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Microtectonics and Electricity: Diffusion Rate Variabilities in Metamorphic Reactions.

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Diffusion rates of chemical species (e.g. atoms, ions, volatiles) in rock are affected by electric field strength variations in addition to mechanisms more commonly studied. Consider that while a rock undergoes deformation and metamorphism, some mineral constituents will present deformation mechanisms that produce or enhance an electric or magnetic field. Brittle fracture, for example, can cause electromagnetic emission; pressure twinning can create piezoelectric fabrics; grain boundary migration can reduce electrical conductivity.[1] Rocks of the same metamorphic grade from different locations (at scales of cm, m and km) can have different mictrotectonic features and different electric fields during metamorphism. The differential presence of these fields can introduce variability in diffusion rates. New diffusion and thermodynamic equations are introduced in this talk to account for variability in electric field strength.[2,3] Variations in the geomagnetic field are also discussed for this purpose. Note that this present work discusses both theory and data, but the data themselves are scant. In practice, these phenomena can be used to account for variability in some situations. This is a new contribution to the field of study.

References:

[1] Helman, D. S. (2013). Metamorphic contributions to electrical phenomena in the Earth's crust. MS Thesis: California State University Long Beach.

[2] Hobbs, B. E., Ord, A., & Regenauer-Lieb, K. (2011). The thermodynamics of deformed metamorphic rocks: A review. Journal of Structural Geology, 33(5), 758–818.

[3] Reverdatto, V. V., Likhanov, I. I., Polyansky, O. P., Sheplev, V. S., & Kolobov, V. Y. (2019). The nature and models of metamorphism. Springer International Publishing.

Attachments:

1. Table from [1] listing deformation mechanisms and associated electromagnetic phenomena.
2. Two sample equations shown.

TABLE 49. Deformation Mechanisms and Associated Electric and Magnetic Phenomena Summarized

Mechanism	Summary
Brittle Fracture	Brittle fracture can cause electrical and electromagnetic emission and fractoluminescence. Magnetic fields weaken materials and promote fracture.
Dissolution-Precipitation	The presence of electrolyte-bearing fluids can promote pressure solution. Mineral precipitation is responsible both for the conductivity anisotropy in the upper mantle shear zone and for magnetic fabrics in some slate, migmatites and granites.
Crystal Plastic Deformation	Dislocations allow for greater charge transfer and conductivity, while high-current discharge can create dislocations in metals. Crystal plastic deformation alters the orientations of magnetic domains and is used to create permanent magnets. It is responsible for similar changes in minerals. It is the cause of magnetic fabrics in some migmatites and other rock.
Pressure Twinning and Kinking	Twinning is responsible for some piezoelectric fabric in rock. Kinking is controlled by the energy to turn bonding into anti-bonding electrons. Pressure twinning can create magnetic anisotropy in materials with ferromagnetic dopants.
Recovery / Annealing Mechanisms	An applied direct electric current can increase the rate of recovery processes at the expense of grain growth rate. The presence of subgrains decreases magnetic susceptibility in ferromagnetic materials.
Dynamic Recrystallization	An applied electric field can increase the rate of dynamic recrystallization in metals, but direct current will decrease the occurrence of grain boundary migration in the direction of the applied current. Grain boundary migration decreases electrical conductivity. An applied magnetic field makes fine-scale grain boundary structure more uniform. Dynamic recrystallization can be used to create permanent magnets in metals.
Diffusion Creep	Vacancies increase both electrical conductivity and magnetic susceptibility.
Granular Flow	An applied electric field promotes superplasticity. If lattice-preferred orientation is destroyed (as with superplastic deformation), other earlier anisotropies will be destroyed as well. The process whereby grains slide past each other in granular flow can create magnetic fabrics.

Notes: Pressure solution–precipitation, crystal plastic deformation, and granular flow have each been singled out as the major cause of magnetic fabrics in different rocks by different authors. References for the summaries in this table are given in the text on p. 63 through 68.

Dissipation rate (Φ) for a rock system. Original after Hobbs (2011).

original

$$\Phi = T\dot{s} = \Phi^{plastic} + \Phi^{mass\,transfer} + \Phi^{chemical} + \Phi^{thermal\,transport} \geq 0$$

new

$$\Phi = T\dot{s} = \Phi^{plastic} + \Phi^{mass\,transfer} + \Phi^{chemical} + \Phi^{thermal\,transport}\ \Phi^{electromagnetic} \geq 0$$

where Φ is the dissipation rate, T is the absolute temperature and s is the specific entropy production rate at a particular point. Superscripts designate the constituent components of the overall dissipation, and the inequality reflects the second law of thermodynamics.

Diffusion (D) of components in a fluid. Original after Reverdatto (2019).

original

$$J_i^D = -\sum_{j=1}^{n} L_{ij}^D \cdot \nabla \mu_j, (i=1,2,\ldots n)$$

new

$$J_i^D = -\sum_{j=1}^{n} \alpha_{ij}^M L_{ij}^D \cdot \nabla \mu_j, (i=1,2,\ldots n)$$

where J_i^D is the flow (diffusion rate) of the i^{th} component, $L_{ij}{}^D$ is a phenomenological coefficient for diffusion of the i^{th} component driven by the gradient μ_i, ∇ is the Hamiltonian operator representing the gradient, μ_j is the chemical potential of the j^{th} component in a fluid, n is the number of components. The new coefficient $\alpha_{ij}{}^Q$ is the modification to the phenomenological coefficient due to electromagnetic effects from each deformation mechanism M.