Textures of Low Temperature Self-Organization

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Abstract

Banded cements, sets of concretions and nodules, sets of stylolites and other low-temperature alteration textures, to the extent they are non-inherited, are conclusive evidence that water-rock systems can drive themselves into spatially alternating behavior. This process of autonomous geochemical "sorting out" of texture and mineralogy into roughly regular patterns is termed geochemical self-organization, and is pervasive in low-temperature systems. Independent experimental and theoretical work indicates that self-organization comes about in disequilibrium systems through the combined action of fluctuations and reaction-transport feedback. Several of these feedbacks are likely or certain to operate in geochemical systems, and the textures predicted to form from them coincide with self-organization textures observed in rocks and in need of an explanation.

Introduction

Some clastic rocks contain evenly-spaced cement bands that cut across the bedding, clearly showing that authigenic minerals can crystallize in non-inherited spatial patterns. Textures such as this one and others contain detailed information on the mechanisms that produced them and on the feedbacks between those mechanisms. Understanding the dynamics of low-temperature alteration (weathering, diagenesis, and metamorphism) includes accounting for the textures produced by these processes. But, it hardly needs to be said, textures are inherently spatial properties of rocks, and thus their description and prediction requires spatial coordinates. Furthermore, the basic mechanisms involved in low-temperature alteration always include transport of ions to, or away from, the sites of mineral growth or dissolution. These two considerations -- the "spatiality" of textures and the necessity of transport -- warrant constructing theories and models that explicitly contain time and in particular space (e.g., Fein et al., 1978; Berner, 1980; Dobrovolsky and Lyalko, 1979; Lichtner, 1985), in order to be able to describe textures and transport and their evolution. (Models of the "pathological" type [Helgeson, 1968; Fritz, 1981; Reed, 1982; Wolery, 1983; and others], which today are used extensively in modelling water-rock interactions, are inherently unable to predict where in the system will mineral grains form. This inability stems from the fact that
the condition of chemical equilibrium, on which the "pathcalc" models are based, is blind to space.)

In addition, the particular significance in this context of repetitive, non-inherited textures, which can be called self-organization textures (Merino, 1984), is that they turn out to result from interactions, or feedbacks, between reactions and transport. The need to model these feedbacks in order to account for those textures is one more compelling reason to build theoretical models that explicitly contain time and space.

The purpose of this contribution is to describe several common low-temperature authigenic textures that demonstrate the ability of geochemical systems to self-organize—that is, to pass spontaneously and autonomously from being texturally uniform to being texturally patterned, and this without being subjected to external, spatially periodic causes. The genesis and dynamics of self-organization are developed by Nicolis and Prigogine (1977). Many specific cases of geochemical self-organization have been quantitatively modelled by Ortoleva and coworkers (Feinn et al., 1978; Haase et al., 1980; Ortoleva, 1982; Ortoleva et al., 1982; Feeney et al., 1983; Merino et al., 1983; Ortoleva, 1984a, b; Ortoleva et al., 1986a, b, c; Merino et al., 1986).

**Self-Patterning Textures**

A repetitive texture, to be a true case of self-organization, must be shown by field, petrographic, and/or chemical criteria, to be non-inherited. For example, repetitive cement bands that intersect the bedding of a sandstone cannot have been inherited from the original sediment, and therefore constitute a certain case of self-organization. At least most of the textures listed below are produced at temperatures less than 300 degrees C. No attempt is made here at compiling an exhaustive bibliography. Other self-patterning textures in low-temperature rocks (such as agates and Mississippian type ores) and in metamorphic and igneous rocks are described by Merino (1984).

**Concretions and Nodules.** These are rounded diagenetic bodies, up to 3 meters in diameter, common in shales, sandstones, limestones, weathering alteration zones, and contact metamorphic zones. (Oribicules in igneous rocks—see Dahl and Palmer, 1983, and Merino, 1984—share striking similarities with some concretions in sedimentary rocks but are not discussed here.) Concretions usually consist of minerals sharply different from those that dominate the enclosing rock. For example, calcite concretions are common in sandstones and shales, and chert concretions are common in carbonate rocks (e.g., Tucker, 1981, p. 80); see Fig. 1. Concretions can be produced by cementation of the pores of an ovoid region (e.g., Raiswell, 1971), or by cementation of pores plus replacement of detrital grains, or (as in many geodes) by physical pushing apart of the surrounding sediment or rock (e.g., Chowns and Elkins, 1974). It is utterly unclear how each of these genetic paths is selected in specific cases. Concretions can be early or late diagenetic. The first are usually identified by wrapping of uncompacted beds around the concretion upon compaction, though one should be careful to tell this apart from similar wrap-around textures produced by late diagenetic concretions of the push-apart type. Curtis et al. (1983, 1986) have interpreted some concretions of carbonate and pyrite as recorders of phases of early diagenesis and pore water chemistry. A late diagenetic origin can be inferred if the concretion intersects bedding or, even better, stylolites (Fig. 2b). The shape of the concretions or nodules of each locality is remarkably consistent. Many concretions have grown around dead organisms, but many have not—for instance, pisolitic concretions produced by surface alteration (Nahon, 1986), concretions in contact metamorphic rocks (Salomon, 1896; Knopf, 1908), and some carbonate concretions in shales (Raiswell, 1971). Some concretions may have started to precipitate in
response to local differences in the water chemical potential themselves driven by differences in surface tension produced by pore size variations from place to place (Tardy and Nahon, 1985). Isotopic study suggests that many concretions have grown from the center outwards (e.g., Gautier, 1982). There is abundant information on mineralogy, isotopic composition, and texture of concretions, but very little on their spatial distribution in a given formation or locality (but see Ralswell and White, 1978). In spite of all this uncertainty, it is clear that concretions and nodules result from the spontaneous "focusing" at some spots of matter that was initially more or less scattered throughout the sediment or rock. This makes concretions and nodules true cases of self-organization.

Patterned Authigenic Cements. Many clastic rocks contain iron-oxide cement patterns which can be planar, concentric, splotty, or cigar-shaped, and which cut the stratification. See Fig. 2. For example, Dalziel and Dott (1970, p. 112 and fig. 27) report elliptical color banding patterns in the Baraboo Quartzite of Wisconsin. Bender (1968, fig. 49) shows arcuate color banding patterns in Cambrian sandstones of Nubian Facies at Petra, Southern Jordan. Bailey and Childers (1979, figs. 3-14 to 3-16 and p. 119) also report similar color bands behind the redox front in uranium roll deposits of Wyoming. In the cement patterns described by Hobson (1930) in so-called "zebra" mudstones of East Kimberley, Western Australia, banded and splotty regions are observed to grade into each other. R. Hereford (pers. comm., 1980) reports cigar-shaped columns of hematite in the Chino Valley Dolomite of Arizona; the columns are (see Fig. 2 in Merino, 1984) one cm in diameter and a few cm long, are perpendicular to bedding, and are arranged in a loose hexagonal pattern. Many chert concretions, themselves a case of self-organization, contain concentric bands of authigenic iron oxide (e.g., DeCellies and Gutschick, 1983).

Still other examples of iron oxide cement bands, specifically studied as cases of self-organization (Merino, 1987), are Mississippian Borden Group siltstones of Southern Indiana (Fig. 3a), Mississippian sandstones of the Cuyahoga Formation in central Ohio, and Upper Precambrian sandstones of the Taoudeni Basin in Northwestern Mali (Fig. 2). In all these cases petrographic and field evidence clearly precludes the interpretation that the rock was fractured and then the fractures filled by iron oxide; the iron oxide is a true cement that fills pores in a sediment. All the cases mentioned are clearly not inherited, because in all of them the bands of cement intersect the bedding, and all are therefore certain cases of self-organization.

A feedback able to yield iron oxide cement bands (from preexisting disseminated pyrite that reacts with incoming oxygenated water) is the supersaturation - nucleation - depletion cycle quantitatively modelled by Ortoleva et al. (1986a): the kinetic competition for oxygen between pyrite on the one hand and the aqueous ferrous ion on the other leads to supersaturation with respect to (and precipitation of) ferric oxide only at some points in the system.

Precambrian Banded Iron Formations. Recent comprehensive summaries on the occurrence and origin of these huge iron ores are those of Mel’nik (1982), Trendall and Morris (1983), and Maynard (1983). Characteristically, these chemical sediments consist of alternating bands of chert and iron minerals. The banding may have simultaneously up to three scales: microbands a fraction of a millimeter thick, mesobands of a centimeter scale, and macrobands several meters thick. All these scales may have great lateral continuity (e.g., Trendall, 1972).

Various ideas on the genesis of the banding have been summarized by Merino (1984) and Garrels (1986). The main one was proposed by Trendall (1972), who attributed the various scales of banding in the Hamersley Iron...
Fig. 1  Chert concretions in Middle Jurassic limestones, Poitiers, France.

Fig. 2. Patterned cements. A, planar iron oxide cement bands at Kassimkara, Mali. B, concentric, closed layers of iron oxide in Upper Precambrian arenites at Namaqualand, Nama. The concentric layers cut across microstylolites. Lens cap for scale.
The image contains a diagram and a photograph, along with some text that is not legible. The diagram appears to be a geological cross-section, possibly showing stratigraphic layers or geological features. The photograph seems to be a close-up of a surface with circular or elliptical patterns, possibly a geological or biological sample. The text is not legible due to the quality of the image.
Wolery T.J. (1984) EQ6, a computer code for reaction-path modeling of aqueous geochemical systems. Lawrence Livermore National Laboratory, Livermore, CA.