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The Development of Redox-pH-fronts in Hydrothermal Systems

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Most mineralised hydrothermal systems show the development of redox fronts with mineralisation concentrated at or near the maximum gradient in redox. In many instances a pH front is also spatially related to the redox front. These fronts occur at all spatial scales from the regional scale where they define the position of mineral camps, to the local scale where they define the positions of individual ore bodies, to the outcrop scale where they define the localisation of grade to the micro scale where they define the positions of metal concentration within say grains of pyrite or arsenopyrite. Such scale invariance (over perhaps 10 orders of magnitude) is reminiscent of critical systems and is characteristic of non-linear systems not at equilibrium. One common explanation of the fronts is the mixing of two or more fluids that originate in diverse chemical and physical environments. In this paper we explore the proposition that a single fluid is involved and that the fronts with this associated scale invariance arise from instabilities in a chemically reacting advecting environment held far from equilibrium by the influx of fluid and heat.

The keys to the development of both temporal and spatial instability in coupled chemical reactions are (i) the presence of autocatalytic behaviour somewhere in the system of reactions and/or (ii) the presence of some process such as mass diffusion, deformation or fluid advection that physically moves chemical components relative to one another and relative to some initial reference frame. The resulting instabilities can be temporal in nature so that the chemical composition of the system oscillates in time, spatial in nature so that gradients or fronts in chemical composition arise or in the form of travelling waves so that waves of chemical change move through the system.

We write the chemical equations commonly used in economic geology to describe the deposition of metals or sulphides and the formation of alteration systems with the additional equation $Fe^{2+}+2Fe^{3+} \rightarrow 3Fe^{3+}+\text{electron}$. This immediately produces a large spectrum of unstable behaviour both in space and time. A variant of this equation is $2H^{+}+2Fe^{3+} \rightarrow 3Fe^{3+}+H_2+\text{electron}$ which introduces a pH inter-relation with the redox relation. Similar behaviour is introduced by including fluid advection to the standard equations.

Our conclusion is that the rich variety of spatial patterns that are observed in hydrothermal mineral systems can be explained, with exploration consequences, by chemical instabilities arising from the influx of a single fluid. If autocatalytic behaviour is included than an even richer spectrum of behaviour arises. The observed scale invariance follows directly from this behaviour.