ELECTRON-EXCITED LUMINESCENCE AS A PETROLOGIC TOOL[1]

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ABSTRACT

Preliminary studies of cathodo-luminescence of rock-forming minerals have shown that several minerals can be rapidly identified, and that structural and composition variations with potential genetic implications can be revealed. Detrital and secondary quartz can be distinguished by color differences. Radiation halos in quartz, caused by zircon inclusions, have been detected. Apatites show a variety of colors, which may be of diagnostic value. Carbonates show red luminescence, except for iron-bearing specimens which yield reduced or no luminescence. Zoning in dolomites is readily detected from variation in intensity of luminescence. Mottled texture probably results from inheritance of manganese and iron from the carbonate replaced by the dolomite. Residual skeletal structure in fossils can be easily delineated by cathodo-luminescence, and it may be possible to ascribe a featureless luminescence to recrystallization. A faint blue luminescence, which rapidly disappeared, has been seen in ovoid structures of a Precambrian chert, and has been ascribed to organic remains. Luminescence may help to establish the validity of doubtful fossil remains. Separate phases in feldspar perthites can be easily detected by color and intensity variations of the luminescence. Analysis of potassium X-rays from lamella in orthoclase-microcline-albite perthites showing mottled luminescence has led to distinction between orthoclase and microcline, and to the possibility that the latter nucleates at the boundary between orthoclase and albite. Occurrence of coarse red and blue banding crossed by fine K- and Na-rich lamellae distinguished by different intensities of luminescence has led to the suggestion of an earlier stage of exsolution now revealed only by the luminescence. Variation of intensity of luminescence in albite lamellae of microcline perthites may result either from formation over a temperature range or from limited diffusion. Cathodo-luminescence has proved useful in characterizing fine-scale impurities, such as apatite in a feldspar host, and in checking homogeneity of natural and synthetic minerals. Fifteen illustrations in color are given.

INTRODUCTION

Thermoluminescence, the emission of light during heating, has been used as a petrologic tool for about fifteen years; but the significance of the conclusions is still controversial. Interpretation of the results for a homogeneous mineral is difficult enough, as has been shown by Medlin (1963*c*), while the averaging of the thermoluminescent properties of the several minerals forming a rock further hinders interpretation. Cathodo-luminescence, the emission of light during electron bombardment, also results from several different causes but does have the advantage that the emission from individual minerals can be seen readily and related to the texture and chemical composition. The electron microprobe is the most suitable instrument for viewing cathodo-luminescence because it is possible to immediately examine the emitted X-rays from regions showing interesting cathodo-luminescence effects. Because of the heating effect of the electron beam on insulating materials, the observed luminescence will change with time. Unless specifically mentioned in this paper, observations have been made using low beam-current densities which do not elevate the temperature significantly.

Among the suggested uses for thermoluminescence have been correlations between rock strata, age determination based on filling of energy levels by natural radioactivity, and indication of ore deposits from presence of trace elements revealed by luminescence of nearby rocks. The nature of the energy levels, the energy transfer mechanisms, and the compositional controls have been determined for carbonates, quartz, and anhydrite by Medlin (1963*a*, *b*) from studies of both natural and synthetic samples. A review of the literature up to 1962 has been given by Angino and Grogler (1962), while an excellent survey has been presented by Medlin (1963*c*).

All investigators using the electron micro-

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probe to study non-metallic minerals and rocks will have observed cathodo-luminescence, but only casual references have been made to its potential uses. It has been recognized by several investigators, particularly J. V. P. Long (1963) and S. O. Agrell (personal communication) that certain minerals, hard to identify by other techniques, can be rapidly distinguished by their luminescence, and that chemical zoning, especially in carbonates, can be readily detected. We have attempted to find possible applications for determining the genesis of minerals and rocks. Because of the complexity of the cathodo-luminescence process we have not been able to provide definite answers to all the phenomena described in this paper. Nevertheless we feel that publication at this time is warranted in order to stimulate discussion and additional observations. A preliminary abstract has already appeared (Stenstrom and Smith, 1963); and this paper was presented at a symposium on microprobe analysis held at Washington, D.C., in October, 1964, under the auspices of the Electrochemical Society.

RADIATION DAMAGE

Pleochroic halos in biotite mica are commonly observed and have been explained by radiation damage caused by emission from radioactive thorium incorporated in zircon inclusions. We have observed quartz crystals showing circular areas of reddish luminescence surrounded by the usual blue luminescence. Normal transmission optical techniques failed to reveal anything at the centers of the red areas, but the presence of zircon crystals was proved by detecting X-rays of the zirconium wavelengths when the electron beam was focused on the center of the red areas.

LUMINESCENCE OF QUARTZ

Optically continuous quartz crystals from sediments sometimes show a line of dust particles or other imperfections from which one can deduce that an overgrowth has formed on a core of detrital origin. If a grain is clear all the way through, it is not possible to tell by normal optical methods whether it consists of two parts. However, the cathodo-luminescence is quite different for the two parts: the core, which probably came from an igneous rock formed at elevated temperature, shows a bright, bluish luminescence while the overgrowth is a dull red. Plate 1, *A*, shows such a grain occurring in a carbonate-rich sediment, while plate 1, *B*, shows the clear distinction between the ce-

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PLATE 1

A, Detrital quartz grain (bright blue) with an overgrowth (black) occurring in a matrix of calcite (mottled red). Two rhombs of dolomite (one rhombic and the other triangular in section) show black Fe-rich border around mottled red center. Using higher beam loading, quartz overgrowth can be seen to emit reddish luminescence. 20 kv, 0.4 μA, 10 min.

B, Space between three detrital quartz grains (bright blue) of an ortho-quartzite has been filled in by quartz cement (dark red) and carbonaceous material (black). Red veins in the detrital quartz crystals probably occur at fractures and result from a structural deformation or a recrystallization. 25 kv, 0.5 μA, 8 min.

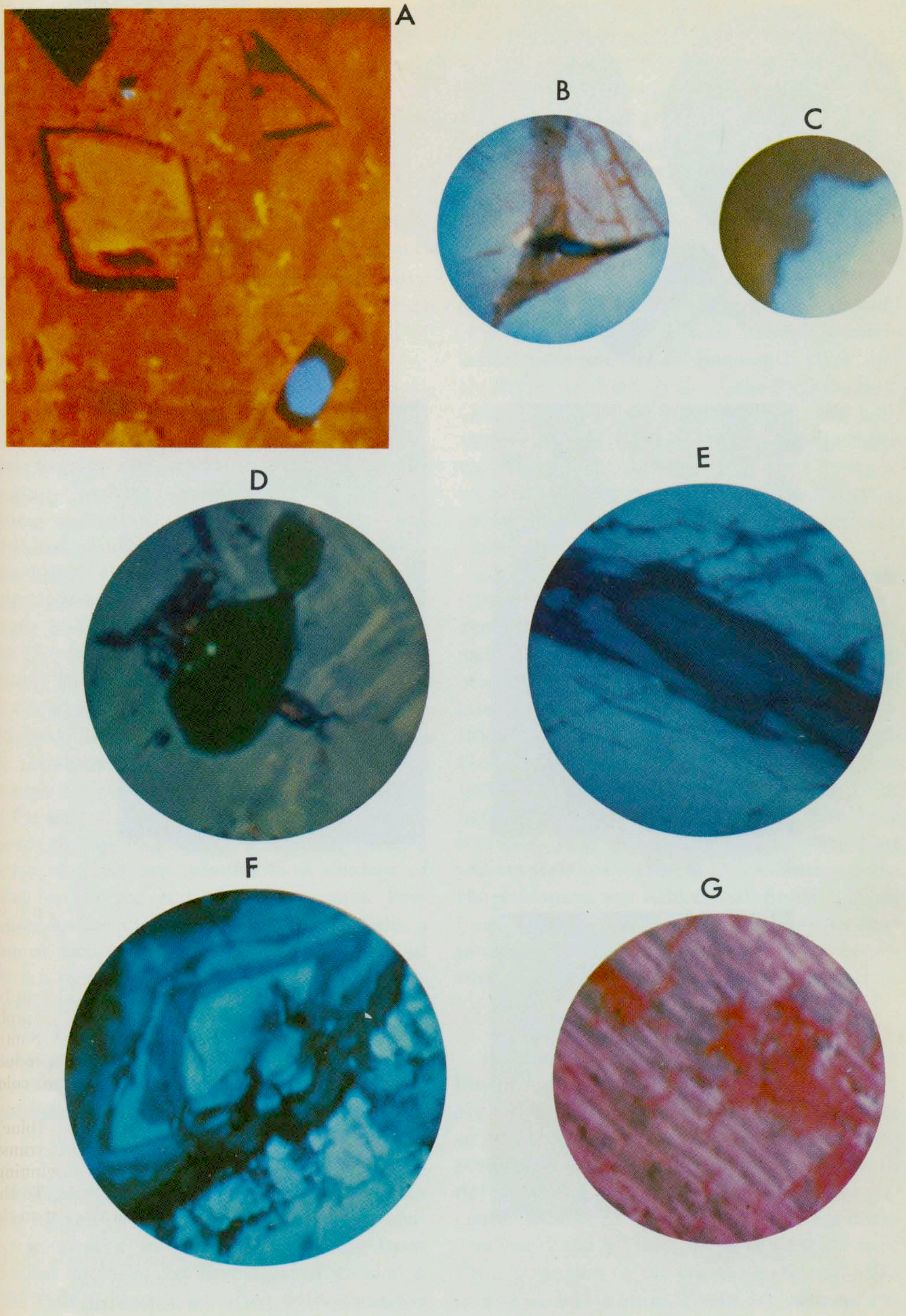
C, Sutured contact between detrital quartz grain (blue) and quartz cement (red). During color reproduction the red color has become brownish. Note that the blue region consists of two parts with different color intensity, suggesting a different growth history. 25 kv, 0.5 μA, 8 min.

D, Two large apatite crystals (green) and calcite (red specks) occurring in a microcline perthite (blue). Color variation in the feldspar is really an intensity variation, but overexposure of the film results in transition from blue to whitish color. Intensity variation conforms to the cross-hatched microcline twinning. Luminescence from the feldspar is polarized, but this photograph was taken without an analyzer. To the naked eye, the apatite is initially yellowish rather than greenish. The calcite is a brilliant red, rather than the pinkish color of the film. 20 kv, 0.3 μA, 15 min.

E, Albite vein (dark blue) occurring in K-rich area (light blue) of a microcline perthite. Note intensity variation across albite. K-feldspar is overexposed; true color is light blue. 20 kv, 0.15 μA, 23 min.

F, Zoning in lozenge-shaped albite area in a microcline perthite. Unzoned area is K-feldspar.

G, Perthite formed of albite (pink and red) and K-feldspar (purple). 20 kv, 0.3 μA, 15 min.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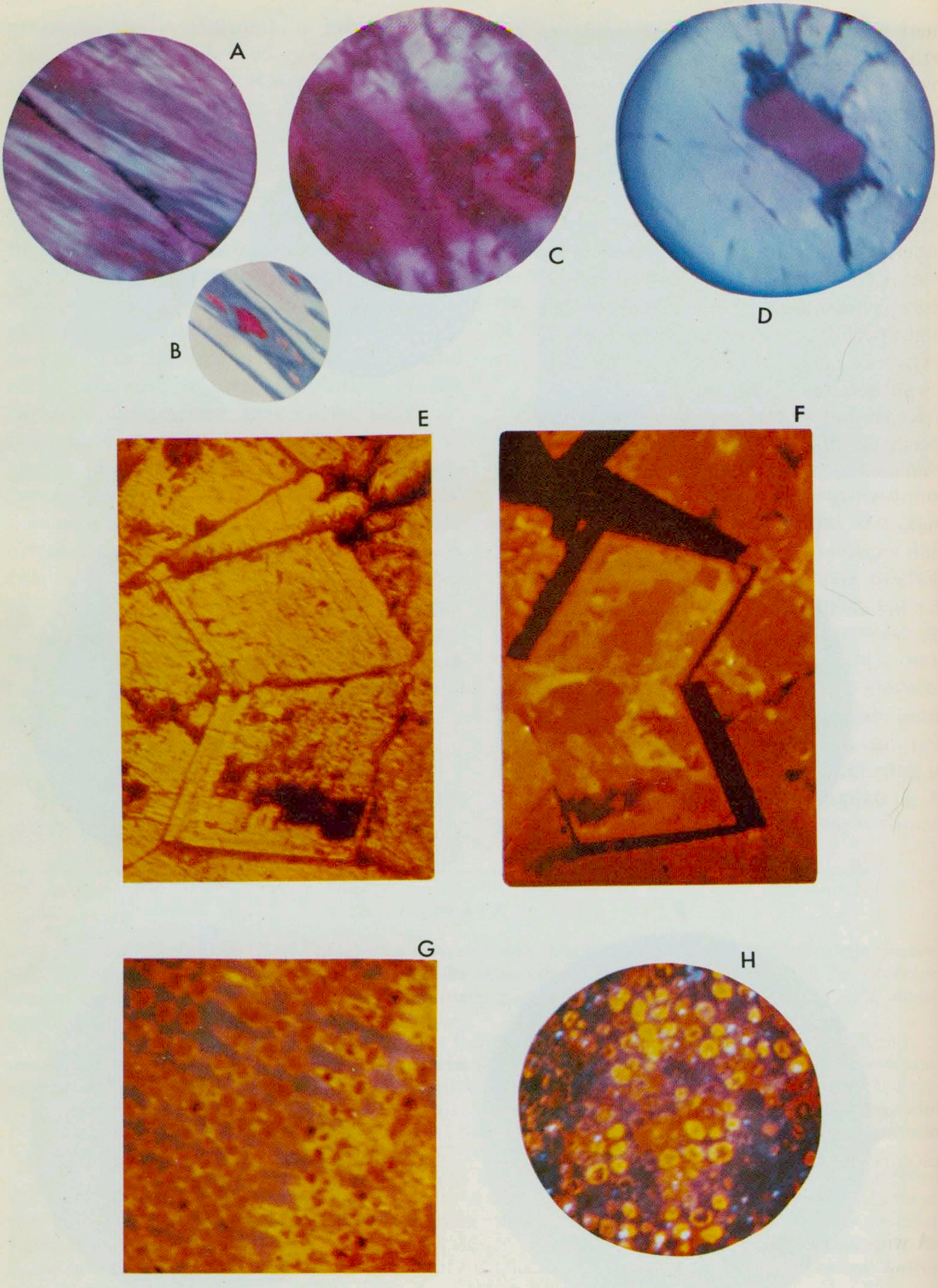
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ment and rounded detrital grains of an orthoquartzite. Thus it is possible to determine the original texture and porosity of a sandstone, even in the absence of conventional criteria such as dust particles for delineating the boundaries between detrital grains and cement. Plate 1, *C*, shows the sutured contact in a quartzite which has undergone deformation and pressure solution. A careful correlation between luminescence phenomena and optical continuity might permit a reconstruction of the original texture of such deformed quartzites and of the subsequent structural history.

Keith and Tuttle (1952) found that most specimens of quartz from granites inverted from the low to the high form at a higher temperature than those from rhyolites. By analogy with conclusions derived for synthetic specimens, and from chemical and physical studies of natural samples, they concluded that the difference arose from impurities. M. L. Keith, of Pennsylvania State University, supplied us with samples F2-15, 48-18, 50-18, 50-20, 50-22, 50-24, 50-26, 49-31, 49-35, 49-95, and 49-98 used in the study with O. F. Tuttle. All showed a bright bluish luminescence, and there was no obvious difference between the two groups.

Prolonged bombardment of the blue-luminescing quartz, using a narrow, intense beam of electrons, results in a change of color to the red end of the spectrum. Presumably the change is consequent upon a rise of temperature, but the possibility of electrical effects on the crystal structure should not be excluded.

We have made no observations on vein and pegmatite quartz, but it is possible that growth features would be revealed by luminescence.

APATITE

A wide variety of luminescence colors, including yellow, brown, lavender, and green, has been seen in apatites. All those from basaltic rocks so far investigated yielded a yellowish luminescence often with a narrow rim of browner color. Presumably this rim reflects a change of chemical composition at the time the groundmass began to crystallize. Apatites from alkaline plutonic rocks from Greenland, supplied by C. H. Emeleus, the University of Durham, yielded a lavender-colored luminescence, while microcline perthites from Precambrian rocks in Finland, supplied by K. Rankama of the University of Helsinki, contain minute apatite crystals with a yellowish luminescence (see below). Specimens from pegmatites yield a variety of colors, including green. A study is now under way to see if there is a correlation between the luminescence color and the type of host rock. Graywackes from Oregon, investigated for R. Dott, the University of Wisconsin, show two, and perhaps three, types of apatite as indicated by luminescence. We are testing the possibility of using apatite to indicate source material in graywackes and other sediments.

In the just-mentioned microcline perthites from Finland, long, thin crystals of apatite, some up to 100 × 1 μ in size, occur as inclusions in the feldspar. About one-fifth of the crystals in one specimen are oriented parallel to [106], a direction in the composition surface of perthites. Some of the crystals are submicroscopic but can still be detected because of the distinction in color between the yellow apatite and the blue feldspar. It is interesting to speculate that the crystals may arise from exsolution from the feldspar, for Ribbe and Smith (1964) have shown from microprobe analyses that phosphorus is incorporated into the structure of some feldspars.

FELDSPAR

All feldspars so far examined show either blue or red luminescence, with the majority giving blue. The sodium-rich and potassium-rich phases of a perthitic intergrowth can be readily distinguished, but it is necessary to determine for each specimen which luminescence belongs to which phase. The luminescence emitted by microcline is a function of the orientation of the crystal lattice and the cross-hatched twinning can be seen as intensity variations in the luminescence (pl.

1, *D*). The light is polarized. This slide also shows a large apatite crystal and small inclusions of calcite (reddish luminescence). Another common impurity in feldspar, epidote, shows up by its greenish color. The Rhomb Porphyry basalts from the Oslo region give spectacular luminescence resulting from the plagioclase feldspar (dark blue) rimmed by anorthoclase (bright blue), calcite (red), apatite (yellow), and epidote (green). Much of the calcium in microcline perthites is not incorporated in the feldspar lattice, and can be readily detected as calcite and apatite impurities from the characteristic luminescence properties. The true calcium content of the feldspar can be determined only by a fine scale analysis such as that permitted by the electron microprobe (Ribbe and Smith, 1964).

Microcline perthites from Finland consist of sodium-rich veins (dark-blue luminescence) in a potassium-rich host (bright blue). The luminescence of the albite veins is not uniform. The margin is always dark, but the interior may consist of one or more strips displaying a brighter luminescence (pl. 1, *C*). Careful studies of the emission of calcium and potassium X-rays have shown that the entire vein is always very close in composition to pure albite. However, when there is a deviation from pure albite, the brightly luminescent strip always contains more potassium and calcium than the margin. Most readings are below or near the $K_1Ca_1Na_{98}$ level, but one specimen shows a calcium content up to 5 per cent. It is tempting to speculate that the intensity of luminescence is a function of the temperature of formation of the albite, with the brighter center representing the beginning of exsolution. However, the possibility of a diffusion-controlled exchange of sodium and potassium between the two phases must be considered also. The multiple structure commonly observed in the veins might be explained either by incorporation of originally isolated blebs into a single vein, or by diffusion which is controlled by irregularly arranged, structural faults. The sharp change of intensity might be explained by the feldspar reaching the temperature for the microcline-orthoclase inversion, at which an abrupt change might be expected for the distribution of the minor elements. Alternatively, the boundary might result from a limitation on the range of diffusion. That incomplete diffusion does occur is shown by a specimen (SM985) from Tammela, Finland, in which the luminescence of the K-feldspar adjacent to the albite veins is uniform while that of the feldspar away from the vein reveals small, elliptical areas of a darker hue. These were shown from X-rays to be blebs of albite. A profile in potassium Kα radiation showed that the composition of the feldspar is K_{98} at the contact and K_{94} away from the albite vein. Specimen AK2312, also from Tammela, contains an albite vein which broadens out into a lozenge-shaped area (pl. 1, *F*). The luminescence of the latter shows eight rings of alternating dark and bright blue luminescence. The presence of the alternations would not be consistent with a normal fall of temperature invoked to explain the variable luminescence in the other veins, nor would it be consistent with simple diffusion. Cyclic temperature variations during growth provides the most obvious explanation. Soldatos (1962) and Laves and Soldatos (1962, 1963) have shown from X-ray diffraction studies that the orientation of the albite lattice may differ with respect to the host K-feldspar and that the orientation of microcline twin components may deviate from the ideal positions. Combination of fine-scale diffraction studies (perhaps by Kossel line or electron diffraction technique) with electron luminescence observations might permit elucidation of the growth history of the albite lamellae. A detailed account of these microcline perthites will be given elsewhere.

Plate 1, *G*, is for perthite number 39 described by G. K. Czamanske (1962) from a small body of biotite granite from the Oslo region. The dark blue luminescence comes from the K-rich phase, and the pink and the red from albite. Both the pink and the red areas yield essentially no Ca and K X-rays, thus confirming the deductions from the cell dimensions by MacKenzie and Smith (1962) that the Na-rich phase is pure albite. The intergrowth between the pink and blue areas has a typical perthitic texture, but the irregular red area is anomalous and not understood at the time of writing.

Plate 2, *A*, is for perthite number T74 from a pegmatite in a quartz-fayalite syenite from the Tuqtodôq complex, SW. Greenland, described by B. G. J. Upton (1960). X-ray data given by MacKenzie and Smith show that a pure albite coexists with a monoclinic K-rich phase (orthoclase) and a triclinic K-rich phase (microcline). The existence of the Na-rich and K-rich areas can be readily seen from the luminescence (pink for the albite and purplish for the K-rich part). By concentrating the electron beam onto the purplish areas it was possible to see that there were irregular beads of a bluer material set in a redder matrix (pl. 2, *B*). Careful adjustment of the electron beam onto the beads and then onto the matrix using the color of the luminescence as a guide led to determination of compositions $K_{90,\ 91,\ 94,\ 96}$ for the bluer parts and $K_{97,\ 97\cdot5,\ 98\cdot5,\ 100}$ for the red parts. It is reasonable to conclude that the blue beads are orthoclase and the red matrix microcline. Consequently, it can be suggested that microcline, the low-temperature variety, forms from orthoclase, the intermediate-temperature variety, by nucleating at the edges of the orthoclase strips, and that the beads represent untransformed material.

Plate 2, *C*, shows a phenomenon not yet explained. It is for specimen T212 from a quartz-fayalite syenite at Central Tuqtodôq, which, according to the X-ray data of MacKenzie and Smith, consists of a pure albite coexisting with orthoclase and microcline. The photograph shows a coarse color banding from reddish to bluish (looks white on the picture because of overexposure in order that the red will be on scale). Crossing the broad bands are narrower strips of Na-rich and K-rich compositions. The albite, although pure according to X-ray emission analysis, in part shows a red luminescence and in part a blue luminescence depending where it lies with respect to the coarse banding. Similarly, the K-rich areas may show a bluish or a reddish luminescence. The luminescence for the K-rich areas is mottled, and this may be the result of an intergrowth between orthoclase and microcline. A possible suggestion is that at high temperature a coarse perthite was formed with the two compositions lying closely together (say, $K_{60}Na_{40}$ and $K_{40}Na_{60}$), and with one part giving a red luminescence and the other a blue. Upon cooling, exsolution took place to (say) $K_{90}Na_{10}$ and K_0Na_{100} producing the narrower banding crossing the broad color

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PLATE 2

A, Perthite formed of albite (whitish strips) and K-feldspar (purplish-red areas). 20 kv, 0.3 μA, 30 min.

B, Enlargement of K-feldspar area with bluish beads set in reddish matrix bordered by albite. 20 kv, 0.1 μA, 4 min. *A* and *B* were overexposed to reveal structure of K-feldspar. To the naked eye the whitish areas are pinkish.

C, Complex banding in perthite showing three color bands (nearly horizontal) crossed by narrower bands (nearly NW.-SE.) with even finer structure visible in these bands. White areas result from overexposure necessary to reveal structure of reddish areas. In each broad band brighter material is albite; darker is K-feldspar. Mottling of K-feldspar may result from an intergrowth of orthoclase and microcline. 20 kv, 0.3 μA, 30 min.

D, Crystal of hematite (red, hexagonal) set in feldspar (blue). Beam moved during exposure. True color of feldspar shown at circumference; whitish color of main part results from overexposure. 20 kv, 0.15 μA, 20 min.

E and *F*, Zoned dolomite growing in calcite matrix: *E*, transmission picture using ordinary unpolarized light; *F*, luminescence picture in the position of a mirror image. Dolomite crystals outlined by black Fe-rich borders. Both calcite and dolomite are mottled. 20 kv, 0.4 μA, 13 min.

G, Cross section of crinoid. Radial direction referred to in text is W.NW.-E.SE. 20 kv, 0.4 μA, 10 min.

H, Cross section of crinoid. Red and black areas are calcite; blue specks are quartz. 20 kv, 0.4 μA, 10 min.

banding. Each exsolved phase retained the luminescent color of its immediate environment, but the albite luminesces more strongly than the K-rich phase. Finally, the orthoclase began to invert to microcline at many randomly arranged points to produce the mottled structure. Spencer (1930, 1935) has described the occurrence of a broad "shadow" perthite crossed by a microperthite, but no recent studies have been made of this phenomenon. He suggested an earlier and later stage exsolution to explain the phenomenon. Correlation of detailed optical, X-ray, and luminescence studies of oriented specimens may elucidate the exsolution sequence of specimens containing more than one type of intergrowth.

Details of these perthites, and of others supplied by R. V. Dietrich, will be given in another publication.

Plate 2, *D*, is of an aventurine feldspar from southern Norway, showing a red hexagonal plate of hematite surrounded by the blue feldspar. It is interesting that the luminescent intensity of the feldspar changes near the hematite inclusion, but no measurements have been made to attempt an explanation.

As mentioned earlier, plagioclase crystals from basalts show bright-blue rims. X-ray emission analyses show that the rims are highly zoned toward an anorthoclase, with the zoning trends similar to those reported by Muir (1962) for ternary feldspars.

CARBONATES

Medlin (1963*a*) has shown from study of synthetic carbonates that the orange thermoluminescence of carbonates results from substitution of divalent manganese. Transition metals, principally iron in natural samples, quench the luminescence. Cathodo-luminescence shows exactly the same relations, as has been proved by several investigators (including Long [1963]) from a correlation of the X-ray emission of iron and manganese with the intensity of luminescence for zoned carbonates.

In sandstones and shales, calcite cement is readily detectable from the orange-red luminescence, thus permitting an instantaneous evaluation of its distribution. A similar evaluation by conventional optical techniques would be slower because of the need to examine each area more closely.

The luminescence feature has proved useful in examining calcitic rocks which have undergone dolomitization. Zoning of dolomite rhombs is readily visible (pls. 1, *A;* 2, *F*). The iron-rich rim of the dolomite in plate 1, *A*, is revealed by the dark border. Another example is given in plate 2, *E*, which shows the view in ordinary transmitted light and plate 2, *F*, the view in luminescence. It is necessary, because of the complex relation between luminescent intensity and chemical composition, to prepare a scanning picture or to make a line profile in X-radiation in order to determine the composition variation of manganese and iron. However, the luminescence provides the fastest qualitative way of revealing chemical variations. In order to determine the factors which control dolomitization, studies have been made of crystals distributed over a hand specimen, and will be made on specimens collected from a wide area. In a hand specimen all dolomite rhombs show the same sequence of zones, indicating that the invading Mg-rich material acts uniformly over specimens of this size. However, local factors play a role, as is evident from the mottling visible in plates 1, *A*, and 2, *F*. The similarity of the mottled texture in the dolomite and the calcite indicates that the former is inherited from the latter. In some dolomite rhombs, mottled units with curved boundaries have been noticed. These may be remains of fossil fragments.

Close examination of the boundary between the dolomite and calcite shows that it is not absolutely straight. In one specimen which was examined in detail the luminescence of the calcite was darker at the points of the dolomite projections and brighter in the calcite lying between the projections. X-ray scanning pictures showed that the brighter luminescence corresponded to a lower iron content. Thus it seems that the dolomite grows most easily from calcite containing substituted iron.

We are indebted to Donald L. Graf of the Illinois Geological Survey for donation of suitable specimens.

FOSSILS

One of the more promising uses of cathodo-luminescence is the delineation of the skeletal structure of prehistoric organisms, and perhaps its assistance in discovering traces of algae and other elusive material. Plate 2, *G* and *H*, shows the luminescence obtained from cross sections of crinoid stems supplied by Matthew Nitecki. The stem originally consisted of long, thin, parallel calcite crystals bonded together by an organic matrix. (The same principle of bonding brittle material with a flexible substance has recently been adopted by engineers in utilizing whiskers.) After death the organic matrix was replaced mainly by calcite, and partly by a silica mineral. Because the crinoid fractures with a flat surface, it is probable that the secondary carbonate is in optical continuity with the original, but we have not yet checked our samples with polarized light to test this. In some crinoids the luminescence is monotonous, and we believe that recrystallization has occurred, producing an even distribution of the minor elements. The crinoid of plate 2, *G*, which is of Pennsylvanian age, shows a radial distribution of beadlike stringers of bright and dark material. Presumably this reflects the original cell structure now revealed by a difference in manganese and/or iron content between the primary and secondary carbonate. Plate 2, *H*, for a crinoid of unknown age shows both monotonous and structured regions, probably the result of partial recrystallization. In this specimen there is no radial structure, and the primary structure appears to consist of irregularly arranged hollow tubes. A small part of the fossil has been replaced by quartz instead of carbonate. A systematic study of crinoids and other fossils of varying age may add valuable information on the evolution of the structure of the hard parts.

Another likely application of luminescence is selection of fossils for study by isotopic methods. Unrecrystallized samples, which are more likely to have retained the original isotopic ratios, might be selected by looking for relics of the internal structure by luminescent techniques. In addition, it would be of value to be able to estimate the percentage of primary and secondary carbonate, thus permitting a correction on the assumption that the secondary carbonate has the same isotopic ratio as neighboring inorganic carbonate.

A possible third application of luminescence is in helping to discover and characterize Precambrian fossils, most of which are hard to identify because of lack of a hard part. Tyler and Barghoorn (1954) describe what appear to be plant remains in the Gunflint chert occurring near Schreiber, Ontario. Through the courtesy of T. Hoering of the Geophysical Laboratory, we have been able to examine a specimen and have found that a blue luminescence is emitted from the ovoidal areas. This luminescence fades rapidly, and the most obvious explanation is that it is caused by retained organic matter, occurring only in the supposed plant remains, which is destroyed rapidly by the heat of the electron beam. A specimen of Transvaal dolomite, also supplied by Hoering, showed a brown, rounded area in ordinary transmitted light. The same area showed a reddish luminescence, and was found by X-ray examination to be formed of dolomite. The X-ray scanning pictures showed a different distribution for the Mg, Fe, and Mn across the dolomite. If selective mineralization of the internal structure of soft-bodied fossil remains has taken place, it may be possible to delineate it by luminescent and X-ray emission techniques. Three pertinent references printed since this manuscript was prepared are: Barghoorn and Stanley (1965), Cloud (1965), and Hooper (1964).

SYNTHETIC CRYSTALS

Although it is not a petrologic application, it is convenient to mention here the use of luminescence to test the perfection of synthetic crystals prepared for laser and other applications. Such an examination of synthetic ruby and emerald crystals has revealed intensity variations which presumably are related to growth features.

The lack of uniformity of synthetic glasses can sometimes be seen from intensity variations of the luminescence.

Difficulty was experienced in measuring the composition of plagioclase crystals grown from glasses with compositions on the albite-diopside join. The calcium content of the crystals was highly variable, rising to values equivalent to that for labradorite. An intense electron beam made it possible to see inside the plagioclase crystals small inclusions with a brighter luminescence. Using the luminescence as a guide in selecting areas for analyses, we found that the high calcium readings resulted from the inclusions and that the plagioclase had a composition in the oligoclase range. The glasses were supplied by W. S. MacKenzie, of the University of Manchester, and the analyses are quoted in Edgar (1964).

CONCLUSION

Although the microprobe X-ray emission analyzer is the most suitable instrument for examining cathodo-luminescence because of the easy correlation between the optical and chemical observations, a simpler instrument is desirable so that cathodo-luminescence may be used routinely in petrography. J. V. P. Long, of Cambridge University, has demonstrated the applicability of a cold cathode electron emitter in a microscope attachment displayed before the Mineralogical Society of London, and it is hoped that similar simple accessories will become available commercially.

In conclusion, it should be emphasized that the present studies are only qualitative, and that many of the conclusions are tentative and should be tested by detailed studies similar to those carried out by Medlin on thermoluminescence.

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APPENDIX

EXPERIMENTAL TECHNIQUE

All photographs were taken on high-speed Ektachrome film with a 35-mm. camera attached by a Zeiss three-way eyepiece to an A.R.L. microprobe. The optical magnification of the A.R.L. optical system is ×286, and the resolution of the pictures is about 1 μ. All specimens were sputtered with carbon to make them electrically conducting. Plate 2, *E*, was made using a polished thin section mounted in the transmitted light holder. In many of the photographs it was necessary to overexpose part of the film in order to have other parts at the correct level. Such overexposed areas are whitish. During long exposures, color changes were sometimes observed, thus giving pictures rather different in color from that seen initially. In addition, the conversion from negative to positive has resulted in a reduction in the intensity of the red component. This is particularly noticeable for the carbonates which appear more yellowish than in the original.

Heinrich (1963) has described a technique using a photomultiplier and color filters to permit display of cathodo-luminescence on an oscilloscope screen. To accomplish this, the electron beams in the microprobe and oscilloscope are synchronized to give the same raster pattern.

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