zero otherwise. The quantities a_i and b_i are constants and the little rectangles A_i do not contain points on the solitary wave trajectory.

Results are shown in Figs. 1 and 2. Solutions of the reaction-diffusion systems were computed by using Lees' modification of the Crank-Nicolson numerical procedure (*9*). Figure 1 shows the computed solitary waves of u and v traveling toward the center of the figure and the initial merging of the waves. In the unmodified system these collision envelopes collapse back to resting values. Figure 2 shows further interactions and the emergence of solitary waves after the collision in the modified system. To check that the modified system still gave solitary waves in response to an initial stimulus of locally elevated u, solutions of the modified equations were computed with $u(x,0)$ and $v(x,0)$ as given above. The result was two solitary waves traveling to the left and right, as had been the case for the original system. It is noteworthy that when slightly asymmetric initial data were employed for the modified system, when two solitary waves collided only one emerged from the collision.

The ramifications of the existence of solitons in reaction-diffusion systems are far-reaching. Models for the activity of populations of neurons have hinted at their existence (*10*) and they may be important in particle physics. The idea of solitons in neuroanatomic structures may be important in possible theories of memory. The reaction-diffusion system in which solitons have been found by numerical computation (which can give only evidence rather than proof of their existence) has been constructed from a system that arises in describing the evolution of ion concentrations in cortical structures. It is hoped that systems will be found whose reaction terms arise naturally and which give rise to soliton solutions. The aim of this investigation has been to obtain evidence that reaction-diffusion systems can support soliton solutions, which had not previously been suspected.

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References and Notes

1. A. C. Scott, F. Y. F. Chu, D. W. McLaughlin, *Proc. IEEE* **61**, 1443 (1973).
2. N. J. Zabusky and M. D. Kruskal, *Phys. Rev. Lett.* **15**, 240 (1965).
3. N. J. Zabusky, *Phys. Rev.* **168**, 124 (1968).
4. A. L. Hodgkin and A. F. Huxley, *J. Physiol. (London)* **117**, 500 (1952).
5. R. Fitzhugh, *Biophys. J.* **1**, 445 (1961).
6. J. Nagumo, S. Arimoto, S. Yoshizawa, *Proc. IRE* **50**, 2061 (1962).
7. H. C. Tuckwell and R. M. Miura, *Biophys. J.* **23**, 257 (1978).
8. C. Nicholson, G. Ten Bruggencate, R. Steinberg, H. Stockle, *Proc. Natl. Acad. Sci. U.S.A.* **74**, 1287 (1977); R. P. Kraig and C. Nicholson, *Neuroscience* **3**, 1045 (1978).
9. M. Lees, in *Numerical Solution of Partial Differential Equations*, W. F. Ames, Ed. (Barnes & Noble, New York, 1969), p. 193.
10. R. L. Beurle, *Philos. Trans. R. Soc. London Ser. B* **240**, 55 (1956).
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Microcracking and Healing in Granites: New Evidence from Cathodoluminescence

Abstract. *Quartz grains in granitic rocks usually have blue cathodoluminescence (CL). Within the blue-luminescing grains, there are often red-luminescing domains which are frequently impossible to detect without CL contrast. This finding suggests that the red-luminescing quartz is sealing preexisting microcracks. The presence of these now-healed microcracks has important implications with respect to the role of pore fluid pressure and fluid transfer in metamorphism, the origin of granites, long-period crustal deformation, earthquake mechanics, physical properties of rocks, and deep-seated geothermal energy.*

In a recent study of the cathodoluminescence (CL) of quartz grains in granites and pegmatites, we have discovered some interesting structures that have not been noticed before. In 84 percent of the granites examined, most of the quartz luminesces blue. In the remaining 16 percent, the dominant quartz CL color is red. Two-thirds of the rocks with blue-luminescing quartz have red-luminescing structures within the quartz grains. The red luminescence is often in linear, elongated domains (Fig. 1, a, d, e, and g). These red-luminescing domains within blue-luminescing quartz are frequently indistinguishable under the microscope with either ordinary or polarized light. Linear red-luminescing domains are sometimes recognized as bubble lines, the intersection of inclusion planes with the surface of the rock thin section (Fig. 1, a, b, c, e, and f). However, in other cases bubble planes are not associated with red luminescence (Fig. 1d).

Earlier studies by Sprunt *et al.* (*1*) and Sprunt (*2*) indicated that blue quartz CL is often associated with higher temperatures of quartz crystallization than red CL; it was found that the CL color of quartz in several quartzites changes systematically from red to blue with increasing metamorphic grade. Moreover, detrital quartz grains in sandstones often have blue CL, whereas the secondary quartz overgrowths and cement have red CL. Sprunt (*2*) found that the major difference between red- and blue-luminescing quartz was the Ti/Fe ratio, with high

Table 1. Samples studied; N, not observed.

Rock	Red veins	High-density red veins	Calcite veins
Baring, Maine	Yes	Yes	Yes
Barre, Vermont 1	N	N	N
Barre, Vermont 2	Yes	N	N
Milford, New Hampshire	Yes	N	N
Chelmsford, Massachusetts 1	N	N	Yes
Chelmsford, Massachusetts 2	N	N	N
Quincy, Massachusetts	Yes	Yes	N
Westerly, Rhode Island	N	N	N
Roxbury, Connecticut	N	N	Yes
Norfolk, Connecticut	Yes	N	N
Nelson County, Virginia	Yes	Yes	Yes
Graniteville, Missouri	Yes	Yes	N
Wausau, Wisconsin 1	N	N	N
Wausau, Wisconsin 2	N	N	N
Troy, Oklahoma	Yes	Yes	N
Mount Ajo, Arizona	Yes	Yes	N
Bergell granite, Switzerland 1	N	N	Yes
Bergell granite, Switzerland 2	Yes	N	N
Bergell granite, Switzerland 3	Yes	N	N

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ratios for blue CL and low ones for red CL. Apparently, high temperature favors high Ti/Fe ratios.

We interpret the domains of red CL in granitic and pegmatitic quartz as relatively lower-temperature quartz deposited in the preexisting high-temperature blue CL quartz. The simplest mechanism for the development of this secondary red CL quartz is the filling of microfractures and open subgrain boundaries in deformed blue CL grains. The fractured nature of the filled regions is suggested by direct inspection of the shapes of the red CL domains (Fig. 1, a, d, e, and g). The linear red domains intersecting each other resemble arrays of microcracks in rocks. Some of these domains have a more diffuse pattern, as if the agent responsible for the red CL has diffused away from the filled crack-like region into the blue CL host grain (Fig. 1e). Whether this is due to real diffusion of Fe and Ti remains to be studied with other tools such as the laser microprobe. Another mode of appearance of the red CL domains is the spotty pattern (Fig. 1i) in which the red CL quartz appears here as filling between shattered grains. Similar filling has been observed with CL petrography in quartz in sedimentary rocks and interpreted as fractures (*3*). The exciting new discovery here is that CL petrography can detect fractures healed with quartz in quartz grains of igneous rocks, which cannot be seen otherwise.

It has long been believed that planes of fluid inclusions in quartz in granites are remnants of healed fractures (*4, 5*). Experimental and field studies show that fluid inclusions may form at temperatures between 350° and 500°C (*6*) and pressures corresponding to a depth of 8 to 11 km in the crust. As mentioned above, some inclusions are aligned with red CL lines whereas others are all in blue CL (Fig. 1, a, b, and d). This observation suggests that microcracks occur in granites at different times throughout their history, including high-temperature periods, and that microcracking may be more abundant than the density of red CL indicates (Table 1). The healed fractures with inclusions may be typical of higher temperatures, whereas healed cracks with red CL, frequently without inclusions, occur at somewhat lower temperatures. If, however, fluid inclusions are no more typical of cracks healed at high temperature than of cracks healed at low temperature, cracks in blue CL healed with high-temperature blue CL quartz would escape notice. This suggests a very extensive, otherwise undetected process of cracking and healing, beginning when the rock cools just enough for the quartz to become brittle and continuing down to lower temperatures until solubility, diffusion, and the mobility of silica become too small for healing in a reasonable period of time.

One possible source of the extensive cracking is the thermal history of the rocks. Quartz is particularly interesting in this respect because the incoherent $\beta \rightarrow \alpha$ transition is associated with large distortional strain. The extensive cracking and subsequent healing may occur after cooling below the transition temperature at about 570° to 600°C [depending on pressure and stress (*7*)]. Other possible sources of extensive cracking are tectonic deformation and differential thermal and overburden stresses in quartz (*7*).

Several samples show not only inclusion planes and red CL domains but also calcite-filled microcracks in both quartz and feldspar and the boundaries between them (Fig. 1, i, k, and l; Table

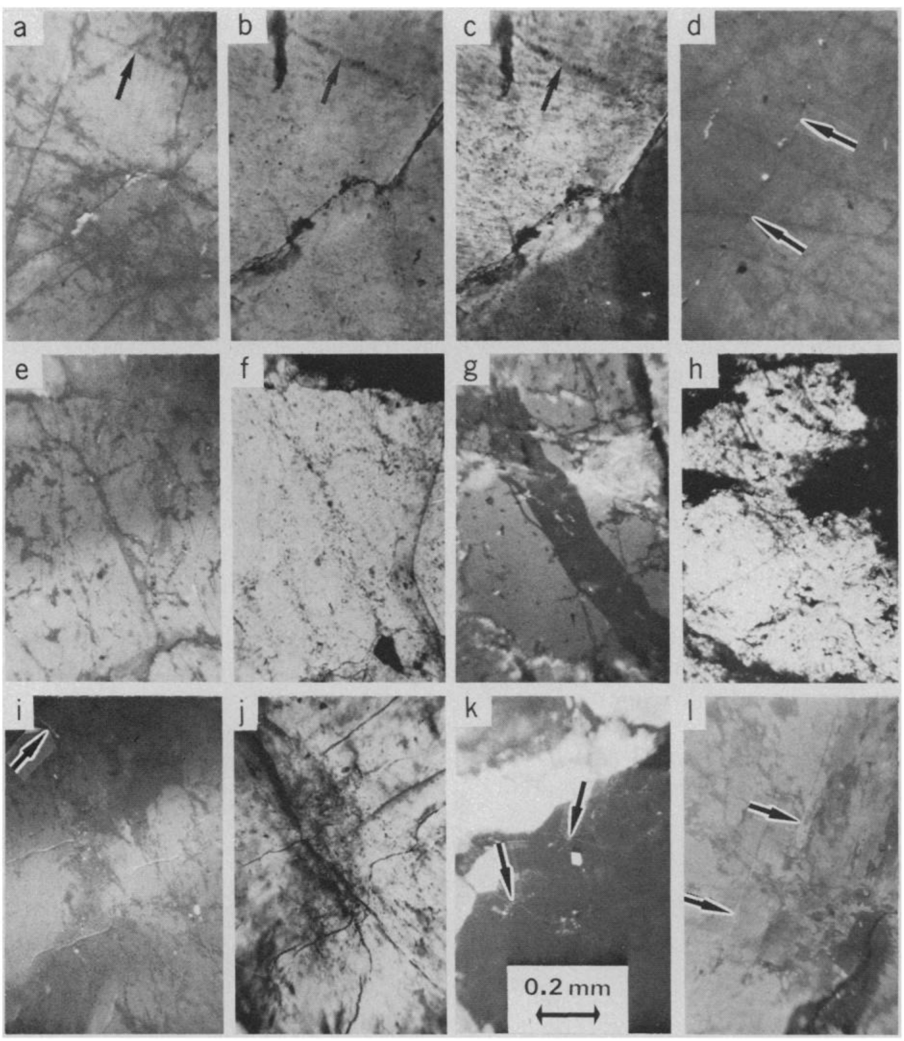

Fig. 1. Photomicrographs of cracks in granites. All the photos are the same magnification, with the scale shown in (k). (a) CL image of quartz in a granite from Nelson County, Virginia. Red CL quartz appears darker than blue CL quartz. Arrow indicates a red CL quartz zone that coincides with a bubble plane. (b) Transmitted-light image of the same microscope field as (a). The bubble plane corresponding to the red CL zone in (a) is indicated by the arrow. (c) Image with crossed Nicol prisms of the same microscope field as (a). The bubble plane is again visible (arrow). Red CL zones are not distinguishable with crossed Nicols. (d) CL image of quartz in a granite from Nelson County, Virginia. Arrows indicate a bubble plane that does not coincide with a red CL zone. Some red CL zones not coincident with bubble planes are visible. (e) CL image of quartz in a granite from Troy, Oklahoma. Several of the red CL zones coincide with bubble planes which can be seen in (f). (f) Transmitted-light image of the same microscopic field as (e). Many bubble planes are evident. (g) CL image of quartz in Graniteville, Missouri, granite. One wide and several narrow red CL zones cross the grain. (h) Transmitted-light image of the same microscope field as (g). The wide fracture seen in (g) is not evident. (i) CL image of quartz in a granite from Baring, Maine. Red CL zones appear to outline subgrains. Arrow indicates a calcite-filled portion of a fracture. (j) Transmitted-light image of the same field as (i). (k) CL image of calcite veins in quartz in Chelmsford, Massachusetts, granite (arrows). (l) CL image of calcite veins in feldspar in granite from Nelson County, Virginia (arrows).

1). Calcite-filled cracks have been observed (*5*), but they are particularly obvious with CL petrography because calcite CL is much more intense than quartz CL. Whether calcite fillings are deposited at the same time as quartz or later is still unclear. It is evident, however, that calcite plays a role similar to quartz in crack sealing.

If our interpretation of new CL evidence is correct, cracking and healing in quartz is much more abundant and common in granitic and related rocks than previously thought (Table 1). This implies that tectonic or thermal strains can induce fracturing rather easily. These fractures are probably the conduits for the transfer of silica which eventually seals them, sometimes leaving behind planes of fluid inclusions. We infer therefore that a fluid phase, probably water with dissolved gases, is present in granites during part of their cooling history. This liquid, the residue of which is found in the fluid inclusions, provides the material needed to eventually seal the fractures. The pressure of the fluid (P) must be at or close to lithostatic overburden pressure. If P is lower, fractures will tend to deform under the overburden so as to increase the pore pressure until it does equal the overburden pressure. Furthermore, under these high P conditions cracks remain propped open, causing relatively high hydraulic permeability.

The possibility that extensive fracturing, high pore pressure, fluid flow, and healing occur in granitic rocks at mid-crustal depth has important implications for several mechanical and chemical problems of crustal history and tectonics including metamorphism, deformation, earthquake mechanics, and the physical properties of the crust. Particularly interesting is the strong evidence of the exchange of oxygen in deep-seated batholiths (up to 19 km) with meteoric water (*8*). In spite of widespread evidence for such exchange, one aspect remained enigmatic: How can oxygen in deep batholiths be exchanged with meteoric water without extensive fracturing? Clearly, diffusion of oxygen in solid rock is much too slow for full exchange even in a few million years. If fracturing and healing are common, the combined process may provide the means by which such exchange can occur. The exchange is usually complete in feldspar but only very limited in quartz (*8*). This is due in part to higher diffusivity in feldspars (*9*); however, our preliminary observations of feldspars (Fig. 1, panel l) appear to provide additional means, as they show a very complex pattern of CL domains with density (much greater than in quartz), which may well be related to extremely extensive and fine microcracking and healing.

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References and Notes

1. E. Sprunt, L. A. Dengler, D. Sloan, *Geology* **6**, 305 (1978).
2. E. Sprunt, *Eos (Trans. Am. Geophys. Union)* **59**, 1216 (1978).
3. R. F. Sippel, *J. Sediment. Petrol.* **38**, 530 (1968); D. F. Sibley and H. Blatt, *ibid.* **46**, 881 (1976).
4. T. N. Dale, *Bull. U.S. Geol. Surv. 738* (1923), p. 1; G. G. Lemmleyn and M. O. Kliya, *Int. Geol. Rev.* **2**, 125 (1952); S. S. Voskresenskiy, G. N. Kolosova, V. B. Naumov, *ibid.* **16**, 26 (1974); S. B. Shirey, M. L. Batzle, G. M. Simmons, *Geol. Soc. Am. Abst. Programs* **10**, 491 (1978).
5. D. Richter and G. Simmons, in *The Earth's Crust*, J. G. Heacock, Ed. (Monograph 20, American Geophysical Union, Washington, D.C., 1977), pp. 149-180.
6. E. I. Dontsova and G. B. Naumov, *Geochem. Int.* **4**, 469 (1967); B. P. Potty, H. A. Stalder, A. M. Weisbrod, *Schweiz. Mineral. Petrogr. Mitt.* **54**, 717 (1974); D. P. Grigoriev, *Cursillos Conf. Inst. Lucas Mallada* **7**, 63 (1960); E. Rodder, *Schweiz. Mineral. Petrogr. Mitt.* **50/1**, 41 (1967); B. W. D. Yardley, *Geol. Soc. Am. Bull.* **89**, 941 (1978); L. S. Hollister and R. C. Burrus, *Geochim. Cosmochim. Acta* **40**, 163 (1976).
7. R. S. Coe and M. S. Paterson, *J. Geophys. Res.* **74**, 4921 (1969); A. Nur and G. Simmons, *Int. J. Rock Mech. Min. Sci.* **7**, 307 (1970).
8. H. P. Taylor, Jr., *Geol. Soc. Lond.* **133**, 509 (1977); M. Magaritz and H. P. Taylor, *Earth Planet. Sci. Lett.* **23**, 8 (1974); *Can. J. Earth Sci.* **13**, 1514 (1976); *Earth Planet. Sci. Lett.* **30**, 179 (1976).
9. B. J. Giletti, M. P. Semet, R. A. Yund, *Geochim. Cosmochim. Acta* **42**, 45 (1978).
10. Research was supported by a grant from the Office of Basic Energy Sciences, Division of Engineering, Mathematical and GeoSciences, U.S. Department of Energy. Rupert Laniz prepared the polished sections.

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Histofluorescence Techniques Provide Evidence for Dopamine-Containing Neuronal Elements in Canine Kidney

Abstract. *Changes induced by hydrochloric acid in the excitation spectrum of catecholamine fluorophores associated with the innervation of the canine renal vasculature show that there are neuronal elements at the glomerular vascular poles containing predominantly dopamine. In contrast, the catecholamine fluorescence in the periadventitial layer of the arcuate arteries is derived from norepinephrine. The dopamine-containing structures may represent the prejunctional counterpart to the pharmacologically identified dopamine receptors in the renal vasculature. As such, this system may be involved in the normal regulation of renal blood flow and renin release.*

Catecholamine-containing terminals in postganglionic peripheral nerves are thought to utilize norepinephrine exclusively as their neurotransmitter. We now report that in the dog kidney the fibers associated with the blood vessels at the glomerular vascular pole contain predominantly dopamine (DA). Many lines of evidence indirectly suggest that DA may have a physiological role in the kidney. First, there is a DA-specific receptor in the renal vasculature mediating the vasodilation produced by exogenous DA (*1*). When small doses of DA are administered to animals or man, there is an increase in glomerular filtration rate, renal blood flow, and Na^+ excretion (*1*). Furthermore, there is evidence that DA may exert a physiological role in the regulation of Na^+ excretion and maintenance of plasma volume. Cuche *et al.* (*2*) reported that when normal human subjects assume the upright position, the urinary excretion rate of DNA decreases and that of norepinephrine increases. Conversely, Alexander *et al.* (*3*) found that with a saline infusion, urinary DA increases while norepinephrine decreases. Faucheux *et al.* (*4*) reported that saline infusion also increased urinary DA excretion in dogs and, in contrast, found that expanding plasma volume by albumin infusion does not affect DA excretion. These studies suggest that DA may have a role in the regulation of the renal excretion of sodium. In addition, Imbs *et al.* and Dzau *et al.* (*5*) reported that intrarenal infusions of DA increased renin excretion in the dog and this effect, like the increase in renal blood flow, was antagonized by the DA antagonist, haloperidol.

A major question is whether the putative physiological roles of DA and the alterations in DA excretion are related to the release of DA from renal storage sites. Catecholamine-containing neurons have been observed in many areas of the kidney by the Falck-Hillarp histofluorescence technique, but no neuronal elements containing DA as the predominant catecholamine have been identified (*6*). Indeed, it is generally assumed that the DA content of peripheral tissues represents a precursor pool for norepinephrine. However, Bell and Lang (*7*)

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