colorless in ordinary light. The slightly speckled texture (reminiscent of birch bark) is characteristic of micas. Muscovite, because of its greater chemical stability, is more common than biotite in most sedimentary rocks. Cretaceous Monte Antola Fm., Italy</td>
</tr>
</tbody>
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*Note: Images are placeholders for the actual photomicrographs.*
A large biotite crystal surrounded by muscovite. Note brown color, excellent cleavage, and dark spots which are 'pleochroic halos' formed around minute inclusions of zircon, apatite, or other uranium-bearing minerals. Biotite crystals are normally pleochoic, with colors ranging from colorless to yellow, brown, red-brown, and green. Biotite weathers readily and if very abundant in a sediment one can suspect a volcanic source.

Ordovician(?) garnet schist, Connecticut

A biotite grain surrounded by quartz. The biotite shows third order birefringence colors and the rough (birch bark) texture typical of micas. Two small pleochroic halos are also visible. Biotite can be derived in small amounts from almost all types of igneous and metamorphic terrains.

Cambrian(?) Hitchcock Lake Mbr. of Waterbury Gneiss, Connecticut

A detrital chlorite grain. Shows anomalous birefringence colors (some chlorite varieties have 'ultra blue' colors; others have more normal low birefringence). The coarseness of this chlorite grain indicates that it probably is an alteration of biotite. Chlorite can be distinguished from clinozoisite (which also has 'ultra blue' birefringence) by the higher relief of the latter mineral. Chlorite is found in most source rock types.

Permian Abo Sandstone, New Mexico
A kyanite crystal showing typical high relief, long and bladed crystal form, two good cleavages, and light color (often pleochroic). Kyanite is only found in high-graded metamorphic source areas and thus is a valuable provenance indicator. It has moderate chemical stability but relatively low abrasion resistance. Many varieties commonly make it useful for stratigraphic correlation.

Ordovician(?) schist, Connecticut

**Sillimanite.** The fibrous crystal form, pale brown color, slight pleochroism, and high relief are characteristic. Sillimanite is found only in metamorphic rocks (mainly high-grade schists and contact metamorphics). This mineral has moderate chemical stability and relatively low abrasion resistance.

Ordovician-Silurian schist, Massachusetts

A large andalusite crystal with excellent 110 cleavage surrounded by muscovite. Andalusite is characterized by high relief, color ranging from colorless to pink (occasionally green, or yellow), variable pleochroism, and excellent cleavage. It is most common in schists and contact metamorphic rocks. Low chemical stability in surface environments explains its scarcity in older sediments; rather common in younger units, however Paleozoic andalusite schist, New Hampshire

A staurolite crystal surrounded by quartz (colorless) and muscovite (stained red in this section). Staurolite has brownish color, moderate relief, moderate pleochroism, abundant inclusions, and prismatic crystal habit with weakly developed cleavage. It is an excellent indicator of a schistose metamorphic source. Detrital grains are rarely well crystallized.

Ordovician schist, Connecticut
Carbonate Rocks
Photomicrographs of nonskeletal grains

Source Text: Atlas of sedimentary rocks under the microscope
(A. E. Adams, W. S., Mackenzie and C. Guilford)

This photograph shows ooids with well-developed radial and concentric structures. (Ooids are spherical or ellipsoidal grains, less than 2mm in diameter, having regular concentric laminae developed around a nucleus.) The nuclei are micritic carbonate grains. The sample shows a range of ooids, from those with a small nucleus and thick cortex (the oolitic coating), to those with a large nucleus and a single oolitic lamina. The latter are called superficial ooids. The matrix between the ooids is a mixture of carbonate mud and sparry calcite cement.

This photograph illustrate ooids with a rather poorly-preserved concentric structure. The structure may have been partly lost by micritization. The speckled plates with thin micrite coatings are echinoderms (an example can be seen half way up the right-hand edge). The pink-stained cement is non-ferroan sparry (authigenic) quartz replacing calcite.

Those grains composed of micrite and lacking any recognizable internal structure are called 'peloids'. This photograph shows a limestone in which the allochems are mainly peloids, circular to elliptical in cross-section and averaging about 0.1mm in diameter. Such peloids are generally interpreted as faecal in origin and are called 'pellets'. The photograph shows pellets at the lower end of the size range for typical pellets, which extends up to 0.5mm.
This photograph shows a large grain which might be described as a "coated bioclast". This is a kind of intraclast, which was once incorporated on the sea-floor of the basin of deposition and was later reworked to form new sediment grains. It comprises a nucleus, which is a fragment of a brachiopod shell, surrounded by a coating of microcrystalline calcite.

This photograph shows aggregate grains. This is made up of irregular aggregates of a small number of recognizable particles cemented together by micrite or fine sparite. The component particles includes ooids (the grain right of center) as well as peloids and a few bioclasts. The opaque material in the top center is bitumen.

This is a photograph of a polished rock surface showing oncoids. Oncoids are presumed to be biogenic, blue-green algae on the grain surface, trapping and binding fine sediment particles. Note the size of the grains, the asymmetrical growth and the wavy nature of many of the laminae, all features characteristic of oncoids. The bluish-grey areas are sparry calcite and the orange-brown areas are stained with iron oxides.
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<tr>
<td><img src="image1" alt="Image" /></td>
<td>This photograph shows grains which are about 2mm in diameter and whose origin is difficult to interpret. The outer surfaces are not as smooth as most ooids, although the concentric lamination is very regular. Grains in the upper right show irregular outer coats of micrite and some particles have apparently grown together to form compound grains (e.g. lower left). This latter feature is unlikely to occur in ooids, where precipitated carbonate laminae are formed while the grain is held in suspension. These grains are therefore interpreted as oncoids.</td>
</tr>
<tr>
<td><img src="image2" alt="Image" /></td>
<td>This photograph shows grains with a regular, well-defined concentric layering, in grains up to 5mm in diameter. This is typical of inorganic growth and these grains may be pisoids. Pisoids are commonly fractured or broken. Broken pieces can be seen towards the top right of the photograph.</td>
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</table>
Photomicrographs of skeletal grains(I)

Source Text: Atlas of sedimentary rocks under the microscope
(A. E. Adams, W. S., Mackenzie and C. Guilford)

This photograph shows a limestone with abundant molluscan casts. In this case shell moulds have been infilled with a few large calcite crystals. Gastropods can be seen, both in long section(lower right) and transverse section(lower left). The long straight shells are bivalve fragments. Careful inspection shows that the long valves in the upper left have a two-layer structure—a thick layer of coarse sparite and a thin layer with a different structure. The rock matrix is micritic sediment.

This photograph illustrates a section through a large thick-shelled gastropod, again preserved as a cast. The outer margin of the shell is picked out by a thin calcite layer, not more than 0.5 mm thick at this magnification, but the inner margin is only clear where sediment has partially filled the internal cavity. The sediment around the shell contains abundant small peloids.

This photograph shows two large pink-stained oyster fragments, each having a foliated internal structure. Fragments of oysters may be difficult to distinguish from brachiopods, although their thick shells with a rather irregular foliated structure are characteristic. Note also how the left-hand end of the upper fragment is upturned and splitting. The rest of the sediment comprises broken-up bioclasts set in a blue-stained ferroan calcite cement. The white areas are holes in the section.
This photograph shows a broken brachiopod of which parts of both valves are present and surrounded by a micrite envelope. The fibrous structure is clearly visible, as are fine tubes at right angles to the shell wall, filled with blue-stained ferroan calcite cement. These are 'endopunctae' and they characterize some proups of brachiopods. The sample also shows a good example of coarse, blue-stained ferroan calcite cement.

This photograph shows a number of small impunctate brachiopods with the large pedicle valve and smaller brachial valve complete. The roughly elliptical fragment in the lower center is a section transverse to the length of the fibres making up the shell wall, and shows a characteristic fine net-like structure.

This photograph shows transverse sections through several spines. They have a structure similar to the brachiopod valve with a foliated inner layer and an occasionally preserved outer prismatic layer. The section through the large spine in the upper left of the picture shows part of the prismatic layer preserved. Note how the shape of the spine gives the foliated layer a concentric structure.
This photograph shows a crinoidal limestone in which the sediment is 75% crinoids. Note the speckled appearance of the plates, most of which have uniform interference colors and are thus single crystals, although the ossicle in the upper left comprises two crystals, one showing a greenish color and one a red color under crossed polars. The clear spar surrounding some of the crinoid fragments is a cement.

This photograph shows one complete transverse section of a spine (lower right of the field), together with a smaller broken fragment. Echinoid spines are circular or elliptical in cross-section and show a variety of radial structures. Like other echinoderm fragments, they are single crystals.
This photograph shows a transverse section and parts of two longitudinal sections of the colonial rugose coral *Lithostrotion*. Note the thick outer wall and septa seen in the transverse section. The columella and thin tabulae are clearly visible in the longitudinal section. Parts of the coral walls have been silicified (brownish color). The pore-filling material is mainly sparite cement with some micritic sediment between the corallites.

This photograph is a transverse section of a stick-like bryozoan colony, showing the overall rounded shape of the 'stem' and of the zooecia within. Some of these have been infilled with fine sediment (upper right of fragment) but most have a blue-stained, ferroan calcite cement infill. In general, most bryozoans had calcite hard parts and a liminated wall structure is preserved.

In this photograph, the two circular, concentrically-laminated grains stained red-brown are brachiopod spines. These are encrusted by a bryozoan. Note the thick calcite wall of the bryozoan and the pores of different sizes within the skeleton, filled with pink-stained non-ferroan calcite cement. Some fragments of fenestrate bryozoans can be seen along the left-hand side of the photograph.
This photograph shows a cross-section of a trilobite (center) and part of a brachiopod shell (base). Note the hooked shape seen at the left-hand end of the trilobite fragment, produced by incurving of the skeleton at its margin. A vein of blue-stained ferroan calcite follows the edge of the skeleton along part of its length. Note that the trilobite is stained mauve and hence consists of slightly ferroan calcite. This contrasts with the brachiopod fragment which is non-ferroan calcite.

This photograph shows discocyclinids, a type of foraminifer with many chambers. The matrix is micrite with many fragmented bioclasts. In general, most of foraminifera are calcite but they show a variety of shapes and wall structures.

This photograph shows a foraminiferal limestone in which the organisms are micrite-walled miliolids. The cement is fine sparite although unfilled pore-spaces remain (e.g. center of field of view). Partly-filled moulds of bivalves can be seen outlined by thin micrite envelopes. These are the elongate curved grains seen on the right-hand side of the photograph.
This photograph shows segments of one of the common forms of codiacean alga, *Halimeda*, which still occurs today. Living examples contain organic filaments embedded in aragonite. The example shown is from a poorly-consolidated Quaternary sediment which had to be impregnated with resin before a peel could be made. The grey areas between the algal segments and in the holes originally occupied by the filaments are the impregnating medium.

The third group of green algae are the charophytes, although these are sometimes classified separately. They are freshwater plants, occurring in the Mesozoic and Cenozoic, and usually only the reproductive parts (oogonia) are calcified. These are small egg-shaped bodies with various ornaments. This photograph shows three oogonia in cross-section.
Diagenesis of Carbonate Rocks

Source Text: Atlas of sedimentary rocks under the microscope
(A. E. Adams, W. S., Mackenzie and C. Guilford)

This photograph shows a section through a coral skeleton (brownish-stained, structure not clearly visible) in which the first generation of cement is acicular aragonite showing a radial-fibrous texture. Note the variation in the length of the crystals which gives a very irregular outer margin to this generation of cement. Such a cement, being aragonite, is not likely to be well-preserved in an ancient limestone. If it undergoes neomorphism, the overall radial-fibrous fabric may be retained although detail will be lost. In the sample shown, there is a second generation of pink-stained fine sparite infilling pores. This is a typical of cement deposited from meteoric waters.

This photograph shows a limestone in which there are two cement generations. The first appears as a rim of crystals of equal thickness on all grains (about 2mm in width in the photograph). Such cements are said to be "isopachous". It may originally have been aragonite, details of the texture having been lost during inversion to calcite, or it may have been a high magnesium calcite marine cement in which the crystals were elongate prisms rather than needles. The final pore fill is an equant sparite, blue-stained and thus ferroan calcite. This latter cements is characteristic of deposition from meteoric waters or from connate waters fairly deep in the subsurface.

This photograph illustrates a drusy mosaic in which cement crystals show compositional zoning, the stain picking out changes in the amount of iron in the calcite brought about by changes in composition of the circulating groundwaters. Ferroan calcite cements are precipitated under reducing conditions. The zoning indicates the position of crystal faces during growth, and shows that the crystals were euhedral at the time, although growth to completely fill the pore spaces has led to the final crystal shapes being anhedral. Crystal bondaries formed by crystals growing together in this way are known as "compromise..."
This photograph shows a peloidal limestone in which either the outer layers of the peloids, or a very thin early generation of cement, has flaked off during compaction. The micritic grains must have been rigid or compaction would have resulted in their deformation. Compaction was followed by the precipitation of a coarse sparite cement which "healed" the fractures caused by the flaking off of the rinds of the grains.

This photograph shows a cross-section of a gastropod preserved as a cast. The inner wall of the organism is marked by a micrite envelope and a thin generation of early cement (see for example the chambers in the upper part of the photograph). The wall of the shell has been fractured and some fragments disoriented during compaction. Both micrite envelope and early cement are fractured and the fractures then healed by a coarse sparite cement. Thus after deposition, the mollusc was micritized and then cemented by a thin early generation of fine carbonate. Then the aragonite wall was dissolved and fracturing occurred, before the rock was finally cemented.

This photograph illustrates a highly compacted bioclastic sediment, consisting of complete two-valved ostracods as well as single ostracod valves and long, thin bivalve fragments. Most fragments are aligned parallel to the bedding but some still show folding and fracturing (e.g. upper left). The complete ostracods have withstood considerable pressure but most eventually fractured.
This photograph illustrates a case of grain-to-grain pressure-solution. Before the pores of a rock are filled by cement, stress is concentrated at the points where the grains meet and part of one or both the grains dissolves. In the example, ooids have undergone solution. The later cement is a mauve-stained, slightly ferroan sparite. Note the small rhombic areas of fine calcite spar (e.g. midway up, half-way between center and left-hand edge). These are calcite pseudomorphs after dolomite.

This photograph illustrates parts of the shells of bivalves which have been subject to neomorphism. The shells consist of a blue-stained ferroan calcite sparry mosaic, but there are lines of inclusions cutting across crystal boundaries and indicating the original foliated structure of the shell. Many crystals are also brown-colored because of their inclusion content. The sediment between the shells is muddy and contains abundant quartz (unstained).
Photographs of Physical Structures

Source Text: Sedimentary structures and early diagenetic features of shallow marine carbonate deposits (Robert V. Demicco and Lawrence A. Hardie)

This photograph shows detail of ripples on Joulter's Cay ooid shoal. Note the rounded crestlines and variable plan morphology of the ripples. Ripples are superimposed on low dunes oriented roughly perpendicular to ripple crest orientation. Ripple spacing approximately 100mm.

Large-scale cross-stratification in Upper Paleozoic grainstones. Skeletal-peloidal grainstone unit in the Mississippian Loyalhanna Limestone from central Appalachians. Cliff face is 19.5m high. Lower 3m and upper 6m mostly flow-parallel views. Central 10m shows flow-perpendicular and oblique views of large troughs.

Reactivation surface in cross-stratified Paleozoic grainstones. Composite set of large-scale cross-strata developed in quartz sand-bearing, skeletal-peloidal grainstones, Mississippian Loyalhanna Limestone, central Appalachians. The four flow-parallel sets of cross-strata that comprise the upper two-thirds of the outcrop include many reactivation surfaces, some of which have small-scale ripples directed up the foreset slope(arrows).
<table>
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<th>Flow paralle view of wave-ripple form set(upper arrow) overlying flow oblique view of wave-ripple cross-stratification(lower arrow). Dolomite mud drapes both cross-stratal sets. Middle Cambrian Arctomys Formation, Canadian Rocky Mountains, southwestern Alberta.</th>
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<td>Wavy to crinkled fine laminae composed of couplets of grainstone layers(dark) and dolomitic mudstone layers(light). Upper Cambrian Conococheague Limestone of the central Appalachians.</td>
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<tr>
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<td>Planar laminae(greater than 5mm thick) and thin beds developed in dolomite mudstone, Lower Proterozoic Wittenoom Dolomite, Hamersley Basin, Western Australia. Pocket knife, lower left center, is approximately 80mm long.</td>
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Flat pebble conglomerate from the Upper Silurian Wills Creek Shale of the Central Appalachians. Clasts overlie sharp erosional truncation of underlying fine, wavy-laminated, fine-grained peloidal grainstone and are themselves composed of cross-stratified and planar stratified fine-peloidal grainstone. Clasts in upper third of bed are imbricated, flow from left to right. Note the shelter porosity developed beneath many of the clasts suggesting they were not deposited on the foresets of dunes.

Cross-sections of mudcrack fills from the Middle Ordovician St. Paul Group of the central Appalachians. Note that the cracks contain several generations of sediment fills with a micro-stratigraphy relatable to overlying layers. These observations demonstrate that these cracks were open at a sediment-air or sediment-water surface a number of times and that these cracks could not have formed from upward "injection" of sediment.

Convolute folding in crinkled laminated mudstones from the Upper Silurian Tonoloway Formation, western Maryland.

Small stromatolitic bioherm encased in thin beds of carbonate mudstone that bend around the bioherm from both above and below. Affected beds thin laterally above and below the bioherm and show increasing dips and thicknesses down the sides of the bioherm. Beds are thickest along the flanks of the bioherm and thin laterally as well. Upper Cambrian Conococheague Limestone, western Maryland.
Photographs of Biogenic and Chemical Structures

Source Text: Sedimentary structures and early diagenetic features of shallow marine carbonate deposits
(Robert V. Demicco and Lawrence A. Hardie)

Wavy to crinkled laminite composed of couplets of peloidal lime grainstone (dark) and dolomite mudstone (light). The lamination is interpreted as due, in part, to the sediment trapping and binding of cyanobacterial surface mats. However, note the three depression-fills composed of fine sand-sized peloidal grainstone at left center (arrows). These are interpreted as trapped bedload and not the result of cyanobacterial trapping. Specimen from the Upper Cambrian Conococheague Limestone, western Maryland.

Continuous, isopachous mudstone laminae with radial crystal sparys separated by detrital peloidal laminae. The isopachous mudstone laminae may be very finely crystalline chemical precipitates. Stromatolite from the Cambrian Waterfowl Formation, Canmore, Alberta. Field of view approximately 2 mm.

Stromatolites nucleated on flat intraclasts of planar and cross-stratified peloidal grainstone. Upper Cambrian Conococheague Limestone, western Maryland. Field of view approximately 10 cm.
Dolomitic stromatolitic bioherm from the Lower Proterozoic Taltheilei Formation, Pethei Group, Northwest Territories. Coin in left center is approximately 30mm in diameter.

Bedding plane exposure of dolomitic columnar stromatolite from the Lower Proterozoic Taltheilei Formation, Pethei Group, Northwest Territories. Field of view approximately 17 inches.

Bedding plane view of burrows disrupting Upper Cambrian dolomitic mudstone from the Gatesburg Formation of central Pennsylvania. Field of view approximately 12 cm.
This photograph shows an epoxy impregnated core of intertidal pond deposits from the modern carbonate tidal flats of northwest Andros Island. This completely bioturbated texture was achieved by random burrowing of rather small annelids and gastropods.

Inversely-graded pisoid bed from the tepee zone of the Permian Capitan "Reef Complex", west Texas. Lens cap about 50mm in diameter.

Nodular masses of microcrystalline gypsum (white patches) that range in shape from ovoid to rectilinear with outlines typical of vertically-oriented, bottom-grown gypsum single crystals (note the "shallow-tail" shape of some of the rectilinear forms). Clearly the microcrystalline gypsum is pseudomorphous after large gypsum single crystals or crystal clusters. It is possible that an early diagenetic stage of dehydration of bottom-grown gypsum crystals to microcrystalline anhydrite was followed by a final rehydration of the anhydrite to microcrystalline gypsum. Dark interlayers are composed of detrital gypsum grains of granule to sand size. Miocene Solfifera Series, Sicily.
Introduction to Cathodoluminescence

Luminescence is the emission of light from a solid which is 'excited' by some form of energy. The term broadly includes the commonly-used categories of fluorescence and phosphorescence. Fluorescence is said to occur where emission ceased almost immediately after withdrawal of the exciting source and where there is no thermal cause, whereas in phosphorescence the emission decays for some time after removal of excitation. The distinction between these so-called types of luminescence is somewhat arbitrary and confusing; for example, many minerals have very long post-excitation decay times. Confusion is avoided by using the term luminescence, and specifying the activating energy as a descriptive prefix. Thus roentgenoluminescence is produced by X-rays, photoluminescence by light (e.g. ultra-violet) and cathodoluminescence (CL) results from excitation by electrons. Thermoluminescence results from heating.

Ultra-violet fluorescence microscopy is a well established technique for petrographic study of petroleum fluid inclusions and often used in examination of hydrocarbon residues in sediments. The interpretation of observed fluorescence intensities and colors is strongly influenced by the type of light source and filter combinations in the microscope. Polished thin section surfaces are required, and a special microscope with UV source and quartz lenses is needed, such as used for immunological work in many biological laboratories. Various wavelengths of UV can be selected by means of filters, and filters can be interposed when viewing the emission. Hydrocarbon inclusions show strong luminescence, the color varying with the gravity of the oil. Recrystallized organic-rich fossils, such as renalcid micro-organisms in the reefs, may show up very well under UV, whereas they may be invisible in transmitted light and CL. Davis & Yurewicz (1985) have shown that in some limestones, cement generations and fine crystal growth zoning can be revealed by UV. Certainly UV microscopy is attractive because it does not require elaborate vacuum arrangements, but inorganic materials such as calcite often show only very weak UV luminescence, so UV microscopy is not a general substitute for CL work.

Cathodoluminescence petrography is now a routine technique that can provide essential information on provenance, growth fabrics, diagenetic textures and mineral zonation, in addition to enabling more precise quantification of constituents and fabrics. Without the support of CL spectroscopy, however, CL petrography can only remain a fabric analysis technique. Although subtle variations in CL color recorded on film give important information, describing luminescence intensity and color from a photographic record is a dubious and subjective affair. The actual CL color is determined by the number and type of emission and quenching centers present. Superposition of several luminescence bands of different intensities can provide quantitative data on the wavelength and intensity of luminescence and the nature of the luminescing centers. CL spectroscopy should become a standard technique used by the luminescence petrographer because it is the only means of recording CL colors and emission intensity objectively and quantitatively, in addition to providing unique information on the nature of luminescence centers.

Fig. Schematic representation of the energies produced from electron beam interaction with solid matter.
Cathodoluminescence Images
for Compaction, Quartz Cementation & Porosity in Sandstone

Source: Luminescence Microscopy and Spectroscopy: Qualitative and Quantitative Applications
(Charles E. Barker and Otto C. Kopp, Editors)

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**Plane polarized light photomicrograph** of a Bromide sandstone sample from Oklahoma illustrating the obscure nature of grain-cement relationships. Field of view shows quartz grains, quartz cement, and a small amount of intergranular porosity (dark blue epoxy has been partly discolored to brown by electron beam). Dust rims are present between some grains and cement, but are insufficient to objectively define grain boundaries. (All bar scales are 200 micrometers long.)

**Bromide sandstone from Oklahoma**

**Crossed polarized light photomicrograph** of same field of view as A, illustrating that crossed polarization does not clarify grain-cement relationships.

**CL micrograph** of same field of view A and B, illustrating clear definition of grain-cement relationships, porosity (P), and additional details not revealed by transmitted light microscopy. Grain contacts can be distinguished as floating (F), tangential (T), long (L), and concavo-convex (C); no sutured contacts are present. Quartz overgrowths display distinct zonation, with an earlier zone of dull luminescence and a later zone of brighter luminescence (white arrow points to contact between zones). Some overgrowths nucleated on one grain are molded against rounded boundaries of other grains (white arrow), suggesting that some grains were better suited for authigenic
quartz nucleation than others. Blue luminescing grain in lower part of micrograph contains a fracture healed by authigenic quartz (black arrowhead).

CL micrograph of Bromide sandstone sample from Oklahoma illustrating grain boundary extension fractures healed by authigenic quartz (black arrowheads). This field of view also shows a variety of grain contact geometries indicative of intergranular pressure solution, zoned quartz overgrowths (O), and porosity (P).

CL micrograph of Upper Cretaceous sandstone sample from the Green River basin illustrating plastic deformation of a ductile lithic fragment, a micritic limestone (bright orange luminescence labeled with a black M) squashed during mechanical compaction. Note distinction between the micritic lithic fragment and more coarsely crystalline calcite cement (black C). This field of view also shows pore filling kaolinite (bright blue luminescing mineral labeled K) and a siltstone lithic fragment (S). All other grains are quartz.

CL micrograph of Lower Cretaceous Muddy Sandstone sample from the Powder River basin illustrating grain and cement truncation along a stylolite (S). Note truncation of both quartz grains and quartz cement (white arrows) along margin of stylolite. The stylolite is composed of authigenic illite (relatively non-luminescent, or black) that precipitated during stylolitization plus accumulations of relatively insoluble silicate minerals, including feldspars (green) and remnants of quartz grains (red-brown). Pore filling kaolinite is bright blue and all grains are quartz. The relatively rough appearance of the micrograph is the result of insufficient polishing of the thin section.
CL micrograph of St. Peter Sandstone sample from the Illinois basin illustrating absence of grain contacts indicative of intergranular pressure solution, presence of dully luminescent quartz overgrowths(O), and presence of anhydrite cement(striped luminescence in pale blue and red-blue; labeled A) that clearly post-dates the quartz overgrowths. All grains are quartz.

CL micrograph of St. Peter Sandstone sample from same area and similar depth as sample shown in G. This field of view illustrates grain contact geometries indicative of intergranular pressure solution, an early zone of dully luminescent quartz overgrowths(white arrows), a later zone of brighter luminescent quartz overgrowths, and remnant intergranular porosity(P).
Cathodoluminescence in Post Carbonates

Source: Luminescence Microscopy and Spectroscopy: Qualitative and Quantitative Applications
(Charles E. Barker and Otto C. Kopp, Editors)

Cathodoluminescent magnesian calcite micrite cement in shelly biomicrite of the Texas Gulf Coast inner shelf. Skeletal fragments are noncathodoluminescent, and siliciclastic accessory grains have a bluish cathodoluminescence.

Texas Gulf Coast inner shelf
Sample courtesy of B. H. Wilkinson, University of Michigan

Bladed and blocky magnesian calcite cements from the lower slope of Little Bahama Bank. Banded cathodoluminescence traceable from bladed cements to blocky cements indicates that these two cement habits are coeval.

Little Bahama Bank

Banded cathodoluminescence in low-magnesium calcite cements from the late Pleistocene of the Yucatan Peninsula. These cements formed within the interstices of corals; the coral skeletal material was subsequently dissolved.

Late Pleistocene of the Yucatan Peninsula
Sample courtesy of W. C. Ward, University of New Orleans
<table>
<thead>
<tr>
<th>Image</th>
<th>Description</th>
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<tbody>
<tr>
<td>(d)</td>
<td>Dully cathodoluminescent dolomite from a 216,000 yr BP reef terrace on Barbados, West Indies. Sample courtesy of J. D. Humphrey, University of Texas at Dallas.</td>
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<td>(e)</td>
<td>Calcite spar cement precipitated in the meteoric vadose zone of the Pleistocene Miami Limestone. Very thin, hairline zones are brightly cathodoluminescent. Sample courtesy of C. E. Barker, US Geological Survey.</td>
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<tr>
<td>(f)</td>
<td>Subhedral and euhedral dolomite crystals containing bright to dully cathodoluminescent zones from the Plio-Pleistocene Seroe Domi Formation of Bonaire, Netherlands Antilles. The noncathodoluminescent areas in this field of view are low-magnesium calcite. Sample courtesy of Plio-Pleistocene Seroe Domi Fm. Bonaire, Netherlands Antilles.</td>
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Cathodoluminescence Images
zoning patterns in carbonate minerals

Source: Luminescence Microscopy and Spectroscopy: Qualitative and Quantitative Applications
(Charles E. Barker and Otto C. Kopp, Editors)

Concentric zoning in a euhedral calcian dolomite. Notice that orientation of concentric zones changes upon crossing a GSB (between arrows). The overall difference in CL intensity of the two narrow opposing growth sectors represents sectoral zoning.

From Feder and Prosky (1986).

Oscillatory concentric zoning in a Mn-doped synthetic calcite crystal. Nonluminescent seed crystal is marked "S". Intrasectoral zoning occurs in the growth sector on the left. Note that concentric zoning cuts across the composition interface of the intrasectoral zoning (arrow).

From Reeder et al. (1990).
Concentric zoning superimposed on sectoral zoning in a calcite cement crystal. Notice that overall CL intensity changes abruptly at the GSBs, some of which are indicated by arrows.

From Reeder and Grams (1987).

Mn-doped synthetic calcite crystal showing sectoral- and intrasectoral zoning. Nonluminescent seed is indicated by "S". Sectoral zoning occurs where luminescence changes abruptly at GSBs (short arrows). Intrasectoral zoning occurs within a 1014 sector at upper left which grew from the corresponding (1014) face. Weak concentric zoning (not visible in photo) remains straight and continuous upon crossing IZ composition interface (long arrow).