Ore textures: problems and opportunities

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Abstract

Over the past several decades, thinking about chemical processes in rocks had been dominated by experimental and theoretical treatments of mineral equilibrium, which is the state from which the time variable has been excluded. But, to an extent exceeding that of any of our sister sciences, we in geology are concerned with the behaviour of things as a function of time; thus equilibrium is but one of several interesting boundary conditions. Textures, (defined as the spatial relations within and among minerals and fluids, regardless of scale or origin) provide a means to sort out and identify successive states. In fact, it is the pattern of evolution of those states that enables us to deduce the processes. We may well draw the analogy with *thermodynamics* and *kinetics*, respectively:

equilibrium textures and phase assemblages, via thermodynamic analysis → *definition of conditions of equilibration,*
whereas
kinetics, as displayed in disequilibrium textures → *sequence of events and processes of mineralization.*

   The interpretation of textures is one of the most difficult yet important aspects of the study of rocks and ores, and there are few areas of scientific endeavour that are more subject to misinterpretation. Although the difficulties are many, the opportunites for new understanding are also abundant. Textural interpretations have many facets: some are well established and accepted; some that are accepted may be wrong; others are recognised to be speculative and controversial; and we trust that still other textural features remain to be described and interpreted. This paper will deal principally with low-temperature, epigenetic ore deposits, and will emphasise silica and sphalerite; but extension to other materials is not unreasonable.

   Ore and gangue minerals react internally, or with their environment, at widely ranging rates, ranging from the almost inert pyrite, arsenopyrite, well-crystallised quartz, and tourmaline to the notoriously fickle copper/iron and copper/silver sulfides. Arrested or incomplete reactions may be identifed by textural criteria and, when appropriately quantified, can provide guides to the duration of geological processes.

   In recent years so much emphasis has been placed on isotopes, fluids, chemistry, and deposit and process models that the textural features have been ignored. In part this oversight occurs because we have grown accustomed to using superposition, cross-cutting, pseudomorphism, mutual intergrowths, exsolution and so on as off-the-shelf tools, to be grasped and applied without evaluation or even description. Surely science must build on previous work without constant and exhaustive reassessment, but for mineral textures a little reassessment may yield substantial benefit.

KEYWORDS: ore deposits, textures, phase assemblages, silica, sphalerite.

Introduction

ORE deposits are among the most complex inorganic features of our planet. They are the products of a complex genesis followed by complex reequilibration; textures are the tool we use to try to see through it all.

Historical perspective

   For more than a century geological reports have shown sketches and photographs illustrating textures observed in ore specimens, but, following the breakthrough in preparation techniques and optical examination of polished surfaces (Campbell and Knight, 1906), studies of ore textures became strongly associated with microscopic observations using reflected light. This relation is not unexpected inasmuch as so many features are visible only in reflected light. The conventional macroscopic geological criteria of superposition and crosscutting were swiftly

applied microscopically to identify mineral sequences, and additional criteria were developed to document and distinguish the widely accepted ideas of replacement and exsolution. Many prominent geoscientists have contributed observations, identifications, and interpretations; but the clear leader has been Paul Ramdohr whose book 'The Ore Minerals and Their Intergrowths' (1960 and 1980) summarised a lifetime of study and had been the ore microscopist's Bible for thirty years. In most of this paper we shall simply build on this older foundation, adding rather than reconstructing.

In addition to the identification of minerals, polished surface studies have historically (pre 1960) focussed on the determination of the sequence and style of mineral deposition (e.g. replacement, exsolution, open-space filling, etc.); in this regard, it appears that interpretations of the nature of intercrystalline boundaries have been worshipped too blindly. In another area of application, textures have long provided guides to benefication strategies for metallurgists. 'Paragenetic' diagrams (meaning those in which the temporal sequence of minerals were displayed), based mostly on microscopic criteria, became standard elements in descriptive parts of mine and district reports from the 1920s onward; but interpretations of those sequences were sparse and weak. In some instances the textural criteria were simply misapplied. For example, as a student in the early 1950s, I was thoroughly indoctrinated with the dogma then current in America that, because sulfides appeared to replace gangue silicates, the class of deposits now known as volcanogenic massive sulfides were supposedly hypothermal replacements (from today's perspective, both the sulfide and silicate crystals are metamorphic products of a long-gone protolith). Even today, some equally erroneous ideas may remain enshrined in our intellectual inventory.

About 1960 several significant changes came about:

First, the electron microprobe was developed by R. Castaing and rapidly became the standard sampling and analytical tool for finely intergrown and growth-zoned minerals typical of ores. From the textural point of view, the strength of the microprobe lies in its ability to sample and analyse tiny volumes without destroying their spatial context. A variety of other 'beam' techniques is available, and all of them permit textural interpretations to go far beyond previous capabilities.

Second, Edwin Roedder and a few other pioneers began to convert the world to the wonders of fluid inclusions, thereby providing an impetus to prepare and study transparent, doubly-polished, mineral plates; such plates have partially replaced the conventional, opaque mounts for microscopic study. Fluid inclusions are features that are very much a part of textural interpretations; although we shall not discuss them further, a large and growing literature is available (for an extensive review, see Roedder, 1984).

Third, a steady flow of a wide variety of phase diagrams and supporting thermochemical data began to provide a firm basis for determining the intensive parameters during mineral equilibration, and to supply a quantitative basis to deal with aqueous fluids and crystalline solid solutions.

Finally, studies such as those of Clendenin (1977), Kopp et al. (1986), McLimans et al. (1980), and Eldridge et al. (1983) began to show that textural interpretation could be made to reveal much more than had been previously recognised about ore-forming processes. Textural studies have evolved further in that the features observed are being interpreted in terms of geologic processes that extend well beyond the specific specimens under examination.

This contribution will principally follow the pattern of studies such as those cited in the preceding paragraph, for it is the reading of the textural record that offers the best opportunity for advancing our understanding of mineralizing processes. The interpretation of textures is simultaneously one of the most difficult and important aspects of the study of rocks and ores, and there are few areas of scientific endeavour that are more subject to misinterpretation (Barton, 1970). Although the difficulties are many, the opportunities for new understanding are also abundant. My purview is myopic to the extent that it reflects experience with epigenetic ores especially regarding sphalerite, and proximity to the western literature. I shall include brief discussions of some enigmatic features, hoping to stimulate additional observations, especially were my own interpretations are too fragmentary for a complete exposition.

The term 'Texture'

Before proceeding, let us pause to recognise a substantial semantic problem in that 'texture', 'structure', 'fabric', and especially 'paragenesis' mean different things to different persons. Where distinctions are made, they must be made thoughtfully, but this is not the place to introduce terminology. Suffice it to note that I shall use 'texture' to refer to *the spatial relations within and*

among minerals and fluids, regardless of scale or origin. I can see no philosophical discontinuity between or among, for example, detailed mapping in the field, hand-specimen examination, binocular microscopic study, use of the ore-petrographic microsope, examination with SEM or TEM, studies of crystallography or crystal physics, or even the construction, interpretation and application of phase diagrams. Few, if any, of us as individuals can do all of these things well, but all such tools belong in the earth-science community's tool kit to deal with textures to read the geologic record.

Textures and equilibrium

We pay great homage to 'Equilibrium', that state of minimum Gibbs free energy. Equilibrium is a beautifully simplifying condition; since the character of the material is independent of the route or time necessary to attain that state, the computation of the intensive physical–chemical conditions of state is greatly simplified. Because the rates of most reactions approach zero as equilibrium is approached, processes do not occur at strict equilibium. Moreover, the very attainment of equilibrium destroys the evidence of how it got that way; thus the processes and rates become moot. If we humans were to equilibrate with our atmospheric environment, we should become gaseous puffs of water vapour, carbon dioxide, and nitrogen with a solid residuum of apatite, quartz, halite, and a few other minor phases. Clearly, it is not to our personal advantage to equilibrate!

It is instructive to contrast the information derived from *thermodynamics* and *kinetics,* respectively:

equilibrium textures and phase assemblages, via thermodynamic analysis → definition of conditions of equilibration,
wereas
kinetics, as displayed in disequilibrium texture → sequence of events and processes of mineralization.

We in the earth sciences, to a greater extent than any of our sister sciences, deal with history and process, and it is textures that testify to history and process. Thus the interpretation of textures permits the reading of the geologic record. The state of 'local equilibrium' (Thompson, 1959), wherein a series of equilibrium states, representing different conditions in time or space, can be identified and differences among them interpreted, is an ideal condition to permit us to sort out successive events and to identify processes.

Observation of textures

Textural study using multiple techniques has much to offer, and it is the integration of conventional reflected light studies with alternative modes that holds the most promise for the future advances.

In our laboratory we routinely prepare doubly polished thin sections (Donnay, 1930; Heald-Wetlaufer *et al.,* 1982). We employ a petrographic microscope with a vertical illuminator and optics uncorrected for cover slips; reflected and transmitted light sources are alternated by using a foot switch. Whereas many others follow Ramdohr in preferring to use oil immersion, especially where mineral identification is the main interest, for textural study we prefer dry optics to minimize the pervasive mess (in a lab shared by half a dozen researchers) and to facilitate frequent shifts to the lower power binocular microscope. We have found that the more informative magnifications tend to be the lower ones; indeed, for features such as the Kuroko clastic ores (Barton, 1978; Eldridge *et al.,* 1983), even a 1× objective provides too high magnification to exhibit the features of a coarse-grained ore. In preparing a 'base map' to provide the documentation for subsequent high-magnification optical, electron microprobe, scanning electron microscope, electroluminesence, or fluid inclusion studies, a single 'low-power' photograph is often still too local; in that case a large field can be 'mapped' rapidly by copying the slide using the sort of copier designed for 35 mm transparencies, or even more quickly, by inserting the transparent thin section into a microfilm reader and 'printing' part or all of the slide as if it were a microfiche.

A wide variety of techniques and tools complements traditional reflected and transmitted light optical study:

electroluminescence can reveal otherwise unsuspected features in many insulating minerals;
infrared microscopy permits examination of some normally 'opaque' phases;
back-scattered electrons reveal differences in the mean atomic masses within the specimen and thereby are powerful guides to textures within crystals or monomineralic aggregates;
X-ray emission excited by other X-rays (X-ray fluoresence, also in an accelerator such as a synchrotron), an electron beam (electron microprobe), or an ion beam (PIXE, proton induced X-ray emission); whether viewed in a one- or two-

dimensional scanning mode or as a pattern assembled from numerous spot analyses, the maps of elemental distribution can reveal much textural detail;

particle release followed by analysis in a mass spectrometer or other detector (ion probe, laser probe) produces spot isotopic or chemical analyses;

crystal physical measurements are possible through the use of such techniques as, for example, Mössbauer, Raman, nuclear magnetic resonance, or crystallographic structures via the transmission electron microscope (TEM).

Some instruments, such as the scanning electron microscope (SEM), TEM, or electron microprobe, offer multiple modes of operation, for example, electroluminesence, back-scatter electrons, or electron diffraction. Several of these techniques provide maps of compositional variation without destroying or disassembling the specimen; thus they are ideal for textural description because they are fundamentally sampling devices.

Nature of the record

Minerals differ widely in both their initial morphologies and their abilities to retain the record of their heritages. Fig. 1 is a qualitative summary (masquerading as quantitative data) of some of the information on time required for equilibration. All reactions of concern to us are accelerated by elevated temperature.
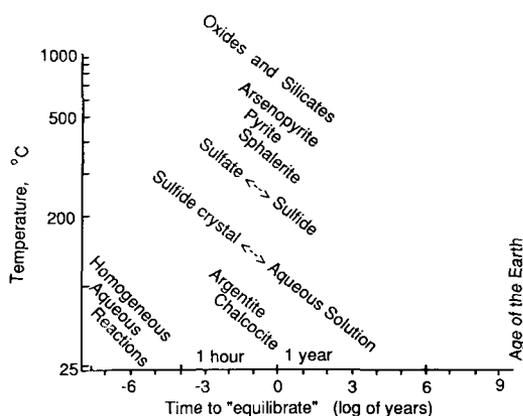
FIG 1. Relative times for equilibration of minerals and fluids, modified from Barton et al. (1963) and Barton and Skinner (1979). The relations shown are highly schematic. The sulfate $\rightleftharpoons$ sulfide reaction applies to aqueous species.

Most homogeneous reactions in aqueous media reach completion in milliseconds, but a few, such as the reduction of sulfate or the oxidation of dissolved methane, are so sluggish that their disequilibria can be significant, even in geologic time.

Reactions involving the precipitation and dissolution of minerals are much slower than most homogeneous aqueous reactions. Carefully measured rates are available only for silica (among others, Rimstidt and Barnes, 1980) and even in this instance the complications of 'poisons' or 'promoters' in solution and the extent of reacting surface area and conditioning make quantitative applications difficult. The degrees of supersaturation required to yield the disequilibrium products illustrated in Plate 1 are almost totally unknown and offer a promising subject for experimentation.

Solid-state reactions among the silver- and copper-rich sulfides are also quite rapid, so much so that these fickle minerals probably preserve a record only of very recent events. Occasionally these minerals may carry useful information about former conditions if individual phases have been isolated since formation, as by being encapsulated in a non-reactive host such as unfractured quartz, or perhaps even pyrite. Such isolation, however, makes the task of recognising the exact event to which the enclosed crystals relate very difficult.

Sphalerite, arsenopyrite, and pyrite are quite refractory with respect to solid-diffusion. It has previously been noted (Barton et al., 1963; Barton and Skinner, 1979) that the refractory nature is correlated with high hardness and high melting point since those properties are measures of the strength of intracrystalline bonds. The combination of relatively rapid rates of solution–crystal equilibration with sluggish solid-state diffusion makes possible two phenemonena: (1) growth-zoned crystals (see Plate 1c and h for examples) in which the compositions of the growing crystal surfaces change in response to changes in solution chemistry and are frozen in their pristine state, and (2) sector zoning wherein different crystal forms, by virtue of their different stereochemical configurations, possess different compositions as a consequence of solution–crystal equilibria, and those compositions are frozen in by subsequent crystal growth. One might imagine geothermometers based on the distribution of components between crystal forms, an example might be CdS or FeS distribution between the positive and negative tetrahedra of sphalerite, as might be exemplified by Plate 1f (however, note also the caption for Plate 1g).

Most silicates and oxides will be even more refractory than any of the sulfides; thus in evaluating the post-depositional behaviour of a rock, for example in a prograde contact metamorphic halo or in a retrograde regional metamorphic environment, the sulfides and silicates complement each other to provide coverage of a wide range of time-temperature space. An example from the Ducktown, Tennessee deposit (massive sulfide in metagreywacke) is given later.

Fig. 1 has one more implication, if the rates of solution–crystal equilibration are rapid, the solution will be effectively saturated in all minerals to which it is exposed (temperature, pressure and composition held constant), and a newly formed crystal would be effectively saturated with respect to all of those earlier minerals to which it is exposed, whether or not they were actually precipitating with the growing crystal. An example might be sphalerite crystals growing in an open vein that contained 'outcropping' pyrrhotine; the FeS content of the sphalerite might well be very close to that in equilibrium with pyrrhotine even though no pyrrhotine was actually precipitating in contact with the sphalerite. This behaviour is the basis for the concept of 'surface equilibrium' discussed by Barton et al. (1963). Therefore, the interpretation of mineral deposition would be more productive if the 'texture' included an assessment of the whole depositional environment, not just the field of view of one's microscope.

Textures as guides to ore genesis and other geologic processes

We shall next consider some examples of textures from hydrothermal deposits in the context of interpretations pertaining to ore genesis.

Textures of hydrothermal minerals indicative of relative levels of saturation

Plate 1 shows an array of mineral aggregates representing a sequence ranging from highly supersaturated through near-equilibrium to highly undersaturated. The specimen photographs are keyed to the saturation sequence shown in Plate 1a. The specimens are described in the figure captions and are numbered approximately in the sequence of decreasing saturation. We see that materials from a wide variety of ores can preserve the record of a broad range of supersaturation levels, as well as evidence for undersaturation.

Individual minerals in the same specimen may differ substantially in either the degree of super-saturation or their response to supersaturation, as exemplified by the skeletal fluorspar intergrown with banded chalcedony in Plate 1b. Sphalerite and galena present puzzles. Both galena and sphalerite are sulfides of divalent metals; both lead and zinc are most probably transported as chloride complexes; and they are commonly closely associated in ores. Yet Plate 1c shows skeletal galena enveloped in fibrous banded sphalerite indicating significantly less ability for the sphalerite to grow crystals than the galena substratum whereas, in great contrast, sphalerite enveloping the skeletal galena in Plate 1d occurs as well-crystallised euhedra. As an additional example of contrasting behaviour, we have two specimens (not shown) from the same stage (but collected a few hundred metres apart) of the epithermal silver–base-metal OH vein at Creede, Colorado, in which one has galena strongly corroded and accompanied by coeval, but unleached sphalerite; whereas the other specimens has etched sphalerite and uncorroded galena. The responses of lead and zinc to most precipitation processes (increasing pH, decrease of chloride ligand concentration, cooling) are similar; why is the textural behaviour of sphalerite and galena so unsystematic?

The fact that we see evidence of chemistries on both the super- and under-saturated sides of precipitation reactions, as well as near-equilibrium crystal growth, demonstrates that the overall depositional process straddled equilibrium. This observation rules out disequilibrium as an *essential* ingredient in formation of these deposits, thereby eliminating gross metastabilites, such as colloidal solutions, as *necessary* elements (this conclusion does not rule out metastable states as intermediaries in the precipitation process, as recognised long ago by Gruner, 1933). It also demonstrates the broad validity of the common practice of applying equilibrium thermodynamics to estimate the conditions of ore formation (provided, of course, that the appreciably super-saturated states are avoided or compensated for in computations).

It should be obvious that quantitative interpretation of phase relations among minerals, as, for example, the distribution of cadmium, manganese or selenium between sphalerite and galena (calibrated experimentally by Bethke and Barton, 1971) would require not only synchronous crystal growth, but simultaneous near-equilibrium growth, followed by preservation without further reaction. Attempts by others to apply element distributions as geothermometers have met with highly variable results, possibly because application to multiphase situations such as those

pictured in Plate 1c, d, or Fig. 5b do not meet the requirement for intraphase equilibrium. Indeed, in detailed studies of the epithermal silver and base-metal deposit at Creede Colorado, the author and coworkers have found that suitable material for trace-element or isotopic distribution studies is difficult to obtain, even in ores having crystals in the >1 cm size range. The depositional process is surprisingly selective in that only a few phases tend to form at a given time. This means that the sites of deposition are not always the sites of buffering (for a brief discussion, see Barton and Skinner, 1979, p. 283–6) of the ore fluid; in the terminology of Korzhinskii (1959), many components are 'perfectly mobile'.

Patchily pigmented or sector-zoned materials (e.g. Plate 1f,g, and the bottom part of h) are presumably a little closer to equilibrium than the skeletal crystals (e.g. fluorspar in Plate 1b, galena in Plate 1c and d, or sphalerite in Plate 1e). Well-crystallised minerals that possess compositional banding that reflects minor changes in the conditions of deposition (as shown on the upper part of Plate 1h) probably grew nearly in equilibrium with their depositing solutions, an interpretation that is supported by the observation that dissolution surfaces are commonly interlayered with such well-banded sphalerite and do not occur, except as cross-cutting features, with the less well crystallised growth textures typical of appreciable supersaturation.

Plate 1i and j illustrate hydrothermal leaching; for Plate 1i the microkarst surface is backfilled with regrowth of the original crystals, but with iron-poor, white sphalerite sharply crosscutting earlier brown and yellow banded sphalerite. In both these examples, the leaching is an integral stage in the depositional history, not a later event such as occurs with supergene oxidation. Hydrothermal leaching is common for fluorspar, barytes, and carbonates as well as sphalerite and galena. Indeed, whenever one mineral replaces another, some sort of dissolution must occur.

The interleaving of dissolution with precipitation textures argues for near-equilibrium conditions; an instance of this would be selective replacement as demonstrated by the 'watermelon' variety of the 'chalcopyrite disease' wherein iron-poor sphalerite plus chalcopyrite replace iron-rich sphalerite (see Fig. 6).

We have few quantitative measures of the degrees of supersaturation that these textures imply, except for quartz. One situation having potential for further study regarding the detection and quantification of significant departures from unit activity (that is, for significant supersaturation or undersaturation) as it relates to mineral

textures, most specifically to Plate 1a, might be addressed experimentally or, alternatively, in natural materials by analysing coeval phases for the level of solid solution; an inverse example of such logic is discussed later in the context of the chalcopyrite disease.

Fig. 2 is redrawn from Fournier (1985); it illustrates the solubilities of the polymorphs of silica in water. One problem in applying such data is the uncertainty as to which protolith (was it opal, amorphous silica, cristobalite, or crypto-crystalline quartz?) represents a specific mineral aggregate such as the banded chalcedony shown in Plate 1b. Supersaturation with respect to quartz can have profound effects on the solubilities of sulfides, as the following illustrates. Probably the most common buffer for hydrolytic reactions in hydrothermal systems is potassium feldspar plus muscovite plus quartz which, in the presence of aqueous potassium ion, fixes pH; pH in turn controls sulfide solubility by controlling the hydrolysis of hydrogen sulfide, a typical net reaction being:

$$3 \text{ KAlSi}_3\text{O}_8 + \text{H}_2\text{S} + \text{Pb}^{2+} =$$
$$\text{KAl}_3\text{Si}_3\text{O}_{10}(\text{OH})_2 + 2 \text{ K}^+ + 6 \text{ SiO}_2 + \text{PbS}$$
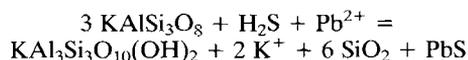
for which the equilibrium constant is:

$$K_{equil.} = \frac{a^2\text{K}^+ \times {}^{a6}\text{SiO2}}{{}^a\text{H}_2\text{S} \times {}^a\text{Pb}^{2+}}$$

Thus a supersaturation in quartz by a factor of 2 (log of activity of silica with respect to quartz = 0.3) would cause an 0.9 decrease in pH and more than sixty-fold increase in solubility for the sulfide of a divalent metal. Such a supersaturation is well
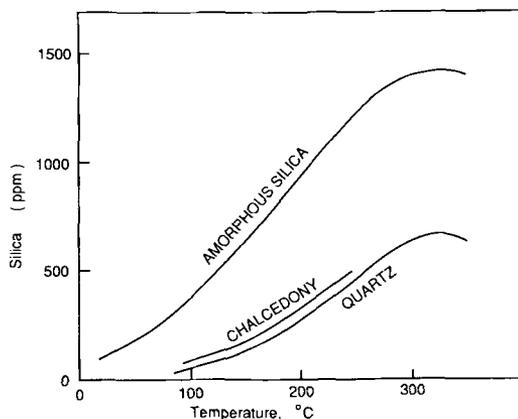
FIG 2. Solubility of various forms of silica in pure water as a function of temperature along the boiling curve. Modified from Fournier (1985).

below the range necessary to precipitate amorphous silica, a possible progenitor of the chalcedony like that shown in Plate 1*b*. Such supersaturation might even eliminate the muscovite field and permit the stable coexistence of potassium feldspar with kaolinite, an association that does occur in some alteration halos (see, for example, Fournier, 1967).

Mineral stratigraphy

The textures within individual crystals or aggregates can be highly complex, as several of the plates and figures (e.g. Plate 1*b,h,i*; Figs. 3,6) illustrate. Although the bandings are obviously responses of the growing crystals to changes in conditions, the complexities are often apparently unsystematic and nearly random. Hence, repetition of the patterns because of some recurrent natural trend or cyclicity, such as fractional crystallisation of a melt or progression of the seasons, is ruled out. Furthermore, because of the low solubilities of most minerals relative to the volumes occupied by the depositing fluid, each growth band that is more than a small fraction of a millimetre thick requires that the depositing fluid be replenished. Thus, regardless of the imponderables regarding the ultimate origin of the complexities, the matching of sequences may provide unequivocal time lines and a 'stratigraphic' record of mineralisation in space and time.

In studies listed above near the end of the section on 'Historical perspective', complexities in growth banding were correlated through individual ore bodies; in the study of McLimans *et al.* (1980) correlations spanned several tens of kilometres in the Upper Mississippi Valley district, thereby showing that the relatively small individual ore bodies were the product of regional-scale events and providing a powerful model for exploration. We (Barton *et al.*, 1977; Bethke and Rye, 1979) have widely correlated growth banding in sphalerite in an extensive epithermal vein system at Creede, Colorado, showing that geographically widespread processes are also reflected in sphalerite textures in the epithermal environment.

In contrast, W. R. Campbell and the author (unpublished data) have noted that some textures of silica banding (of which Plate 1*b* and Fig. 3 are examples) at Creede are apparently only of very local extent. Fig. 3 illustrates how local such variations can be; in the figure three stratigraphic columns are displayed. The question of whether these columns correlate might be argued; for example, the lower thick white chalcedony band is present only in the centre and right pair,
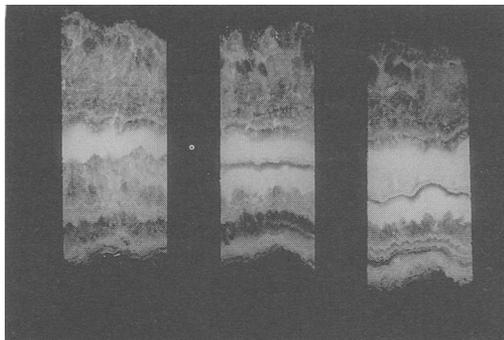
Fig 3. Comparison of three stratigraphic columns containing chalcedonic silica. This is actually a single hand specimen having a total width of only 100 mm. Two opaque screens have been applied to cover transitional zones to emphasize the extreme local variety of some growth banding. Specimen from Creede, Colorado, U.S.A.

whereas the lower dark band is much thinner in the right column. In fact, all three columns belong to the same sawn surface of a single hand specimen; the spatial relations are exactly as shown, and the photo merely has the intervening portions masked out. Thus the process responsible for determining differences in the chalcedony must be locally controlled on the scale of a hand specimen. In other situations we have observed wide ranges in thickness of growth zones of many minerals depending on whether the growing surface was exposed to freely moving solutions or was deprived of nutrients by being in a semistagnant situation.

The point of this brief discussion is that textures can be very important in deducing processes and that textural study can, and often should, encompass a field much larger than that viewed through a microscope.

Geopedal features

C. G. Amstutz and co-workers have extensively discussed geopedal features, and these natural plumb-bobs are well recognised. However, some features justify expanded interpretations:

1. *Stalactites.* One texture that is rarely noted, and even then merely as a curiosity, is the stalactite. Unpublished studies by W. R. Campbell and the author have expanded the discussion by Plumlee (1989) of stalactites in the Creede district where we have found nearly monomineralic ones composed of silica, sphalerite, or pyrite. They are up to a few cm long, volumetri-

cally trivial, and are usually underlain, and overgrown by ordinary hydrothermal ore or gangue minerals. Their significance is that they almost surely record the presence of an interface between liquid water and vapor (perhaps CO_2-bearing) and thus demonstate the former, momentary presence of a vapour-dominated hydrothermal system. The vapour-domination condition rarely develops spontaneously in modern geothermal systems, and its occurrence in ore deposits has significant implications about the distribution of mineralization, and the structural and hydrologic evolution of the host system.

2. *Settled crystals.* It is a common observation that crystals of some minerals may sometimes perch on the tops, and only the tops, or earlier minerals. In general they are reliable top indicators; there are two variations:

The first is the 'snow-on-the-roof' texture in which the sizes and degree of aggregation of the 'snow' crystals suggest that they grew as enlargements of nuclei which had settled in a nearly quiescent fluid under the action of gravity. Such texture demonstrates that the seed crystals either nucleated homogeneously from solution or were suspended clasts which acquired further growth until they sank. Using such a model, Barton *et al.* (1971) studied hematite flakes encapsulated and buried on what once were upper surfaces of sphalerite crystals; they deduced that the vertical component of the velocity of depositing solutions was a few millimetres per second.

The second variation is the sedimentation of slurries which probably originate through tectonic agitation and comminution of vein materials and which then accumulate on any projecting substratum, often forming graded beds (for example, see Schieber and Katsura, 1986). This second mechanism usually leads to multimineralogic accumulations whereas the first often has a very simple mineralogy representative of the particular phase(s) being precipitated at that moment. One very puzzling observation is of sedimented vein filling from the Creede deposit in which a quartzose sandstone with minor chlorite, hematite, and sulfides; it occurs as a vein filling at least 15 cm in stratigraphic thickness, complete with graded bedding and scour-and-fill features. In some places similar-looking sandstone is lithified into an ordinary-looking quartzite having equant grains with sutured contacts. In others, apparently similar initial material recrystallizes to a spectacular reticulated texture (Fig. 4) very similar to that described by Lovering (1972) as diagnostic for jasperoids. Lovering, in agreement with classic studies of W. Lindgren, assigns an
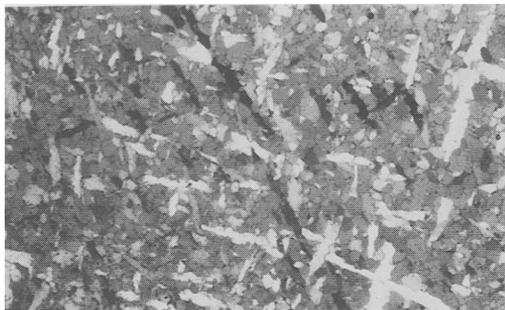
FIG 4. Reticulated texture in a recrystallized quartzose sediment filling a former open space in a vein from Creede, Colorado, U.S.A. Partially crossed polars; note the parallelism of many sets of the quartz grains, each of which shows parallel extinction. The width of the field is 2 mm.

origin by progressive replacement of carbonate rock in which the principal reticulated grains are the pioneers in the replacement process. His model is reasonable for most jasperoids but is difficult to accept for the sample figured because the original lithology was probably a clastic silicious sediment (or could it be that the texture is a relict of replacement of an otherwise cryptic carbonate precursor?).

Kuroko and other massive sulfide deposits

As I noted in the Introduction, textures have played an important role in the interpretation of massive sulfide ores. Ohashi (1919) long ago recognised the syngenetic character of the Kuroko deposits of Japan, but his insight was overwhelmed by those under the spell of an origin featuring replacement by hydrothermal fluids. In a sense, both camps were correct; the ores are syngenetic and they do exhibit extensive replacement textures (although the time and site of the replacement differs sharply from that envisaged by the hydrothermalists of a few years ago). Observations of doubly polished thin sections (e.g. Barton, 1978; Eldridge *et al.*, 1983) clearly show that the ores contain a mechanical blend of clastic fragments (Fig. 5a,d) having greatly contrasting characteristics that could not result from the simple replacement of pre-existing sediments. But the black-ore minerals (principally sphalerite and galena) themselves were indeed replaced by chalcopyrite as the deeper parts of accumulating sulfide piles on the seafloor bacame hotter.

Because massive sulfide deposits occur in geological settings of sedimentary and volcanic rock accumulation, they are buried, incorporated throughout the continental mass, metamor-
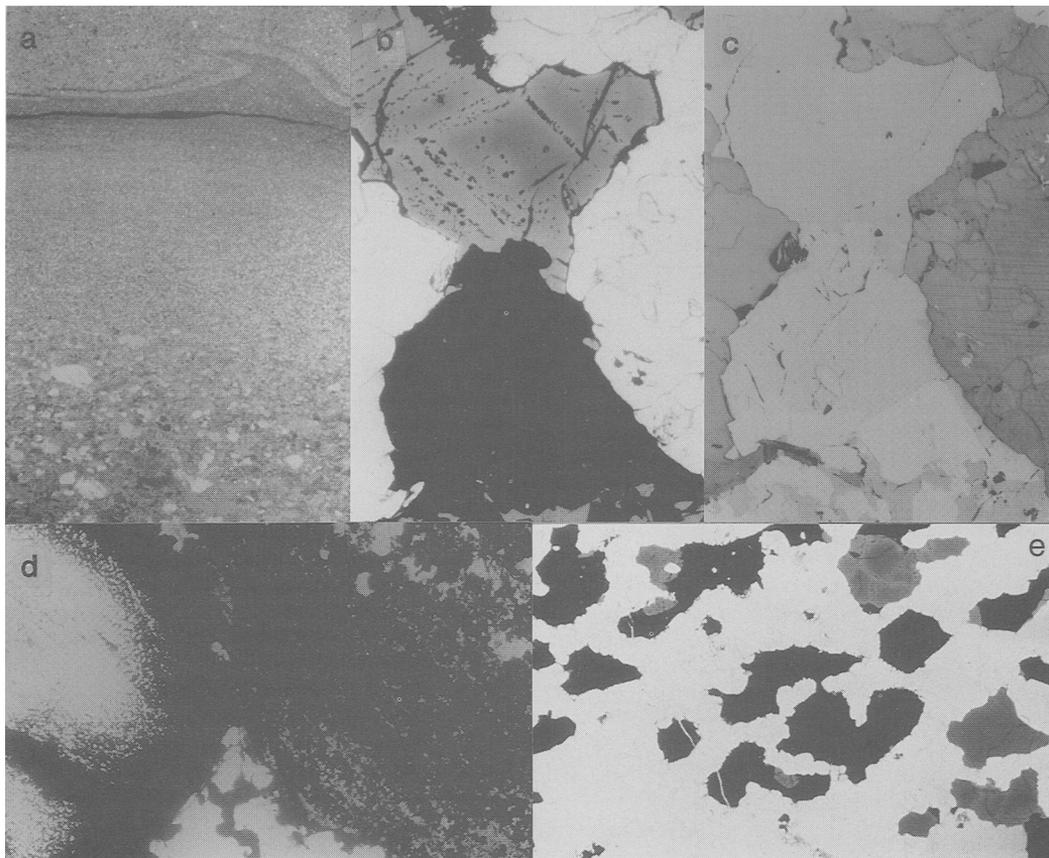
FIG 5. Textures from Kuroko and other massive sulfide deposits. 5a. Graded bedding and soft-sediment deformation insulfides from the Furutobe deposit, Akita Pref., Japan. Most of the clasts are pyrite, but other sulfides, gangue minerals, altered wallrock fragments and fragments of polyminerallic ore are present. This is from the same specimen whose photo forms the frontispiece for Economic Geology Mongraph 5. The width of the field is 2 mm. 5b. Detail of the sphalerite contact zone analysed and discussed in the text. Transmitted light. This sphalerite grain is in the southeast corner of Fig. 5e. and is here rotated clockwise by about 90°. The opaque specks in the sphalerite are chalcopyrite; the large opaque mass is pyrrhotite and pyrite. The width of the field is 1.3 mm. 5c. Same field as Fig. 5b, but in reflected light. The bright square is pyrite; pyrrhotine is dull white; and the sphalerite is light grey. 5d. Detail of clastic ore from Furutobe showing contacting clasts of sphalerite, the large, dark mass to the right is a single clast having very fine-grained texture and probably constituting an essentially unaltered chemical sediment; the other clast is a single crystal of sphalerite (probably originally deposited as a open-space filling) that has its margin dusted by the chalcopyrite disease. Transmitted light. A coloured version of this figure is available in Barton, 1978. The width of the field is 0.4 mm. 5e. Low-power view of a small patch of marble within massive sulfide ore from Ducktown, Tennessee, U.S.A. Transmitted light. Sphalerite is various shades of grey, the darker being more iron rich. Pyrrhotine (containing cubes of pyrite and anhedra of chalcopyrite) is opaque. Calcite is clear. Note that some of the sphalerite isolated in the calcite (especially in the lower right corner) is uniformly dark (about 14 mole percent FeS) whereas sphalerite in contact with iron sulfides is much paler (9 mole percent FeS). The width of the field is 7.5mm.

phosed, and preserved to a far greater degree than most continental hydrothermal deposits which are formed under eroding surfaces and sooner or later are themselves eroded. The mineral assemblages in massive sulfide deposits offer great opportunites for interpretation of regional geological processes and events, complementing the silicates by filling in the lower-temperature record.

During geological events following deposition,

ore and gangue minerals react internally, or with their environment, at widely ranging rates, ranging from the almost inert pyrite, arsenopyrite, well-crystallised quartz, and tourmaline to the notoriously fickle copper/iron and copper/silver sulfides, as shown schematically in Fig. 1. Phases such as the copper/silver sulfides react during cooling, even in the relatively rapid 'quenched' epithermal deposits whereas the 'inert' minerals may preserve their initial character even under contact or moderate regional metamorphic conditions. Original sphalerite textures are recognisable, for example, in some of the ore from the lower Paleozoic volcanogenic massive sulfide deposit at Buchans, Newfoundland and the Triassic East Shasta district of California. However, in most massive sulfide ores the growth-zoned sphalerite has been completely homogenized by metamorphism. Arrested or incomplete reactions may be identified by textural criteria and, when appropriately quantified, can provide guides to the duration of geologic processes. T. Mizuta and S. D. Scott (Scott, personal comm., 1990) have developed a 'sphalerite speedometer' to assess the time–temperature trajectories for skarn deposits.

P. Toulmin, L. Wiggins, and the author have recognised retrograde textures in sphalerite + pyrrhotine + pyrite + chalcopyrite + calcite associations in the metamorphosed massive sulfide ore from Ducktown, Tennessee. Fig. 5b,c, and e show an example in which sphalerite embedded in calcitic marble exhibits a range of colours (yellow to red brown in the polished thin section, and respectively light grey to dark grey in Fig. 5b) depending on how close the sphalerite is to a potential consumer or supplier of FeS (pyrrhotine + pyrite, or an FeS 'pipeline' such as grain boundaries, a persistent crack, or solid pyrrhotine or chalcopyrite). Isolated sphalerite in marble and the cores of large sphalerite grains (note Fig. 5e) are darker grey and have compositions of about $Zn_{0.86}Fe_{0.14}S$ which we interpret to be the composition of the sphalerite buffered throughout the specimen by pyrite + pyrrhotine during the metamorphic maximum (in the vicinity of 7 kilobars at 550°C). The sphalerite now in close proximity to pyrite + pyrrhotine (or the 'pipelines' to such a buffer) has compositions of $Zn_{0.91}Fe_{0.09}S$. Detail of the contact between these two regimes is shown in Fig. 5b and c. It is instructive to note that at least three independent, modern studies of sphalerite composition at Ducktown did not report this now-obvious texture; which proves the old adage that one tends to see only that for which one is looking.

If we examine the compositional gradients along contacts by closely spaced electron microprobe analyses we find a smooth compositional progression whose shape can be fitted to a simple diffusion curve. Such a diffusion curve represents a whole family of time/temperature/composition conditions. The diffusion constants for FeS in sphalerite from Mizuta (1988) would give about 0.63, 26, and 126 million years respectively from temperatures of 240, 220, and 200°C. He has also tabulated effective closing temperatures for diffusion in sphalerite as functions of grain size and cooling rate; the values reside in the vicinity of these temperatures for spherical grains of the order 0.1 millimetres in diameter, which is consistent with the compositional profiles resulting from the gradual quenching of sphalerite as the host metamorphic terrane cools through the 240–220°C temperature range at pressures of the order of 6.5 kilobars (thereby achieving a thermal gradient comparable to the modern Sierra Nevada). Although the numerical treatment given here is based on specific measurements, it is presented only to demonstrate potential, and to encourage additional studies, not to provide a definitive answer for Ducktown. Far more work should be required to reach dependable geological conclusions because I have oversimplified the discussion by assuming the process to be isothermal, by using an average sphalerite composition for the diffusion constant at constant pressure (Mizuta shows composition and pressure each to be a minor variable), by assuming that the position of the boundary remains fixed during diffusion, and by not having measured enough gradients to guarantee that the section interpreted does indeed represent the geometry having a prependicular orientation to the contact.

Even if we consider the Ducktown textures in a strictly qualititive manner (for an overview see Hutchinson and Scott, 1981), it is obvious that the Southern Appalachians cooled at high pressure. In contrast, the iron content of sphalerite in other pyrite + pyrrhotine-bearing assemblages in metamorphosed massive sulfide deposits is much higher, which suggests more rapid uplift and erosion, and cooling under much lower pressures.

An enigmatic set of curiosities: the chalcopyrite disease in sphalerite

Sphalerite and chalcopyrite have been noted in a variety of intergrowths for almost a century (see Ramdohr, 1980, for examples). One of the most common associations, in unmetamorphosed epithermal and massive sulfide deposits, is the dusting of fine (c. 0.001 mm) chalcopyrite through sphalerite. Some of these dust-like intergrowths

are quite complex and have been described and classified as the 'chalcopyrite disease' (Barton and Bethke, 1987).

The chalcopyrite disease is specifically the formation of chalcopyrite in sphalerite accompanied by a marked decrease in the iron content of the immediately adjacent host sphalerite. Iron-rich sphalerite is preferentially attacked. Original banding (distinguished by variations in FeS content) of the sphalerite is preserved (see the right side of Fig. 6) in such detail that any process involving dissolution and redeposition on a scale visible under the optical microscope is precluded. In the 'water-melon' variety, which is shown on the left side of Fig. 6, three successive zones consistently appear: (1) an outer fine dusting constituting the 'rind'; (2) a zone of clear sphalerite nearly free of chalcopyrite; and (3) a 'seedy' core of coarser, myrmekite-like chalcopyrite in low-iron sphalerite. The obvious conclusion regarding the origin of such a texture is the selective replacement of the FeS component of the sphalerite by a copper-bearing solution. Indeed, a synthetic texture similar to the dusting had been created by Eldridge *et al.* (1989) by such a process. One problem is that such a process must involve diffusion, yet the textures typically do not have any visible open channels, and even intergranular grain interfaces that might promote a flux of components are not evident. Furthermore, the preservation of sharp compositional differences within the unaltered primary sphalerite attests to very sluggish solid-state diffusion. Thus the disease presents a paradox wherein the same partially diseased crystal (as is shown in Fig. 6) may present strong evidence both for and against diffusion.

Because the crystal stuctures of sphalerite and chalcopyrite are very similar, because experimental studies at high (700–800°C) temperature have shown a large amount of mutual solid solution, and because reaction rates are relatively rapid (at least compared to those in rock-forming silicates), exsolution became the standard explanation for 'all' such intergrowths. However, studies of massive-sulfide and epithermal deposits (Eldridge *et al.*, 1983; Barton and Bethke, 1987) clearly show that replacement and co-depositional processes are important as well as exsolution. Moreover, a series of experimental studies (Wiggins and Craig, 1980; Hutchinson and Scott, 1981; and Kojima and Sugaki, 1984 and 1985) have clearly shown that at typical low to moderate hydrothermal temperatures (below 400 or 500°C) copper simply is too insoluble in sphalerite to support exsolution for features such as those illustrated in Fig. 6. One might argue that
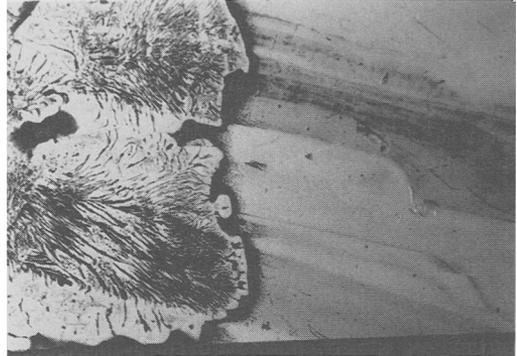
FIG 6. Chalcopyrite disease in sphalerite. Banded sphalerite being invaded (from left to right) and partially replaced by the chalcopyrite disease. Transmitted light. The unaltered sphalerite is strongly banded with sharply-bounded, darker, but still transparent, iron-rich growth zones. At the replacement front the original sphalerite becomes an opaque mixture of fine-grained chalcopyrite and iron-poor sphalerite. The replacement advances preferentially along the iron-rich layers, although this aspect is not well displayed in the figure. Elsewhere in the same specimen the sphalerite is much less strongly banded and the disease is simply a dusting of fine chalcopyrite emanating from grain boundaries as cracks. Essentially this field of view with microprobe analyses along traverses across the banding are given in Fig. 2d in Barton and Bethke, 1987. Specimen from Creede, Colorado, U.S.A. The width of the field is 0.8 mm.

supersaturation at low temperature in the depositing solution with respect to chalcopyrite (e.g. $a_{CuFeS_2} > 1.0$, perhaps as high as 2 or even 5) might trap enough copper in sphalerite to permit exsolution. Such an explanation is ruled out for the chalcopyrite disease because microprobe analyses show far too little copper in fresh, primary sphalerite (see Barton and Bethke, 1987).

We (Barton and Bethke, 1987) have described another texture, termed 'bead chains' for chalcopyrite dispersed within sphalerite, see Fig. 7a and b. In well-crystallised sphalerite individual chains may be followed for tens of millimetres. They usually trend approximately normal to the growth surface of the host, but some are very irregular. Some even make smooth 'U' turns, and in a few instances they outline perfect angular forms such as tetrahedra. Inasmuch as the total copper involved in such chains is miniscule, even with respect to the low level of copper in primary sphalerite, these tiny features may well be exsolved chalcopyrite localised by growth defects such as spiral axes or spiral intersections. Such defects may promote diffusion through the host
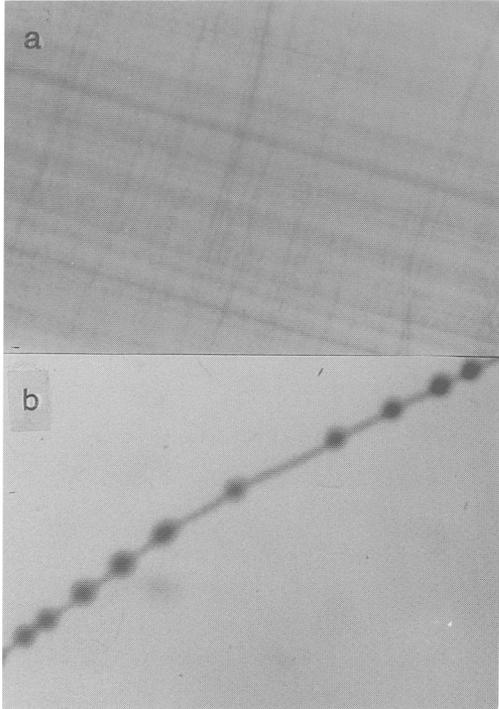
FIG 7. Bead Chains. 7a. Low magnification view of bead chains in sphalerite. Transmitted light. The WNW–ESE striking bands are the growth bands, younger toward the top. This field is very similar to one that might be viewed in the smoothly banded, orange-brown part of Plate 1h. Specimen from Creede, Colorado, U.S.A. The width of the field is 0.4 mm. 7b. High magnification of bead chains from Creede. Transmitted light. The beads are very probably chalcopyrite; the 'threads' connecting them are of unknown character. This photo is of the same field pictured in Barton and Bethke (1987), Fig. 11a. The width of the field is 0.02 mm.

sphalerite, yet the fact that fluid inclusions in sphalerite from the epithermal environment do not seem to leak means that the defects are not very effective pipelines for brines through the crystals. The role of bead-chain-related defects in propagating the sphalerite disease is enigmatic; they would appear to be logical foci for diffusion, yet the geometry of the diseased volumes appears generally to follow fractures and specific growth bands and not the bead chains (except at the few-micrometre scale on the fringes of 'water-melon rinds').

Textures in perspective

Textural features can attest to close approaches to equilibrium, as when granular textural arrays with homogeneous minerals are produced by regional metamorphism. However, more informative textures usually deal with nonequilibrium features, quenched thanks to sluggish reaction rates, that thereby preserve the record of past events. Some of these features record original conditions of formation; others record arrested post-depositional processes.

Surely science must build on previous work without constant and exhaustive reassessment, but for mineral textures a little reassessent may yield substantial benefit. In recent years we have learned much from studies such as those concerned with isotopes, fluids, chemistry, phase relations, and deposit and process models. But in doing so the textural features have all too often been taken for granted. In part this is because we have grown accustomed to using superposition, cross-cutting, pseudomorphism, mutual intergrowths, exsolution, and so on as off-the-shelf tools, to be applied without evaluation or even description. Moreover, we have not paid enough attention to textures *within* minerals. I have tried here to indicate some directions for further investigation, emphasising textures as integral parts of the geologic setting, to be interpreted within the geologic context and to supply information to help interpret the geology. Mineral deposits may yet tell us more about the geology of the host than the other way around.

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Plate 1   P. B. BARTON, JR.

PLATE 1. Textures typical of various degrees of supersaturation during crystal growth.

(*a*) Schematic sequence of features as function of relative levels of supersaturation. The arrows indicate increasingly large degrees of supersaturation and undersaturation; they do not point at anything specific. Modified from Barton *et al.*, 1977.

(*b*) Chalcedonic and well crystallised quartz (some of it amethystine) growing upward and enclosing dendritic fluorspar (the coral-like growth to the right centre), from Creede, Colorado, U.S.A. We have observed this texture for fluorspar only in association with chalcedonic silica and suspect that 'dumping' of the silica rapidly removes the complexing agent (dissolved Si^{4+}) for fluoride ion. The width of the field is 140 mm.

(*c*) Fibrous sphalerite (possibly including polytypes or even wurtzite) radiating outward and enveloping skeletal galena, from San Cristobal, Peru. Transmitted light; the galena is opaque. The width of the field is 6 mm.

(*d*) Skeletal galena decorated by equant, clear sphalerite, from Creede, Colorado, U.S.A. The galena is elongated along (111). Transmitted light. The width of the field is 6 mm.

(*e*) Skeletal sphalerite showing sector zoning, from the Kokkionya mine, Cyprus. This came from the inside of an arcuate specimen that very probably was from a former 'smoker' vent; the texture is typical of zinc sulfide from modern deep-sea 'smokers'. The width of the field is 0.5 mm.

(*f*) Sector zoning in sphalerite, from the Upper Mississippi Valley district, Wisconsin, U.S.A. Transmitted light; view is of a section parallel to (111). The diameter of the crystal is 15 mm.

(*g*) Sector zoning delimited by twin planes in sphalerite from the kuroko deposit of the Furutobe mine, Akita Pref., Japan. The field is >99% sphalerite. Although iron in sphalerite always creates colouring, this type of sector colouration is frequently not associated with detectably different iron contents. The growth banding is evident as a brown marker horizon in the upper left part of the photo and striking NNE except where deflected by the same twin feature that shows the sector with darker colour near the centre of the photo. The black spots are chalcopyrite-disease localized along twin planes. The width of the field is 0.6 mm.

(*h*) Evenly growth-banded sphalerite demonstrating near-equilibrium crystal growth (upper part), and minor sector zoning (lower part) from Creede, Colorado, U.S.A. The bright spot is a hole, possibly from a larger former fluid inclusion. Immediately adjacent to the upper right part of the hole is a nearly uniform orange-brown growth band having a myriad of tiny 'bead chains' oriented normal to the former crystal surface and similar to those seen at higher magnification in Fig. 7. Transmitted light. The width of the field is 10 mm.

(*i*) Microkarst in sphalerite from Creede, Colorado, U.S.A. A few patches of dark brown sphalerite mark a 2 mm wide growth zone in otherwise pale yellow to colourless sphalerite. The growth direction was upward from a substratum of wallrock. Subsequent to the deposition of the dark zone, deep hydrothermal etching removed more than 75% of the dark zone as well some of its underlying weakly-banded, lighter sphalerite; the redeposition of colourless sphalerite overgrew the corrosion surface filling the cavities in crystallographic continuity with the substratum. The same photograph is shown in Fig. 2*j* in Barton and Bethke, 1987. The width of the field is 10 mm.

(*j*) Hydrothermally etched galena from Creede, Colorado. The width of the field is 50 mm.