Journal of Scientific Exploration, Vol. 17, No. 1, pp. 37–71, 2003 0892-3310/03

Rocks That Crackle and Sparkle and Glow: Strange Pre-Earthquake Phenomena

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Abstract—Seismic waves are the most dramatic and most intensely studied manifestations of earthquakes. However, we also know of non-seismic phenomena, which precede large earthquakes. Some of them have been reported for centuries, even millennia. The list is long and diverse: bulging of the Earth's surface, changing well water levels, ground-hugging fog, low frequency electromagnetic emission, earthquake lights from ridges and mountain tops, magnetic field anomalies up to 0.5% of the Earth's dipole field, temperature anomalies by several degrees over wide areas as seen in satellite images, changes in the plasma density of the ionosphere, and strange animal behavior. Because it seems nearly impossible to imagine that such diverse phenomena could have a common physical cause, there is great confusion and even greater controversy. This explains why reports on non-seismic pre-earthquake phenomena are regarded with suspicion in the scientific community. This may change with the recent discovery that igneous and metamorphic rocks, which make up a major portion of the Earth's crust, contain electric charge carriers, which have been overlooked in the past. These charge carriers are defect electrons in the valence band, i.e., positive holes. Under normal conditions they are dormant, but when they "wake up", the rocks begin to sparkle and glow. This paper describes the physical and chemical nature of these positive holes, how they are introduced into minerals and rocks, and how they become activated. Evidence will be presented that, once the positive holes are generated, currents propagate through the rocks leading to electromagnetic emission, to positive surface potentials, to corona discharges, to positive ion emission, and to mid-infrared radiation. These phenomena are expressions of the same fundamental process: the "awakening" of dormant positive hole charge carriers that turn rocks momentarily into p-type semiconductors.

Keywords: earthquakes — pre-earthquake phenomena — earthquake prediction — defects in minerals — positive holes — ground currents — ground potentials — corona discharges — ion emission — electromagnetic emissions — magnetic anomalies — earthquake lights — thermal anomalies — ionosphere

Introduction

This paper addresses non-seismic pre-earthquake phenomena. Such phenomena have been reported for centuries and from every tectonically active region of the world. Some have been well documented by decades of painstakingly detailed fieldwork. These non-seismic phenomena include observations as diverse as changing well water levels, ground-hugging fog, earthquake lights from ridges and mountain tops, low frequency electromagnetic emission, local magnetic field anomalies up to 0.5% of the Earth's dipole field, temperature anomalies by several degrees over wide areas as seen in satellite images, changes in the elevation of the Earth's surface, changes in the plasma density of the ionosphere, and—most enigmatic of all—strange animal behavior and possible human premonition of impending earthquakes (Tributsch, 1983). Some of these observations are part of mainstream science, such as changes in elevation and lateral movements of sections of the Earth's crust, studied by geodesic methods using satellite data and other techniques. Others are still considered enigmatic and controversial (Geller, 1997; Turcotte, 1991).

Three reasons can be identified why many in the geophysical community remain deeply skeptical towards most non-seismic pre-earthquake phenomena:

(i) The reported phenomena are so varied that it is hard to believe that they could be correlated or caused by any one known process taking place in the Earth's crust;
(ii) While some earthquakes produce recognizable non-seismic precursory phenomena, others of similar magnitude and similar geological settings fail to produce them;
(iii) There seem to be no physical processes that could satisfactorily explain any one of the more enigmatic precursory phenomena, let alone their whole suite.

It is not the intent of this paper to review the range of non-seismic pre-earthquake phenomena, how difficult it is to observe them, and how efforts to find acceptable physical explanations have been frustrated in the past. These issues have been treated in some excellent papers and books (Gokhberg et al., 1995; Johnston, 1997; Sornette, 1999; Wyss & Dmowska, 1997). The approach taken here is different. We begin by accepting the notion that if phenomena have been reported so many times by a wide range of observers across centuries and from different parts of the world, they must hold some truth. If we cannot offer a good physical explanation, the reason could be that we still lack basic knowledge about the processes which underlie these phenomena.

We start with the question: What are the most fundamental physical processes that take place in the Earth's crust during the pre-earthquake period? As Alfred Wegener proposed early in the 1910s and 1920s (Wegener, 1966) and as mainstream geoscience finally accepted in the 1960s, the plates that form the Earth's surface are in constant motion. They shift relative to each other. They separate or collide or slide past each other. The plate movements are driven by convections in the Earth's mantle, which may originate deep at the mantle-core boundary or at shallower boundary layers marked by discontinuities in the density of the rocks. The forces that derive from these convections act slowly but inextricably. The movements lead to stress wherever plates collide or rub against each other. As a result the rocks either yield or break. When they break, they suddenly release accumulated mechanical energy, causing large volumes of rock to jerk relative to each other along fault planes. This process converts stress energy into seismic waves that radiate from the fault plane and cause earthquakes.

Table 1 conveys the order of magnitude of the seismic energy released during earthquakes, compared to the energy released during explosions of TNT or Hiroshima-class nuclear bombs. Though large, the seismic energy radiated during catastrophic rock failure represents only a fraction of the total energy. A large portion goes into frictional heating of the rocks along the fault or may be converted into potential energy when tens of thousands of cubic kilometers of rocks are thrust upward, with displacements reaching at times several meters.

Another point is to be made regarding the distribution of the mechanical energy building up prior to an earthquake. It is physically unreasonable to presume that the stress energy, accumulated through the relative motion of two plates, would be released all at once during the moment of the earthquake. Some processes must take place before catastrophic failure, processes which channel or leak some of the stress energy into other, non-seismic processes. The question then becomes:

- What are these leakage channels?
- What physical effects do they produce?
- Do they cause recognizable precursory signals?

For this we look at the various processes that take place in the Earth's crust while the tectonic forces push or rub large volumes of rock against each other.

In the upper portions of the crust, where temperatures are moderate, generally not higher than 300–400°C, rocks tend to behave as brittle bodies, especially when dry or nearly dry. When one block of rock is pushed at a constant speed against another one, both deform. Starting from zero stress, the deformation will at first be elastic, as shown by the solid linear section of the stress-strain curve in Figure 1. An elastic response means that, if the pushing forces were removed, the brittle body would return to its original shape. When the range of elastic deformation is exhausted, plastic deformation sets in, as indicated by the non-linear response.

On the scale of the individual mineral grains, which make up rocks, plastic deformation means that dislocations are generated and begin to move. Dislocations are linear defects in crystals where the lattice on one side is slightly off-set with respect to the lattice on the other side, for instance by one half or one quarter the distance between atoms or ions on regular lattice positions. Dislocations typically move by a process in which one atom or ion at a time jumps a short distance from one side to the other side. This "zipper-like" motion allows dislocations to move without the need to overcome very high activation energy barriers. As dislocations "sweep" or "climb" through the

TABLE 1
Comparison Between the Seismic Energies Released During Earthquakes With Tons of TNT and Nuclear Bombs Equivalent

Earthquake magnitude [M]	Energy [erg]	Energy [tons TNT]	No. Hiroshima nuclear bombs
4.0	6.3×10^{17}	15	0.001
4.5	3.6×10^{18}	85	0.006
5.0	2.0×10^{19}	480	0.03
5.5	1.1×10^{20}	2,630	0.2
6.0	6.3×10^{20}	15,000	1
6.5	3.6×10^{21}	86,000	6
7.0	2.0×10^{22}	478,000	30
7.5	1.1×10^{23}	2,640,000	200
8.0	6.3×10^{23}	15,000,000	1,000
8.5	3.6×10^{24}	86,000,000	6,000
9.0	2.0×10^{25}	480,000,000	30,000

mineral structures, the crystals respond by changing their shape permanently (Miguel et al., 2001).

The plastic flow, made possible through the generation and ‘‘climbing’’ of dislocations, must eventually come to an end because, at high densities, dislocations tend to become entangled and locked. The next phase—still on a scale of atoms and individual mineral grains—involves the coalescence of dislocations. The microcracks thus formed grow to larger cracks, which in turn coalesce into fissures. Because microcracks and fissures occupy space, the volume of the rock now begins to increase. This is when geodesic methods may detect buckling of the Earth’s surface, indicative of rocks deep underneath entering the phase of volume expansion (Brace et al., 1966; Lockner, 1995; Moore & Lockner, 1995; Tapponier & Brace 1976).

However, under the influence of the tectonic forces that do not relinquish pushing at a constant speed, any brittle system becomes increasingly unstable, as indicated in Figure 1 by the rapidly rising stress-strain curve and its asymptotic approach of infinity. Blocks of rock that enter this phase evolve toward criticality, with the possibility of sudden failure along some segment of a contact or fault as its natural outcome (Ohnaka, 1995; Renshaw & Schulson, 2001). When and where this failure may occur is part of the stochastic guesswork that seismologists have to rely upon when assessing the probability of an earthquake along a certain fault.

Viewed from this perspective, we identify one basic process on the atomic scale, nested between the elastic response and the onset of microcracking and cracking: generation and movement of dislocations. The dotted curve in Figure 1 traces schematically the rate of generation of dislocations dn/dt, where n is the number of dislocations and dt a time interval. Next we ask: What are the consequences when dislocations sweep though mineral grains?

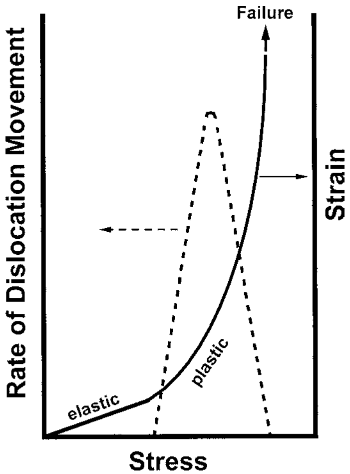


Fig. 1. Stress–strain curve (solid line) of a brittle material undergoing at first elastic, then plastic deformation, leading to failure, and rate of dislocation movement (dashed line).

Electric Charges in Rocks—Where Do They Come From?

Several of the pre-earthquake phenomena listed at the beginning of this paper require as a *sine qua non* condition large electric currents flowing in the ground. Examples are local magnetic field anomalies and low frequency electromagnetic (EM) emissions, both of which have been documented beyond reasonable doubt prior to a number of well-studied earthquakes (Akinaga et al., 2001; Draganov et al., 1991; Fraser-Smith, 1992; Ohta et al., 2001; Parrot, 1994; Serebryakova et al., 1992). When local magnetic field anomalies occur during the weeks or days prior to a seismic event, they require electric currents of considerable magnitude. Obviously these currents did not flow before. Their generation is linked to the earthquake preparation process, but how this process works has remained a mystery. Likewise, if EM emissions are recorded from an area where an earthquake will occur, electric currents are required that vary with time.

Given this suspected linkage between the observed signals and the inferred currents we postulate that the generation of the electric currents is linked to the mechanical processes at depth, when rocks are subjected to ever-increasing stress, causing dislocations to form and to move.

For decades the attention of many researchers who take an interest in pre-earthquake phenomena has indeed focused on the generation of electric currents in the Earth's crust. Of all processes that have been discussed, two candidates have emerged with a physically well-understood mechanism of charge generation and separation. These are piezoelectricity and streaming potentials.

(i) Piezoelectricity describes a fundamental property of certain crystals that belong to non-centrosymmetric symmetry classes (Bishop, 1981; Finkelstein et al., 1973). Of all naturally occurring, rock-forming minerals, only quartz falls into this category. Quartz crystals, when squeezed in certain crystallographic directions, generate ± voltages on opposite surfaces due to minute displacements of their ions relative to each other along a polar axis. Within the validity of Hooke's law, i.e., within the range of elastic response, the voltages are proportional to the applied stress. When the stresses are high, the voltages generated can be large enough to draw sparks. This finds applications in household appliances, for instance in the ignition of gas-burning stoves. Conversely, if voltages are applied to quartz plates cut along certain crystallographic directions, via electrodes deposited on opposite faces, the crystals change their dimension. They become thinner or thicker depending upon the polarity of the applied electric field. This finds application in electronic devices such as quartz clocks, where the frequency of the applied electric field is tuned to the thickness of the quartz plates so that the quartz crystals go into resonant oscillations. In rocks such as granites, which contain a high percentage of quartz, the application of stress will of course lead to piezoelectric voltages on each individual quartz crystal. If the crystals are randomly oriented (which they normally are in batholitic rocks), the local piezoelectric voltages will cancel so that no long-range electric field is generated.

(ii) Streaming potentials describe the fact that, when fluids forcibly move through narrow openings and long capillaries of a porous body, there are always some electric charges, which adsorb on the walls of the flow channels. The fluid retains charges of opposite sign to those that have been absorbed by the walls. As it moves on, charge separation takes place (Bernabé, 1998; Revil et al., 1999). In highly insulating fluids such as transformer oil or aircraft fuel, which are pumped through long narrow conduits, streaming potentials can generate very high voltages that can cause sparks with disastrous consequences (Oommen, 1988). In natural systems, in porous rocks through which water or brines forcibly flow along a pressure gradient, the voltages that build up as a result of streaming potentials are limited by the inherent ionic conductivity. At concentrations of dissolved salts as commonly encountered in aqueous pore fluids, the maximum voltages may be as low as a few millivolts over distances as large as a kilometer (Jouniaux et al., 2000; Morgan et al., 1989; Morrison et al., 1989).

Even though simple laws of physics limit the usefulness of piezoelectricity and streaming potentials as a mechanism to generate large currents in the ground, both processes have been widely invoked to explain EM emissions and magnetic anomalies before earthquakes. Unfortunately, neither piezoelectricity nor streaming potentials stand up to scrutiny, unless boundary conditions are allowed to exist, which are generally thought to be quite unrealistic. Therefore, some other processes have been considered, such as triboelectricity, which is loosely used to describe any form of electrification during fracture (Balbachan & Parkhomenko, 1983; Iwamatsu, 1986; Molchanov & Hayakawa, 1998).

Thus we are faced with a conundrum: There seems to be no *bona fide* physical process by which electric currents, i.e., currents of sufficient magnitude, could be generated in crustal rocks.

Electrical Conductivity of Rocks

At this point it is advisable to revisit the question of electrical conductivity of minerals and rocks. Oxide and silicate minerals that make up the bulk of the igneous and high-grade metamorphic rocks in the Earth's crust are mostly good insulators. Except for sulfide minerals, which are often quite conductive, the only oxide mineral that shows an appreciable electronic conductivity is magnetite, Fe_3O_4. In magnetite, Fe^{2+} and Fe^{3+} alternate on neighboring sites, allowing for Fe^{2+}/Fe^{3+} valency fluctuations to delocalize over the cation sublattice and to thus conduct electricity (Dieckmann, 1986; Stacey & Johnston, 1972). All other rock-forming minerals, including silicate minerals that are rich in transition metals in different oxidation states, are non-conductors. If the minerals do not conduct electricity, the rocks, which they form, must also be considered good insulators, at least as long as they are dry.

There are only a limited number of publications on the electrical conductivity of minerals and rocks coming from a relatively small group of dedicated researchers who have built their careers around such laboratory measurements. They have determined that the only significant electrical conductivity in minerals and rocks is caused by ionic conductivity. For ions to contribute to the transport phenomena, however, high temperatures are needed. For instance, in MgO, which can serve as a model, ionic conductivity is dominated by Mg^{2+} cations hopping into Mg^{2+} vacancies, and this process sets in at around 700°C. In olivine, $(Mg,Fe)_2SiO_4$, the onset of conductivity is placed between 700 and 800°C. Any conductivity below this temperature range is thought to be due to adventitious "dirt" or to mysterious carbon films on the surface of samples (Constable & Duba, 1990; Schock et al., 1989; Wanamaker & Duba, 1993). Likewise for rocks, conductivity is believed to be essentially nil until the temperature reaches high enough values to lead to partial melting, at least along the grain boundaries (Roberts et al., 1999). Once partial melt forms, with or without participation of water, ionic conductivity becomes great (Hermance, 1979; Matsushima, 1989). If enhanced conductivity is observed at lower temperatures, it is dismissed as being due to either insufficient drying or to intergranular carbon films (Constable & Duba, 1990; Roberts et al., 1999; Shankland et al., 1997).

Given that this published information comes from respected laboratories where the electrical conductivity of minerals and rocks has been routinely measured for decades, those in the geoscience community who tried to understand earthquake-related electrical phenomena were faced with a dilemma.

Based on the reported laboratory results of electrical measurements, no mechanism seemed to exist that could account for the generation of those large currents in the Earth's crust, which are needed to explain the strong EM signals and magnetic anomalies that have been documented before some earthquakes. Therefore, the only available alternatives were piezoelectric effects and streaming potentials. However, as most researchers acknowledge upon closer scrutiny, piezoelectricity and streaming potentials are inadequate in more than one respect to generate large currents in crustal rocks. This led to an irreconcilable conflict between field observations and our capability to provide a physically meaningful and substantiated explanation.

Unfortunately, when a set of observations cannot be explained within the framework of existing knowledge, the tendency is not to believe the observation. Therefore, a general *malaise* has taken root in the geophysical community when it comes to the many reported non-seismic and non-geodesic pre-earthquake phenomena.

Imperfectly Designed Electrical Conductivity Measurements

Here we take a different approach. Instead of accepting "existing knowledge", we raise the question whether the experiments, on which such "existing knowledge" has been built over the course of decades, may have been performed inadequately and may have therefore led to "wrong" results. These "wrong" results then became part of mainstream science. To substantiate our point we take a closer look at the way electrical conductivity experiments of minerals and rocks are routinely performed.

Figure 2 depicts typical sample configurations used in electrical conductivity experiments of poorly conducting single crystals. First, samples are prepared with well-defined and clean surfaces. The goal is to measure the electrical conductivity through the bulk. The simplest configuration shown in Figure 2a is rarely or never used, because currents that flow along the surface of the sample tend to overwhelm those that flow through the bulk. As a remedy against this "dirt" effect, a guard electrode is applied as shown in Figure 2b. Its function is to ground any undesirable surface current.

The literature on electrical conductivity measurements of minerals and highly insulating oxide materials like MgO is replete with cryptic hints regarding how difficult it is to properly eliminate surface conductivity. These hints are usually buried in the section where the sample preparation is described. For instance, the authors may state that the mere application of a guard electrode was not enough to eliminate surface conductivity, implying that the assumed layer of "dirt" on the sample surface continues beneath the guard, causing leak currents. To overcome this problem the researchers routinely resort to prolonged high temperature treatments, for instance in vacuum for MgO or in reduced CO/CO_2 gas mixtures for olivine and other minerals, which come from crustal or the upper mantle environments that are naturally reduced (Constable & Duba, 1990). Seldom is

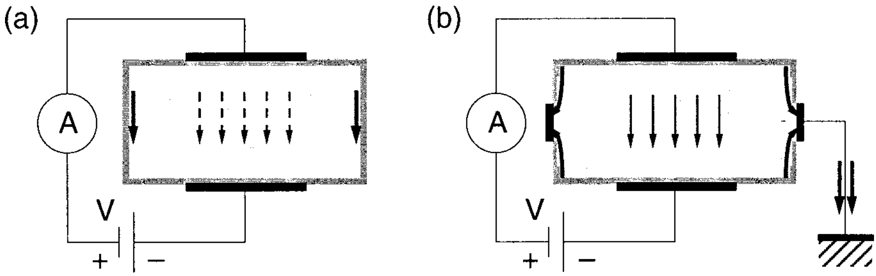


Fig. 2. Sample-electrode arrangements for electrical conductivity experiments. (a) Two electrodes. (b) Two electrodes plus guard electrode to drain surface conductivity to ground.

there any detailed description of how exactly the conditioning of the sample at high temperatures was done, though the procedure can often be gleaned from the context: samples are nearly always subjected to high temperatures for a long time, long enough to make sure that the unwarranted surface conductivity is reduced by orders of magnitude or is eliminated.

Of course, such any prolonged high temperature pretreatment is done with the best intentions. The aim of the researchers is to achieve conditions under which a given sample exhibits a reproducible conductivity response to start with and can subsequently be subjected to controlled conditions, most commonly different oxygen partial pressures or fugacities. Measurements performed under such conditions then provide insight into the ionic conductivity. The underlying rationale is that ionic conductivity is the only conductivity mechanism that counts (Ballhaus et al., 1990; Duba et al., 1974; Ryerson et al., 1989).

A question that seems to have never been asked is: Could it be that the enhanced surface conductivity at moderately high temperatures, before the onset of ionic conductivity in essentially all oxide and silicate materials, both in laboratory-grown single crystals and natural minerals and rocks, is not really a "dirt" effect? Maybe the experiments that have been designed to annihilate this so-called "dirt" conductivity destroyed an important piece of information that is germane to the samples under study? Maybe the long-sought answer lies in this lost information?

Enhanced Surface Conductivity Is Not a Dirt Effect

The very first hint that there is something weird about oxide materials was obtained in the mid-1970s through a study of finely divided MgO, which had been prepared by thermally decomposing ultra–high purity $Mg(OH)_2$ (Martens et al., 1976). Residual hydroxyl anions, OH^-, which became trapped in the MgO crystallites as they formed from the collapsing $Mg(OH)_2$ structure, did not combine to split off water as expected, $2\ OH^- = O^{2-} + H_2O$, but rather yielded H_2 molecules instead. The amount of H_2 released from these MgO samples was astounding, of the order of 1–2% relative to the number of O^{2-} in the system. Since the MgO used in these experiments was of ultra-high purity, with less than 5×10^{-6} (5 ppm) cation impurities, the evolution of H_2 could only be understood, if we assumed that the oxygen in its prevailing 2-oxidation state had provided the electrons needed to reduce two protons to hydrogen molecules: $2\,H^+ + 2\,e^- = H_2$. This led to the formulation of a reaction, $2\,OH^- = O_2^{2-} + H_2$, with two oxygens changing from the 2- to the 1-oxidation state and subsequently forming an O^-–O^- bond known as a peroxy bond.

Such a reaction belongs to the group of redox conversions, in the course of which reaction partners exchange electrons in such a way that one partner becomes reduced, while the other becomes oxidized. What was unusual about the proposed conversion of OH^- pairs to peroxy plus molecular H_2 was that oxygen had to act as the electron donor. Oxygen, however, is known not to donate easily an electron to a proton. In fact, an electron transfer from oxygen normally takes a relatively large amount of energy. This is borne out by the fact that one of the glorious "inventions" of Life is oxygenic photosynthesis, where an H_2O molecule is split into its components H plus O through an intricately complex biochemical reaction pathway, with the help of sunlight.

At first, the observation of H_2 coming off finely divided MgO during the decomposition of $Mg(OH)_2$ was thought to be an oddity, of interest only to understanding catalytic reactions (Martens et al., 1976). By the early 1980s, however, it had become clear that the same redox conversion takes place in MgO single crystals grown from an H_2O-laden melt, which retained some dissolved water in the form of OH^- (Freund & Wengeler, 1982). It was also noted that the presence of oxygen in 1- oxidation state in the matrix of MgO had a profound effect on the electrical conductivity of MgO single crystals (Kathrein & Freund, 1983). Further studies indicated that this redox conversion is not limited to MgO. The same type of *in situ* redox conversion also takes place in other crystals, including silicate minerals that crystallized in H_2O-laden environments, where the O^-–O^- bond of the peroxy anion in MgO would have to be replaced by a peroxy link of the type $O_3Si/^{OO}\backslash SiO_3$ (Freund, 1987). The ubiquity of this reaction is due to the fact that any oxide or silicate mineral crystallizing in an H_2O-laden environment is bound to incorporate small amounts of H_2O in the form of OH^-. Apparently, wherever OH^- pairs exist in these mineral matrices, the stage is set for this unusual redox conversion. This, however, implies that minerals in any terrestrial igneous and high-grade metamorphic rocks will contain at least a fraction of their oxygen anions in the -1 oxidation state, presumably in the form of peroxy bonds in their crystal structures.

Valency Fluctuations on the Oxygen Sublattice

In essence, an O^- in a matrix of O^{2-} represents a defect electron or "hole" that resides in the O 2p-dominated valence band, also known as a positive hole or p-hole for short. As long as the peroxy bonds remain intact, the p-holes are self-trapped, immobilized in the MgO matrix and, hence, do not contribute to the electrical conductivity. In order to make such a contribution, the O^{-}–O^{-} bonds or $O_3Si/^{OO}\backslash SiO_3$ links have to be broken. To underline the semiconductor aspect of our approach we designate the intact O^{-}–O^{-} bond or $O_3Si/^{OO}\backslash SiO_3$ link as "positive hole pair", or PHP.

A major step towards a better understanding of p-holes in an otherwise insulating material like MgO was brought about by a theoretical analysis from a semiconductor viewpoint (King & Freund, 1984). The result most directly relevant to our discussion of the contribution to the electrical conductivity was that when p-holes are activated in a medium with a dielectric constant ε_{sample} surrounded by a medium of a lower dielectric constant $\varepsilon_0 = 1$ as vacuum or $\varepsilon_0 \approx 1$, such as air, they will redistribute in such a way as to form a thin surface charge layer.

This theoretical prediction allowed us to approach the question of enhanced surface conductivity from an entirely new perspective. Instead of treating enhanced surface conductivity as a "dirt" effect, which has to be eliminated before any meaningful conductivity measurements can be made, it now appeared that this annoying surface conductivity might in fact be an integral part of the minerals and rocks under study. Suddenly both the surface charge layer and enhanced surface conductivity were consequences of the way conductivity experiments are carried out and, in fact, have to be carried out in the laboratory. Indeed, in order to measure the conductivity of any mineral or rock in the laboratory, it is necessary to remove the samples from their environments, i.e., from the medium of the same dielectric constant ε_{sample}, in which they had resided within the Earth. The samples are then placed in a medium with a lower dielectric constant, vacuum with $\varepsilon_0 = 1$ or air with $\varepsilon_0 \approx 1$. Under these conditions, once activated, the p-holes are bound to come to the surface and form a surface charge layer. This must create problems for conductivity experiments. Vexing as this may be, we have to recognize that the p-holes and their enhanced surface conductivity contribution are an integral part of the minerals or rocks under study, and to annihilate them through extended high temperature pretreatment, as has been routinely done for decades in all conductivity measurements, alters the samples in a significant way.

By the late 1980s we had developed a new technique, Charge Distribution Analysis (CDA), based on measuring the dielectric polarization in an electric field gradient of reversible polarity, contact-free, under minimum perturbation conditions (Freund et al., 1989). CDA enabled us for the first time to "see" positive charge layers appearing on the surfaces of otherwise insulating dielectric materials when PHPs start to dissociate and to inject p-holes into the valence band. By the mid-1990s we had combined CDA with electrical conductivity, magnetic susceptibility, thermal expansion, and refractive index measurements of MgO, each technique shedding light on a different aspect of the thermally induced dissociation of lattice-bound PHPs and on the concomitant generation of p-hole charge carriers (Freund et al., 1993, 1994).

When CDA was applied to olivine, evidence was obtained that olivine crystals from the upper mantle also contained PHPs. Upon heating olivine crystals, PHPs in their structure generated p-holes under almost the same conditions as in MgO. Hence, these p-holes were expected to influence the electrical conductivity of olivine in a similar way as they had done in MgO. Other minerals, such as feldspars and garnet, or rocks from various environments, such as dunite, andesite and diorite, exhibited a similar CDA response indicative of p-hole charge carriers.

There was sufficient indication to make the rather sweeping statement that PHPs are probably present in most if not all minerals and rocks from igneous or high-grade metamorphic environments that crystallized from H_2O-laden environments. Publishing such observations and their implied consequences in the mainstream geoscience journals, however, proved difficult. The reviewers argued that because PHPs are, chemically speaking, peroxy entities and, hence, highly oxidized, they should not exist in any mineral or rock from a reducing environment. This argument is, of course, fallacious because it presupposes thermodynamic equilibrium conditions. The redox conversion of OH^- pairs to O^-–O^- plus H_2 takes place during cooling in a temperature range, around 400–500°C, where thermodynamic equilibrium with respect to major structural adjustments can no longer be achieved and conditions can be sustained in minerals that are in a metastable equilibrium state (Freund, 2002b).

Waking Up p-Holes With a Bang

Whereas all electrical conductivity and CDA measurements mentioned so far were done as a function of temperature, i.e., by heating the samples, there was one experiment which suggested that PHPs may also be activated by other means. Upon fracturing MgO crystals in front of a fast mass spectrometer we noted the rapid evolution of atomic oxygen from the fracture surface, within μsec, followed by an evaporation of Mg atoms, which lasted up to 300 msec (Dickinson et al., 1986, 1987). To understand these observations we had to assume that PHPs were activated by the sharp, intense acoustic wave, which the brittle fracture generated. The p-holes thus released came to the surface and disproportionated: $O^- + O^- = O^{2-} + O$. Once the outermost layer of oxygen was lost, the exposed Mg^{2+} apparently took over electrons from additional O^- arriving at the surface: $2\ O^- + Mg^{2+} = 2\ O^{2-} + Mg$.

Realizing that PHPs can apparently be activated by a passing acoustic wave suggested that the activation involved straining or bending the O^-–O^- bond or $O_3Si/^{OO}\backslash SiO_3$ link. If this was true, any process that causes the O^-–O^- bond or $O_3Si/^{OO}\backslash SiO_3$ link to bend or "wiggle" could potentially break the coupling and liberate p-holes.

The first series of experiments to pursue this idea involved impact experiments on rocks. A bullet that hits a target rock sets the clock, at which time the process begins. It allowed the appearance of p-hole charge carriers to be studied as a function of time. Two velocity ranges were used: low velocities of the order of 100 m/sec with 3.2–6.3-mm stainless steel spheres, impacting in air, and medium velocities of the order of 1.5 km/sec with 6.3-mm aluminum spheres, impacting in vacuum (Freund, 2000, 2002a).

In both cases the rock samples were instrumented in ways as to take into account the peculiar properties of p-holes. This required the use of capacitive sensors to "see" the arrival of a p-hole charge cloud at the sample surface, the installation of induction coils to pick up any EM emission from the propagating charge carriers, and contact electrodes to control the injection of electrons from ground in response to the positive charge build-up at the surface. In addition, in the case of the low-velocity impact experiments, photodiodes were installed to detect any light emission from the rock upon impact and subsequently, when the p-hole charge clouds reached the surface.

The idea for deploying photodiodes came from the theoretical study (King & Freund, 1984), which had suggested that for a dielectric with $\varepsilon_{sample} = 10$, the potential would be positive and reach values around 400 mV on a flat surface bordering vacuum with $\varepsilon = 1$. According to this analysis, the surface charge layers would be very thin, on the order of 10–100 nm depending upon the concentration of p-holes. Thus, very high electric fields were expected to result at the rock–air interface, of the order of 400,000 V/cm. Such high fields are enough to cause dielectric breakdown of the air, in particular at edges and corners. This led to the prediction that when p-hole charge clouds arrive at the sample surface, closed-loop corona discharges may occur from the edges to the flat surface, and this prediction led to the installation of the photodiodes.

Figure 3a shows an example of a rock cylinder instrumented with a ring capacitive sensor near the front and a plate capacitor at the end, plus a photodiode to monitor the front face where the impact occurs. The oscilloscope trace for the photodiode (lower curve) shows the small triboluminescence blip that marks the impact. About 100 μsec after impact, the ring capacitor near the front (upper curve) indicates the build-up of a positive charge. About 50 μsec later, the plate capacitor at the end (middle curve) responds to the arrival of a positive charge. As the potential recorded by the ring capacitor reaches values around 400 mV, the photodiode recorded a major flash (lower curve), which separate experiments showed had come from the outer rim of the rock.

Figure 3b depicts schematically what happens after the projectile hits the front face of the rock. Because the energy deposited into the rock is relatively small, p-hole charge carriers are activated only in a small volume near the impact point. From there they spread along the axis of the cylindrical rock sample, arriving successively at the capacitive sensors after 100–200 μsec. This is consistent with the expectations formulated above: the "wakening up" of p-holes upon impact and their propagation through the rock at high speed. In addition, the build-up of a positive surface charge of a magnitude close to or exceeding the calculated value, 400 mV, leads to a corona discharge from the rim of the rock, seen as a flash of light. From the time the charge cloud takes to

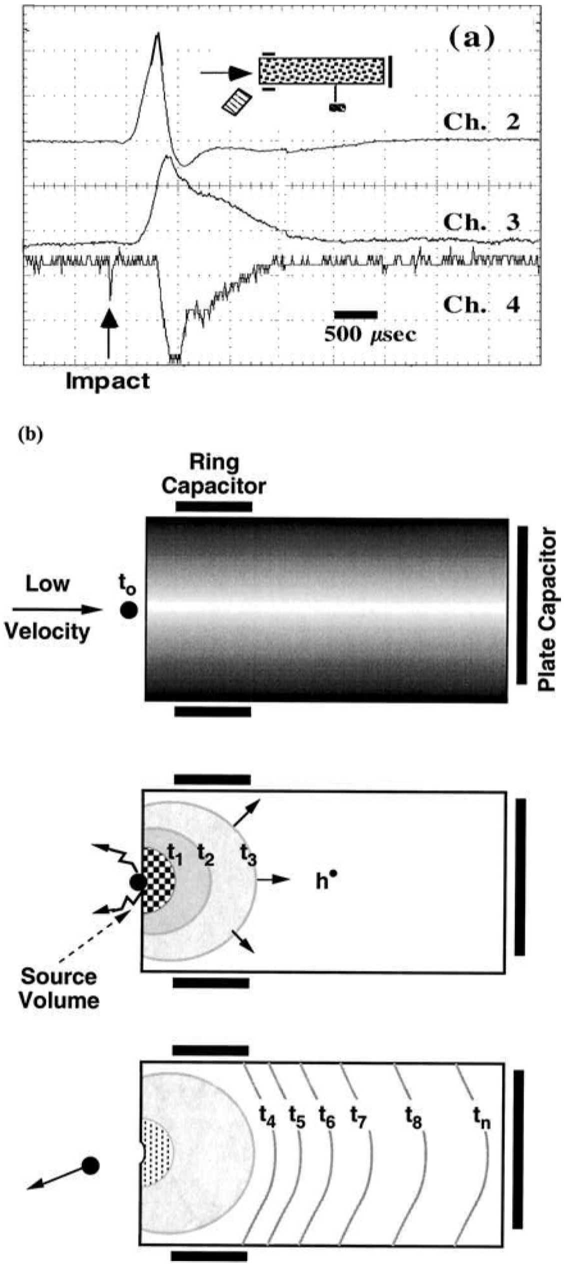
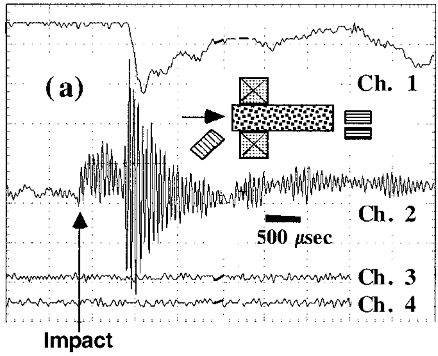


Fig. 3. (a) Low-velocity impact experiments showing in channel 4 the small light signal at the impact, due to triboluminescence, in channel 2 the arrival of the positive charge at the front end ring capacitive sensor, in channel 3 the slightly later arrival of the charge at the back end plate capacitive sensor, and in channel 4 a delayed flash of light. (b) Schematic representation of the generation of positive charges in a small source volume near the impact point and their propagation along the cylinder axis of the rock sample.



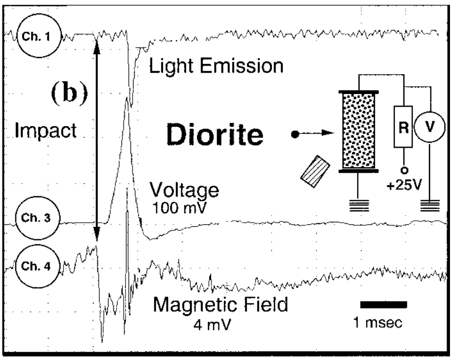


Fig. 4. (a) Low-velocity impact experiments illustrating the EM emission at the time of impact and later, when the flash occurs. (b) Set-up to show that the rock becomes conductive as the p-hole charge cloud propagates from the point of impact into the rock volume.

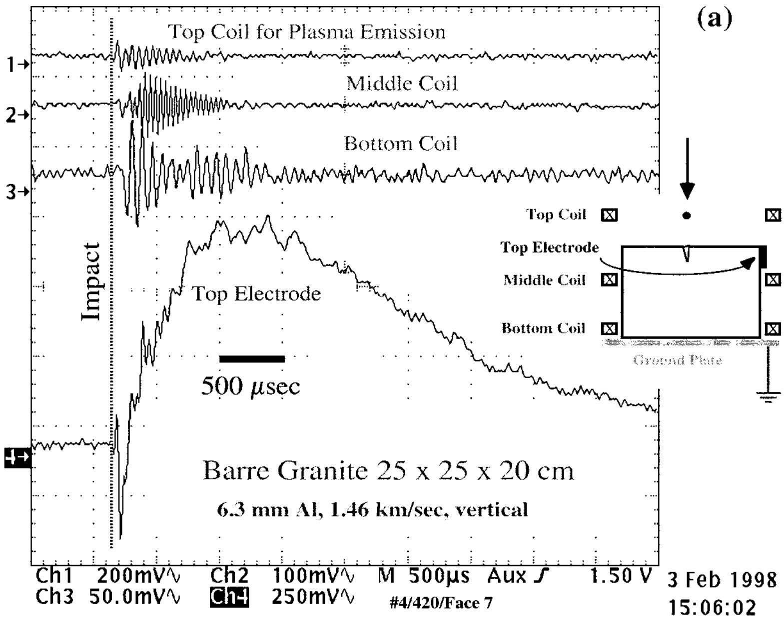
reach the capacitive sensors, the speed of the p-holes can be obtained. The values range between 100 and 300 m/sec (Freund, 2000, 2002a). We can compare the measured speed with the maximum speed allowed by theory. The propagation of a p-hole through an O^{2-} matrix involves electron transfer from O^{2-} to O^{-}. The electron jumps can maximally occur at the frequency of thermally activated lattice phonons, of the order of 10^{12} Hz. Therefore, with the jump distance between neighboring oxygen positions being on the order of 3 **Å**, the speed with which a p-hole can be expected to propagate through a matrix of O^{2-} at 100–300 m/sec. This estimate is in agreement with the experimentally observed values.

Figure 4a shows another example from the same series of experiments where a magnetic pick-up coil recorded a high-frequency EM emission upon impact and an EM spike at the onset of the flash. The coincidence between the flash and the spike in the EM emission confirms that the light comes from a corona discharge from the front of the rock. Two photodiodes looking at the far end of the rock, at the flat face and the rim, did not record any flash in this particular experiments but did so in other similar ones (Freund, 2000, 2002a).

Figure 4b shows a variation of the experimental conditions. In this case a rectangular piece of diorite, a low–quartz igneous rock, measuring 10 × 10 × 40 mm, was impacted from the side, while 25 V were applied to gold electrodes, vapor-deposited on the end faces. A photodiode monitored the light emission, and a magnetic pick-up coil (not shown) monitored the EM emission. The current flowing through the rock was measured by means of the voltage drop across a 2.4 MΩ resistance. As the oscilloscope traces show, the moment of impact is marked by the sudden onset of the EM emission. About 150 μsec later, a current begins to flow through the rock, indicating that it has suddenly become conductive. As the current rises, a flash of light is emitted, accompanied by a sharp spike in the EM emission, indicating a corona discharge. Instantly the current breaks down and even reverses, and this reaction is followed by a weak oscillation that lasts for several msec.

Figure 5a and b show what happens when a 25 × 25 × 20–cm granite block is impacted in vacuum by a 6.3-mm Al sphere at 1.5 km/sec. A total of 8 sensors were installed. Three magnetic pick-up coils were used to record (i) the EM emission from the plasma plume that rises from the rock surface after impact, (ii) the propagation of acoustic waves and charge waves at mid-height and (iii) near the bottom. Three capacitive sensors on one side of the block recorded the surface charge appearing near the top, at mid-height and near the bottom. Two contact electrodes on the opposite side of the block, near the top and near the bottom, recorded the electric current flowing into the rock from ground.

As discussed in greater detail elsewhere (Freund, 2000, 2002a), these medium-velocity impacts showed that the propagation of the seismic P and S waves (at velocities around 6 and 3 km/sec, respectively) can be seen through the piezoelectric response of quartz, a major component in the granite. Even the reflection of the P and S waves from the bottom of the block could be discerned. After the P and S waves had died down within about 200 μsec after impact, a pervasive cloud of positive charges arrived at the surface of the rock, as recorded by the capacitive sensors. The speed with which this charge builds up is consistent with the speed of propagation of p-holes, 100–300 m/sec, assuming that the passage of the intense P and S waves had activated the PHPs throughout the rock volume. The p-holes thus released spread to the surface, i.e., to the rock-vacuum or rock-air interface. There the surface charge builds up, reaching values that apparently far exceed 400 mV. As a result electrons are injected from ground through the contact electrodes. The electron injection causes the positive electric field recorded by the capacitive sensors to collapse. This in turn momentarily shuts off the electron injection. As long as the p-holes continue to propagate from within the bulk to the surface, the surface charge recovers. This causes the system to oscillate. Within 1–2 msec, however, the p-holes reach their steady state distribution between surface and bulk. At that point in time the EM emission and oscillations stop, and the surface potentials return to zero.



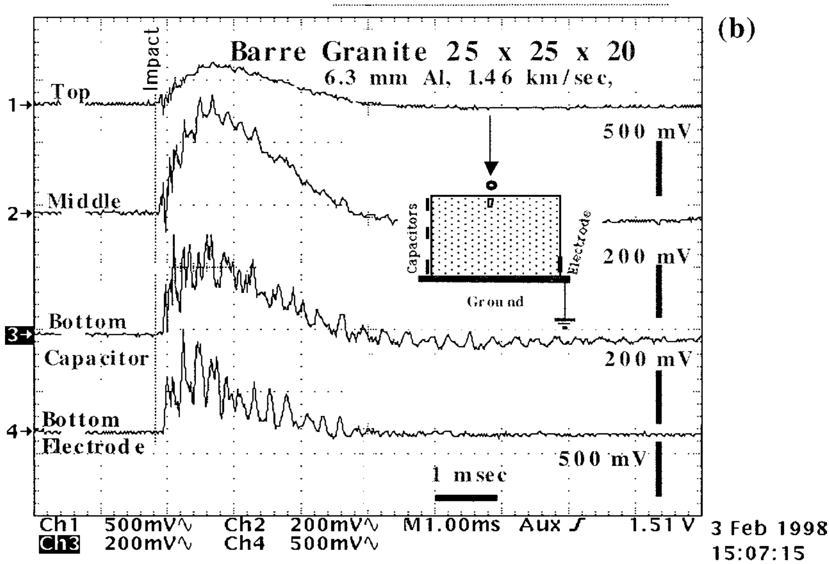


Fig. 5. (a) Medium-velocity impact on granite recorded by means of three magnetic pick-up coils arranged at different height above the block, at mid-height and near the bottom, plus one contact electrode on the opposite face, close to the top. (b) Medium-velocity impact on granite recorded by means of three capacitive sensors arranged at different height on one face of the block and one contact electrode on the opposite face, close to the ground plate.

When we compare the 100 m/sec and 1.5 km/sec impact experiments, the observations are consistent with the notion that by low-velocity impacts, p-holes were activated only in a small volume near the impact point, whereas the medium-velocity impacts had enough "punch" to activate the p-holes in the entire rock volume. The critical parameter seemed to be the amplitude of the acoustic waves, hence the amount of momentary bending or "wiggling" that the PHPs undergo during the passage of these waves.

Squeezing Rocks

Once we understood that O^-–O^- bonds and $O_3Si/^{OO}\backslash SiO_3$ links can be activated by the passage of an acoustic wave, leading to the liberation of p-hole charge carriers, we were one step closer to the central issue of interest here, namely the source of non-seismic pre-earthquake phenomena that require electric currents to be generated in the crust. With this we return to the earlier section in which we introduced the deformation of rocks under high levels of stress.

One way to strain or bend or "wiggle" the O^-–O^- bonds or $O_3Si/^{OO}\backslash SiO_3$ links is to let acoustic waves pass through as we just discussed. Another way is to plastically deform a rock. Most of the plastic deformation occurs by way of dislocations that are generated under high levels of stress and sweep through the mineral grains. Each time a dislocation intersects a PHP, it momentarily tears the O^-–O^- bond or $O_3Si/^{OO}\backslash SiO_3$ link apart and causes it to dissociate. Given the high density of dislocations typically achieved during plastic deformation, of the order of 10^{12}–10^{15} cm^{-2} (linear centimeter per cubic centimeter)(Arias & Joannopoulos, 1994), every PHP in the matrix will have a good chance to become activated. Under these conditions the triangular dn/dt curve in Figure 1, which describes schematically the rate at which dislocations are created or move during plastic deformation, becomes the p-hole generation function. In a simple situation, assuming an initially unstressed volume of crustal rocks that is subjected to compression at a constant speed, p-hole generation will begin at the end of the linear section of the stress–strain curve. The p-hole generation rate is expected to reach a maximum somewhere during plastic flow and to decline, when dislocations begin to coalesce, leading to microcracking and fissuring. Thus, towards the end of the process, before catastrophic failure, the p-hole generation rate should drop.

There is yet another point that deserves attention. Because p-holes represent defect electrons in the valence band of O 2p-dominated oxide/silicate insulators, they propagate through the valence band. This, however, means that they will be able to spread from any place where they are generated to portions of the sample where they are not actively produced. It means that they will flow from one oxide/silicate material to the next. The only requirement is that there is a continuous path of grain–grain contacts along which the valence bands are connected. In some way, the propagation of p-holes through an insulator or an ensemble of mineral grains in a rock resembles the propagation of electrons through metal or through different pieces of metal that are in electric contact.

This concept can be further developed to account for electrical charges generated during rock deformation. We have not yet conducted experiments to measure such currents directly, though such work has been done elsewhere without, however, the benefit of knowing about the p-hole charge carriers (Hadjicontis & Mavromatou, 1994; Morat & Le Mouel, 1987). Taking a different approach, we have tested whether the surface of a rock becomes positively charged under load. The experiment was carried out with a large block of granite, $25 \times 25 \times 13$ cm^3, of which the central portion, a cylinder of 13.5 cm in diameter, was loaded at a constant stress rate. The block was insulated from ground. Its surface potential was measured with an electrometer connected to a capacitive sensor and grounded at a contact electrode through a 2.3 GΩ resistance. Thus, the distance between the location of the capacitive sensor on the rock surface and the stressed inner volume of the block was 7.5–15 cm (Freund et al., 2002).

Figure 6 shows with reference to the left scale how the potential measured on the outer surface of the granite block changes as a function of the load applied to the central portion. As the load builds up, a positive surface potential appears, which increases with increasing load, reaching a value as high as +1.7 V at failure of the rock. The block was also equipped with an ion collector plate, about 500 μm above the rock surface, biased either at −47 V or + 47 V. With reference to the right scale Figure 6 shows the ion current in pA. At positive bias no ion current flows. At negative bias the ion current takes off at a high value of 80 pA and stabilizes around 40–50 pA. The experiment therefore suggests that positive ions are emitted from the rock surface due to the high electric field associated with the positive surface charge layer. The ion emission may involve air molecules that become ionized upon contact with the rock surface, for instance, H_2O transferring an electron to the surface, $H_2O - e^- = H_2O^+$, and then being repelled from the surface by the outermost positive charge layer.

The emission of positive ions from the Earth's surface may also have to do with the observation that, not infrequently, ground-hugging fog or haze occurs prior to earthquake activity or during a sequence of aftershocks (Corliss, 2001). Air-borne ions are known to act as condensation nuclei for droplets and thus would be expected to enhance the fog and haze formation (Byers, 1974).

Though we are only at the beginning of this research, two important points are to be noted from Figure 6: (i) the positive surface charge builds up a distance of around 10 cm from that part of the rock volume that undergoes deformation, and (ii) the electric field associated with this charge layer seems to be so high that ions of positive sign are emitted. Point (i) represents an extension of the CDA experiments mentioned above, where positive charges were shown to appear on the sample surface when the sample was heated. The rock deformation experiments have provided evidence that the positive charges can be activated also through deformation of the rock and that the p-holes propagate outward

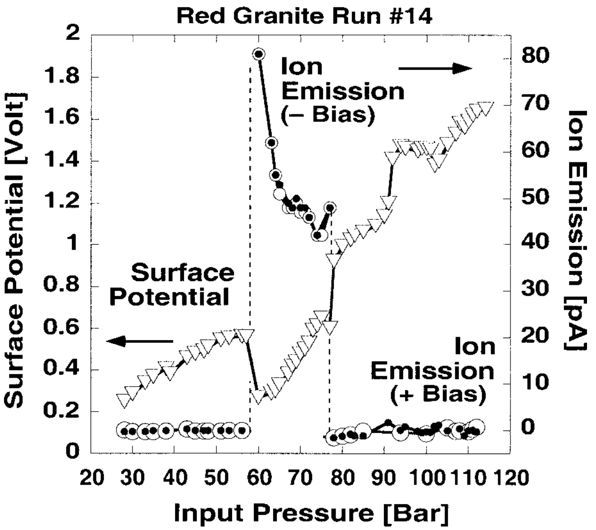


Fig. 6. Surface potential (left scale) and ion emission (right scale) of an "Imperial Red" granite block, measured during deformation of the central portion of the block.

from the volume in which they are generated, flow through unstressed rock, and appear on the outer surface. Point (ii) validates the early theoretical work (King & Freund, 1984), which had indicated that, though the surface potential may only be in the hundreds of mV to 1–2-V range, the associated electric field can reach hundreds of thousands of Volts per centimeter, enough to cause not only field ionization but also dielectric breakdown of the air and, hence, corona discharges.

Thermal Anomalies—A Seemingly Inexplicable Pre-Earthquake Phenomenon

On the basis of satellite infrared thermal images of the Earth's surface, thermal anomalies have been identified that are associated with large linear structures and fault systems in the Earth's crust (Gorny et al., 1988). Sometimes, days before an earthquake, short-lived thermal anomalies develop in the area around the future epicenter, often elongated and measuring tens to hundreds of kilometers, with a positive deviation of 2–3°C. They reportedly begin 5–10 days before and disappear rapidly 1–2 days after the earthquakes (Li et al., 1997; Qian et al., 1996; Qiang et al., 1991, 1999; Tronin, 1999, 2000, 2002).

This increase in the Earth's apparent ground temperature is not understood. It cannot be a true temperature increase of the ground due to heat coming from below. There are at least two reasons why heating from below can be ruled out: (i) from known heat capacity data we can calculate that the energy required to heat by just 1°C such large volumes of rocks, as needed to explain the lateral extent of the observed thermal anomalies, would exceed the total energy released during an M = 7 earthquake; (ii) from known heat conductivity data we can calculate that such large volumes of rock can never heat up by several degrees and cool down again within a few days. Hence, we have to look for other causes.

In the literature the only causes offered to explain the thermal anomalies are warm gases that may be released from faults. To account for the lateral extent of the thermal anomalies and their apparent uniformity it has been assumed that the warm gases spread laterally along the ground or provide conditions creating local greenhouse conditions (Gorny et al., 1988; Tronin, 1996). Such greenhouse conditions would have to affect the entire area that shows the thermal anomaly and be resistant to changing winds and other meteorological conditions.

With the knowledge acquired about p-holes we can propose a very different mechanism. We know that rocks contain PHPs, which release p-hole charge carriers when high levels of stress are applied. We also know that, at least in one granite deformed experimentally in the laboratory, p-holes spread out from the source volume and reach the surface. Could it be that the recombination of p-holes at the surface leads to the emission of infrared light in a wavelength region, which a satellite would register as ‘‘heat’’?

Using a 1500-ton press at the Geophysical Laboratory, Carnegie Institution, and a 256 × 256 array QWIP (Quantum Well Infrared Photodetectors) camera from NASA Goddard Space Flight Center, maximized at 8.3 μm with 0.025 K resolution, we recorded the infrared emission from granite blocks during loading until failure (Freund et al., 2002).

Figure 7 shows how an enhanced infrared emission began above a load of 20 bar, equivalent to about 80 tons on a 9×9–cm^2 face of a $9 \times 9 \times 13$–cm^3 block. The emission came from the flat surface and edges of the rock. It increased with increasing load up to an intensity equivalent to a radiation temperature increase of ~0.5 K at the 4σ level. In other words, we have a 160:1 probability that the effect is real. Upon approaching the point of failure, when audible cracking occurred in the rock, as indicated by the shaded area in Figure 7, the intensity of the infrared emission decreased. Close to failure we observed rapidly evolving bright spots along the edges of the rock, suggesting electric discharges similar to those observed during the low-velocity impact experiments. When we turned the block on its side and loaded only one half, infrared was emitted not only from the surface of that half of the rock, which was undergoing deformation, but also from the surface of the other unloaded half. The distance between the emitting surface and the portion of the rock undergoing deformation was about 5 cm, i.e., much too far to allow heat to diffuse to the surface within the available time of the experiment, on the order of a few minutes.

The observed infrared emission from the surface of the granite is clearly non-thermal. It is definitely not due to an increase of the actual surface temperature. This supports the hypothesis presented here that p-hole charge carriers,

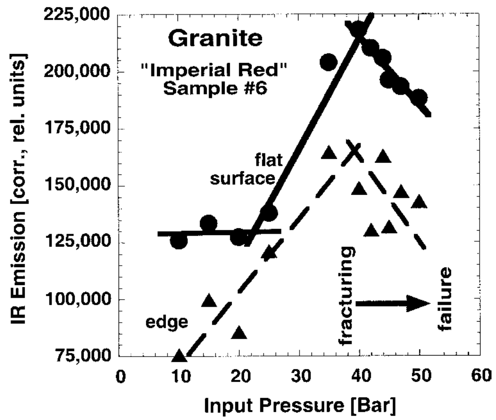


Fig. 7. Infrared emission from the flat surface and the edge of a granite block undergoing deformation, measured with a QWIP camera at 8.5 μm. The observed infrared excess intensity is equivalent to a black body temperature increase of 0.5 K.

generated in the rock during deformation in the core region of the rock, spread through the entire volume and reach the surface, where they recombine with the emission of infrared photons.

Discussion

In the remaining portion of the text I draw with a broad brush an outline of the many interconnected phenomena that can be caused by p-holes. Three basic processes have been identified:

(i) Activation of PHPs in highly stressed rocks and injection of these p-hole charge carriers into the valence bands of the otherwise insulating silicate minerals in rocks.
(ii) Spreading of p-hole charge carriers out of the source volume into the surrounding rocks.
(iii) Arrival of p-hole charge clouds at the Earth's surface.

Process (i), which starts the chain of events, has already been discussed in some detail.

Current Pulses in the Earth's Crust

Process (ii) is equivalent to saying that, if a rock volume becomes a source of p-holes, the outward spreading of the p-holes represents an electric current that flows into the surrounding rocks. Such electric currents are self-limiting. The reason is that any charge, which spreads into the surrounding rocks, sets up an electric field. The polarity of this field is such that it counteracts the outflow of p-hole charges and will eventually stop it. The source volume, which loses p-holes, becomes negatively charged while the surrounding rocks, which acquire p-holes, become positively charged.

The consequence of such a polarization field is that it will initiate a backflow of charges from the surrounding rocks into the source volume such that the polarization field is reduced. Candidates of backflowing charges are protons, H^+, arising from the electrolysis of pore water in the surrounding rocks, or electrons from the pervasive planetary electric ground. We add one more piece of information, still speculative, that the outflow of p-hole charge clouds from a source volume may not be a slow, continuous process but rather a violent one, occurring in the form of a solid state plasma that breaks out of its confinement when the p-hole concentration in the source volume has reached or exceeded a threshold value.

Combining these ideas leads us to the first "broad brush" scenario, illustrated schematically in Figure 8: When a rock volume, here represented by an inclined slab pushed from the right, turns into a source volume for p-holes due to high levels of stress, p-hole charge clouds spread out into the surrounding rocks and initiate a backflow of compensating charges.

Details of this scenario are of course still highly uncertain. We don't know how p-hole charge clouds spread, how their spreading would be modified by the geometry of the source volume and the conductivity of the surrounding rocks, and from where the compensating charges would come that flow back into the source volume. However, we can make some rather sweeping statements, in particular if we admit to the possibility that p-hole charge clouds may spread in the form of a solid state plasma. In this case any outbreak of a p-hole charge cloud represents a current pulse that could propagate outward at a speed comparable to the values measured during the impact experiments (Freund, 2000), 100–300 m/sec. Any such current pulse is accompanied by a local magnetic field. Because the current waxes and wanes, it emits EM radiation, the frequency of which depends on the time derivative of the current pulse.

Any p-holes that flow out have a given mobility, which is different from the mobility of the charge carriers, protons or electrons, that flow in. Two currents in opposite directions that are coupled through their electric field can go into oscillations. Hence, the outflow of p-holes from the source volume and the backflow of compensation charges may lead to repetitive current pulses that could last as long as the p-hole generation process is ongoing.

Magnetic Field Anomalies

Figure 9a through c illustrates a case, which may be an outstanding example of oscillating currents and their associated magnetic field anomalies. In 1999 an 8-station magnetometer network was in operation in Taiwan, recording the magnetic fields at their locations every 10 min. Two stations are situated close to the 120-km-long, S–N-trending fault line that ruptured during the September 21,

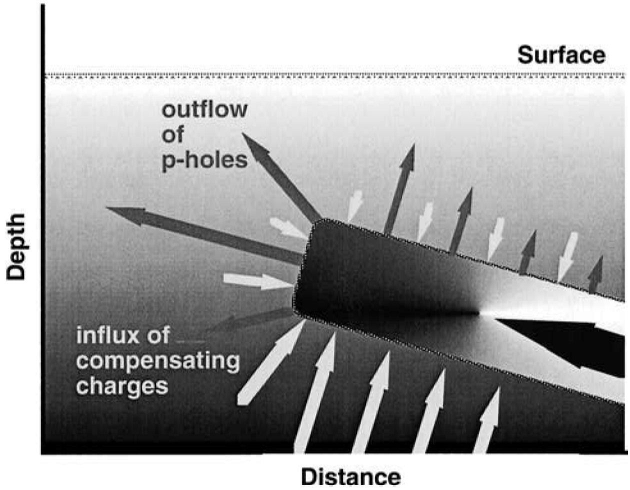


Fig. 8. Cross section through a slab (source volume) pushed from right to left with p-holes flowing out and compensating charges flowing into the rock.

1999, M = 7.7 Chi-Chi earthquake, causing vertical displacements of nearly 10 m: station LY about 20 km N of its northern end and station TW about 60 km S of its southern end, close to the October 22, 1999, M = 7.1 Chai-Yi aftershock. LY recorded strong magnetic field fluctuations that began about two months before the Chi-Chi earthquake and lasted until the Chai-Yi aftershock. TW recorded fluctuations that moved southward after the Chi-Chi event and ended shortly after the Chai-Yi aftershock. None of the HL, YL, and TT stations along the Pacific coast recorded any comparable fluctuations (Liu et al., 2001).

The signals recorded at the three Pacific coast stations were subtracted from the LY signals to remove ionospheric magnetic storm contributions, due to the solar wind interacting with the Earth's magnetosphere and ionosphere. The subtraction leaves a small ripple of diurnal variations during quiet time (Figure 9a). The ripple and the offset in the overall values are due to latitude differences in the station locations. By contrast, large magnetic field pulses were recorded during active time, prior to the Chi-Chi earthquake and through the aftershock series. The magnitudes of the magnetic field anomalies are of the order of 100–200 nT, almost 0.5% of the Earth's magnetic dipole field (Figure 9b). These anomalous pulses are local and as such are associated with the impending earthquake. They display a complex periodicity. The individual magnetic pulses during the last days before the Chi-Chi earthquakes are well separated from each other (Figure 9c). Most are slightly asymmetric with a sharp onset and trailing end as one would expect from an oscillating coupled two-current system, where each pulse begins with a sudden outflow of charge carriers. Each pulse lasted typically for several hours.

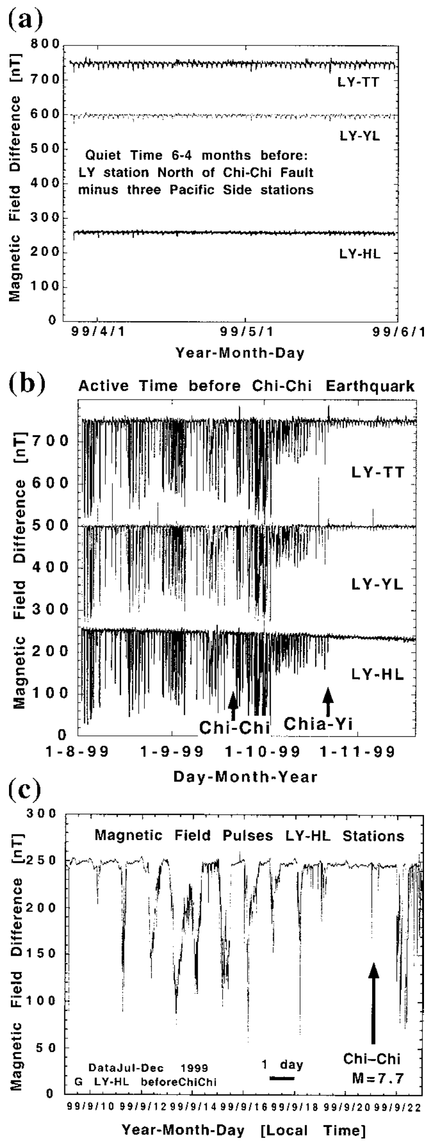


Fig. 9. (a) LY-TT, LY-YL, and LY-HL signals during a quiet period, April–June 1999; (b) LY-TT, LY-YL, and LY-HL signals during an active period, August–December 1999, which includes the Chi-Chi earthquake and Chai-Yi aftershock; (c) enlarged LY-HL section, 14 days long, spanning the Chi-Chi event (unpublished data, courtesy of Horng-Yuan Yen, National Central University, Taiwan).

Low-Frequency EM Signals

When currents wax and wane in the Earth's crust over periods of a few hours per pulse, strong enough to generate magnetic field anomalies as shown in Figure 9, they will radiate strongly in the low-frequency magnetic regime. Indeed, around the same time as the magnetic field anomalies began in Taiwan, an increase in the ultra–low frequency (ULF) noise level in the 0.007–0.013-Hz window was observed in Japan (Akinaga et al., 2001; Ohta et al., 2001), suggesting that the ground currents in Taiwan led to EM emission, which propagated over more than 4000 km through the ionospheric conductor.

There have been numerous reports, some very well documented, of earthquake-related ULF, ELF and VLF (extremely and very low frequency–) EM emissions measured on the ground (Bilichenko et al., 1990; Dea et al., 1991; Fraser-Smith, 1992; Ismaguilov et al., 2001; Molchanov et al., 1992; Park et al., 1993) and measured from satellites (Hayakawa et al., 1990; Molchanov et al., 1993; Parrot, 1994; Serebryakova et al., 1992). Likewise, there have been attempts to devise a mechanism that could account for these phenomena (Chen et al., 1994; Molchanov & Hayakawa, 1998). These attempts have not led to a broadly accepted explanation, presumably because p-holes had not yet been recognized as the charge carriers that can be generated in the crust and produce currents of large magnitude. With this knowledge now available, it may be possible to re-evaluate earlier ULF, ELF, and VLF observations and provide physically more advanced explanations for these and other observations to come.

Earthquake Lights, Ball Lightning, and High-Frequency Static Noise

If and when p-hole charge clouds reach the surface of the Earth, high electric fields develop locally at the ground-to-air interface, as outlined above. The fields will be particularly high at topographic convex points such as hills, ridges, and mountain peaks. As a consequence of these electric fields a thin layer of near-ground air will become ionized, causing an instant and dramatic rise of the conductivity of the air. At nearby concave points the electric fields will naturally be lower. Hence, lateral electric field gradients develop, which may initiate corona discharges similar to those observed by Brady and co-workers during laboratory experiments (Brady & Rowell, 1986; Cress et al., 1987) and similar to the delayed flashes of light observed during the time-resolved low-velocity impact experiments (Freund, 2000, 2002a). These flashes came from the edges of the rock cylinders as mentioned above, i.e., from places with small radii of curvature, where the p-holes would reach the highest densities, create the highest electric fields, and initiate closed-loop discharges.

When such corona discharges occur in nature, several consequences can be predicted. Light emission from ionized or electronically excited air molecules during corona discharges is the probable cause of those luminous phenomena that have been reported as earthquake lights as reviewed by Derr (1973, 1986).

Such earthquake lights were photographed on September 26, 1966, during an episode of the Matsushiro earthquake swarm in Japan, that began in mid-1965 and produced over 60,000 earthquakes with magnitudes up to 5.5 over a period of nearly two years (Corliss, 2001). Over 100 sightings of earthquake lights have been reported in Québec, Canada, between November 1988 and January 1989, during the Saguenay earthquake sequence, including a rapidly propagating sheet of light just before the largest shock, witnessed 19 km from the epicenter (Ouellet, 1990; St-Laurent, 2000). This moving sheet of light, which was accompanied by a bristling noise in the trees, might have been the front of a solid state plasma produced during the last moments before the catastrophic rupture of rocks, spreading ahead of the seismic waves.

High-frequency EM emissions that accompany corona discharges are also a plausible cause for the high-frequency noise, i.e., static, that has been noted for years by radio operators and airplane pilots prior to major earthquakes and that affected very wide areas before the large 1960 Chile and the 1964 "Good Friday" earthquake in Alaska (Davis & Baker, 1965; Warwick et al., 1982).

The phenomenon of ball lightning, called "an unsolved problem in atmospheric physics" (Stenhoff, 1999), may be another example of an unusual phenomenon. Ball lightnings are free-floating volumes of ionized air that detach themselves from the ground. According to eyewitness reports, small ball lightnings have entered into rooms through windows, often without leaving a trace or any cracks in the glass, or have entered rooms through telephone jacks and electric sockets. While drifting through the air, the balls reportedly produce a faint hissing sound. They explode with a bang after a few seconds and leave behind a smell of ozone (Grigor'ev et al., 1992). Such balls of ionized air seem to appear before or during large thunderstorms and before or during seismic activity. In the case of earthquakes, these plasma balls may detach themselves from the ground when clouds of p-hole charge carriers arrive at the Earth's surface, leading to high electric fields, similar to the fields measured during periods of intense thunderstorm and lightning activity (Derr & Persinger, 1986).

Animal Response to Impending Earthquakes

When Tributsch published his book *When Snakes Awake* (Tributsch, 1983), he reported on the rich folklore that surrounds numerous non-seismic pre-earthquake phenomena. After telling of his own childhood experience during the M = 6.6 Friuli earthquake of May 6, 1976, in the Italian Alps north of Venice, he describes observations reported from many parts of the world across centuries and across cultures. Implicit in Tributsch's description is the belief that observations made at so many different places and at different times by people who did not know of each other must be based on real effects occurring in nature, and that the reported phenomena, enigmatic as they are, will one day become accessible to scientific clarification. It is difficult to say whether this time has already come, but the discovery of PHPs, the dormant charge carriers in igneous and high-grade metamorphic rocks, and of p-holes, which the PHPs release when activated, gives us hope that we may be one major step closer to an elusive goal.

Among the most enigmatic and controversial pre-earthquake phenomena are the various expressions of unusual animal behavior. Tributsch (Tributsch, 1983) took the title of his book from the widely reported observations that hibernating ground-dwelling animals such as snakes have been seen crawling out of their dens in mid-winter. Other, lower animals such as earthworms reportedly emerge from the earth in unusual numbers and at unusual times. Chickens and other birds get restless, horses and cows become agitated, and dogs howl the night before a major earthquake. The tone regarding how to deal with these reports has been set by the remark in the 7th edition of Milne's classical textbook *Earthquakes and other Earth Movements* (Milne & Lee, 1939): ''The most common report of the behaviour of dogs at the time of the San Francisco disaster of 1906 was that they howled during the night preceding the earthquake, implying that they sensed the impending disaster. It is very difficult to accept such a suggestion for there is no scientific explanation as to why dogs should have been gifted with these premonitions''.

Later attempts to find a rational explanation for the thousands of anecdotal reports on animal behavior have centered on low-intensity and low-frequency ground vibrations or on very weak ULF–VLF emissions, to which animals may possess a heightened sensitivity (Adair, 1991; Kirschvink, 1992; Maximova, 1987). I have described above the laboratory evidence that relatively modest positive potentials at the surface of granite in which p-holes are activated can lead to such high electric fields as to induce the emission of positive ions. This observation fits well into the overall picture of corona discharges and similar electric phenomena, and it opens the door to an entirely different explanation for the strange animal behavior observed before many earthquakes.

Air-borne ions have reportedly a pronounced biological impact on humans and animals (Charry, 1984; Krueger & Reed, 1976). Exposure to negative ions is generally perceived by humans as pleasant, may enhance the cognitive performance, and has overall beneficial health effects (Baron, 1987). By contrast, positive ions elicit adverse reactions including headaches, nausea, depression, and overall ill feelings. Adiabatically compressed, katabatic winds, blowing downslope, are known in the Alps as Foehn, in the Rocky Mountains as Chinook, and in Southern California as Santa Ana (Byers, 1974). Such winds are laden with positive ions and are reputably the source of increased levels of tension and irritability in the general population.

Combining these known adverse physiological effects of positive ions on humans with the build-up of positive surface charges at the Earth's surface, due to the arrival of p-hole charge clouds, suggests that animals may react to the positive ions that are most likely emitted from the ground. This would provide a more consistent, and probably testable, explanation for the reported unusual animal behavior prior to large earthquakes than the alleged sensitivity of animals to minute vibrations or very low-intensity EM emission, which seem not to be supported by other evidence.

Ionospheric Perturbations

Going from the small to the large, the list of pre-earthquake phenomena includes many reports on ionospheric perturbations on the scale of 1000 km or more (Davies & Archambeau, 1998; Davis & Baker, 1965; Gokhberg et al., 1988; Pulinets, 1998). These perturbations are generally observed about 5–10 days before large seismic events and disappear within 1–2 days. They are well documented in Taiwan (Liu et al., 2000), where they are characterized by a modification in the lowermost ionospheric layer, the F layer. The F layer is dominated by positive ions and, hence, is positively charged. It appears that, prior to large earthquakes, a strong electric field builds up on the ground, the polarity of which is most often such that it pushes the F layer aside, allowing energetic electrons from the higher ionospheric layers to penetrate to lower levels.

Such a positive electric field rising from the ground is consistent with the ideas presented here, namely that p-hole charge clouds, which arrive at the Earth's surface, generate a positive ground potential. What may be surprising is the magnitude of the electric field on the ground required to have an effect on the ionosphere more than 100 km above the Earth's surface. The lithosphere–ionosphere coupling has been modeled (Grimalski et al., in press; Pulinets et al., 2000) in spite of the uncertainties about the mechanism that causes such fields.

The discovery of p-holes as powerful charge carriers that are activated through high levels of stress in the Earth's crust before earthquakes may also provide an answer to ionospheric perturbations. If p-hole charge clouds spread to the surface, they not only generate high electric fields at the rock-to-air interface but also lead to an overall increase in the ground potential. If the Earth's ground reaches sufficiently high positive values, we have a situation that can be described as a capacitor. The Earth's surface represents one fixed capacitor plate. The lower edge of the highly conductive ionosphere represents the opposite capacitor plate, which can move up or down or to the side. If the positive ground potential increases due to the arrival of p-hole charge clouds, the associated electric field is bound to affect the ionospheric capacitor plate.

In this context it is worth noting that very little seems to be known how the ground potential of the Earth—the common "ground" to which we reference locally all electric installations and measurements—changes over lateral distances of hundreds and thousands of kilometers and as a function of time. It would appear to be an attractive project to devise methods for monitoring the ground potentials on a regional scale and to correlate the measured values with earthquake activity.

Conclusions

What is so attractive about p-hole charge carriers is that they seem to provide a unified concept that links together an array of apparently disconnected phenomena reported in the context of impending earthquake activity. These phenomena span the range from animal behavior to ionospheric perturbations, with a number of hitherto poorly understood electric, magnetic, electromagnetic, visible and infrared emissions nested in between. Over the years a sufficiently large body of knowledge has accumulated, which allows me to be optimistic that we have correctly interpreted the basic properties of p-holes and their parents, the peroxy bonds or PHPs, even though many details remain unexplored and must be studied in the years to come.

These hopeful words should not hide the fact that, until now, the geoscience community at large has not accepted the notion that p-holes exist in minerals and rocks, and that they may have a profound effect on many properties of these materials and on processes of general geological and geophysical interest. There are several causes for the widespread resistance.

Published information about p-holes, in particular about their contribution to the electrical conductivity of minerals and rocks, is still scarce. This is largely due to the fact that the peer review system often creates near-insurmountable hurdles against the publication of data that seem contrary to long-held beliefs. Most editors of mainstream science journals are themselves part of the mainstream circle. Hence, in cases of adversarial comments from mainstream reviewers, they tend to lean to the "safe" side and reject manuscripts submitted for publication.

For over a hundred years geoscientists have been trained to think of oxygen anions in natural materials as O^{2-} and nothing but O^{2-}. To introduce O^{-} as a new variant, but at the same time point to the fact that O^{-} is not an ion but an electronic state with unusual properties, most appropriately discussed within the framework of semiconductor physics, requires a level of rethinking for which most geoscientists are ill-prepared.

Lastly, once fully told and understood, the "story" of p-holes is basically so simple that many mainstream geoscientists are left to wonder why it has taken so long for them to be discovered. If they are so ubiquitous as they appear to be, why did p-holes go unnoticed for over a hundred years? Confronted with this question, by a twist of logic, many "mainstreamers" succumb to the impulse to reject the p-hole concept out of hand.

The difficulties encountered in the connection with p-holes are similar to others that have punctuated the history of science. The discovery of the p-holes as dormant yet powerful charge carriers in the Earth's crust calls for a new paradigm in earthquake research and beyond. More often than not, any call for a new paradigm elicits opposition. Therefore, I close with a quote from the philosopher Arthur Schopenhauer, who ventured to say: "All truth passes through three stages. First, it is ridiculed. Second, it is violently opposed. Third, it is accepted as being self-evident".

Acknowledgements

The ideas underlying my approach to non-seismic pre-earthquake phenomena evolved over many years, starting with work on defects introduced into oxide crystals through the dissolution of small amounts of gaseous components, in particular H_2O. The early work was supported by the Deutsche Forschungsgemeinschaft in Germany, later work supported by grants from NASA, including grants from the NASA Ames Research Center Director's Discretionary Fund and from NSF. A number of students helped with laboratory experiments and data analysis. I am indebted to my former doctoral students Reinhard Martens, Hendrik Kathrein, Heinz Wengeler, and Rolf Knobel, as well as to students from San Jose State University, in particular Eun-Joo Whang, Michael M. Masuda, Tuyen Vo, and Paul Gosling. My introduction into the wide-open field of earthquake precursor phenomena has been greatly helped by discussions with Masashi Hayakawa, University of Electro-Communications, Tokyo; Seiya Uyeda, Tokai University, Japan; Jann Yeng Liu, National Central University (NCU), Taiwan; and Dimitar Ouzounov, NASA Goddard Space Flight Center. Ying-Wei Fei, Geophysical Laboratory, Carnegie Institution of Washington, provided access to crucial high-pressure equipment. Horn-Yuan Yen and his coworkers at NCU provided unpublished data on the magnetic field anomalies linked to the Chi-Chi earthquake.

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